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Étude du confort et l'efficacité énergétique d'un ERP en milieu méditerranéen

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Study of the comfort and energy efficiency of an ERP building in a Mediterranean environment

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With heartfelt gratitude,

Keovathana RUN
À Montpellier, le 15 juin 2024

Résumé

L'intersection entre le confort de l'usager, la qualité de l'environnement intérieur (QEI) et l'utilisation de l'énergie vise à concevoir un environnement bâti durable peu énergivore qui respecte le confort de l'usager. Bien que l'Union Européenne cherche à réduire la consommation énergétique du secteur du bâtiment, équilibrer efficacement les trois aspects reste un défi majeur. Malgré les recherches sur la performance énergétique post-rénovation, des lacunes persistent concernant son impact réel sur la QEI et la satisfaction du confort des usagers.

L'objectif principal de cette étude est d'analyser en profondeur la QEI, en se focalisant sur le confort thermique et la qualité de l'air intérieur dans les bâtiments universitaires avant et après les rénovations, tout en prenant en compte la satisfaction des usagers. Des capteurs climatiques et des compteurs électriques ont été installés sur le campus de l'IUT de Nîmes, situé dans le sud de la France. 43 salles de classe, 35 ateliers et 16 bureaux répartis dans quatre bâtiments du campus ont été équipés de capteurs climatiques, surveillant en continu la température, l'humidité relative et les niveaux de CO_2 depuis 2020. Des enquêtes ont également été menées à quatre reprises pour évaluer les perceptions des étudiants concernant la QEI en fonction de l'état des bâtiments (avant et après la rénovation) pendant l'hiver et l'été. Cette étude a utilisé des approches rationnelles et adaptatives pour évaluer le confort thermique.

L'étude révèle un défi persistant pour atteindre le confort thermique à l'IUT de Nîmes pendant l'été, en particulier dans les salles d'atelier malgré les rénovations, en raison des conditions climatiques très chaudes de la région. Les bâtiments rénovés ont montré de meilleures performances en termes de consommation d'énergie sans compromettre excessivement le confort des utilisateurs, mais leur étanchéité accrue a rendu la qualité de l'air intérieur plus dépendante des systèmes de ventilation mécanique, suscitant des préoccupations quant au maintien d'un débit de ventilation constant et adéquat.

Les précédentes thèses du LMGC sur le sujet (Batier, Abbas) utilisaient des scénarios très simplifiés. Cette recherche conclut qu'étudier des paramètres de bâtiments réels est très complexe et rend une analyse peu précise en raison des diverses variables incontrôlables telles que les conditions environnementales intérieures et extérieures, les activités, les comportements des occupants. Dans le futur, il faudra envisager un intermédiaire entre ces deux approches.

Mots clés: confort thermique, qualité de l'air intérieur, bâtiments éducatifs, rénovation, énergétique du bâtiment

Abstract

The intersection between user comfort, Indoor Environmental Quality (IEQ), and energy usage forms a sustainable built environment centered around user needs. The European Union is seeking to reduce the energy consumption of the building sector, however, effectively balancing the three aspects remains a major challenge. Following the energy-efficient renovation, the energy performance has been studied and discussed amongst researchers, but significant gaps remain in investigating its impact on IEQ and user comfort in real settings.

The primary goal of this study is to conduct a comprehensive analysis of the IEQ, focusing on thermal comfort and indoor air quality within university buildings before and after renovations by taken into account the users' satisfaction. For these objectives, climate sensors and electric meters were installed within the IUT of Nîmes campus, situated in the south of France under a Mediterranean climate. A total of 43 classrooms, 35 workshop rooms, and 16 offices across four buildings on the campus were equipped with climate sensors, which have been continuously monitoring indoor temperature, relative humidity, and CO_2 levels since 2020. Moreover, field surveys were conducted four times to report the students' IEQ perceptions in response to the building states (pre- and post-renovation) during the winter and summer. To assess thermal comfort, this study employed both rational and adaptive approaches.

The study reveals an ongoing challenge with attaining thermal comfort in the IUT of Nîmes during the summer, particularly in the workshop rooms despite renovations due to the region's hot climate conditions. Overall, the renovated buildings have proved to perform better in terms of energy usage without excessively compromising indoor climates or users' comfort. However, it is noteworthy that the now-airtight buildings have made indoor air quality more reliant on mechanical ventilation systems, raising concerns about maintaining a consistent and adequate ventilation rate.

Previous LMGC theses on the subject (Batier, Abbas) used very simplified scenarios. This research concludes that studying the parameters of real buildings is very complex and renders the analysis imprecise because of the various uncontrollable variables such as indoor and outdoor environmental conditions, activities, and occupant behavior. In the future, an intermediary between the two approaches should be considered.

Keywords: thermal comfort, indoor air quality, educational buildings, renovation, building energy

Résumé étendu (Extended summary in French)

Introduction

En réponse au réchauffement climatique et aux enjeux de sécurité énergétique, la rénovation des bâtiments existants pour accroître leur efficacité énergétique suscite un intérêt croissant. Le secteur du bâtiment, grand consommateur d'énergie, offre une opportunité majeure de réduire les émissions de carbone. En Europe, où 35% du parc immobilier remonte à avant 1960, entraînant une faible performance énergétique, la rénovation de ces bâtiments s'aligne sur les objectifs énergétiques de l'UE et améliore la qualité de l'environnement intérieur (QIE).

Cependant, il est crucial d'équilibrer soigneusement les stratégies de rénovation, car elles peuvent parfois avoir un impact négatif sur la QIE. La relation entre les rénovations énergétiques et la qualité de l'environnement intérieur doit être gérée avec précaution.

Objectifs de la recherche

Cette thèse vise à établir le lien entre le confort des occupants et la consommation énergétique de chauffage, intégrant ainsi le confort thermique dans la conception de bâtiments écoénergétiques. Les objectifs sont les suivants :

1. Examiner le climat intérieur, en tenant compte des éléments déterminants du confort thermique et de la qualité de l'air avant et après la rénovation des bâtiments.
2. Évaluer l'impact des rénovations énergétiques sur le confort thermique des occupants.
3. Analyser la performance énergétique des bâtiments post-rénovation.

Étude de cas

Conditions climatiques

L'étude de cas se déroule à Nîmes, située à 43,49° de latitude nord et 4,19° de longitude, est une ville du sud de la France, dans la région Occitanie. Proche de la mer Méditerranée, Nîmes est

influencée par un climat méditerranéen de type Csa selon la classification de Köppen et Geiger, se caractérisant par des hivers doux et humides ainsi que des étés chauds à très chauds et secs.

IUT de Nîmes

Cette étude se concentre sur la rénovation énergétique récente des bâtiments scolaires existants du campus de l'IUT de Nîmes, comprenant six bâtiments indépendants construits à la fin des années 1960, totalisant 23 217 m^2 de surface utile. Ces bâtiments comprennent un bâtiment administratif (BC), quatre bâtiments d'enseignement (GMP/SGM, GC, GEII, GEA), et un bâtiment résidentiel, avec les bâtiments BC, GMP/SGM, GC, et GEII représentant 91% de cette surface.

L'objectif principal des projets de rénovation de l'IUT de Nîmes est d'améliorer l'efficacité énergétique des bâtiments, impliquant les actions suivantes :
- Ajouter une isolation extérieure à l'enveloppe du bâtiment
- Remplacer les fenêtres
- Mettre en place un nouvel éclairage
- Intégrer un système de ventilation mécanique à simple flux
- Améliorer le contrôle et la surveillance de la consommation énergétique du bâtiment

Outils et méthodologie

Mesure physique et hypothèses

Depuis 2020, les bâtiments de l'IUT de Nîmes sont équipés de capteurs climatiques (Class'Air et Elsys) qui mesurent en continu la température de l'air intérieur (T_{in}), l'humidité relative (RH_{in}), et les niveaux de dioxyde de carbone (CO_2). Class'Air a une précision de ± 0,1°C, 1%, et ± 50 ppm + 3%, avec une fréquence de 60 minutes. Elsys offre une précision similaire de ± 0,2°C, 2%, et ± 50 ppm + 3%, mais avec une fréquence de 15 minutes.

Les données relatives au taux métabolique, à l'isolation des vêtements, et à la vitesse de l'air ont été estimées selon la norme ISO 7730. On a supposé que les vêtements de l'étudiant offraient une isolation de 1 clo en hiver et de 0,5 clo en été. Le "clo" est une valeur qui décrit le degré d'isolation fourni par un article vestimentaire. Une valeur clo de 1 correspond à la quantité de vêtements nécessaire à un être humain au repos pour maintenir son confort thermique à une température ambiante de 21°C (1 clo = 0.155 $K.m^2.W^{-1}$). Le taux métabolique a été fixé à 1,2 pour une activité sédentaire. Les vitesses d'air ont été estimées en fonction de la saison, soit 0,2 $m.s^{-1}$ en été et 0,0015 $m.s^{-1}$ en hiver, en se basant sur les taux de renouvellement d'air naturel en hiver et l'ouverture des fenêtres en été.

Questionnaire d'enquête

Pour étudier l'impact de la rénovation, une enquête a été menée en trois phases : hiver 2022, hiver 2023, et été 2023, permettant ainsi d'analyser les conditions avant et après la rénovation pour ces deux saisons.

Au total, 1 047 réponses ont été obtenues, réparties entre 339 pour l'hiver 2022, 437 pour l'hiver 2023, et 271 pour l'été 2023. En raison de données manquantes dans les capteurs physiques, le résultat final comprend 981 réponses valides, collectées dans trois bâtiments (GC, GEII, et GMP) et 36 pièces (27 salles de classe et 9 ateliers).

Résultats

Climat intérieur

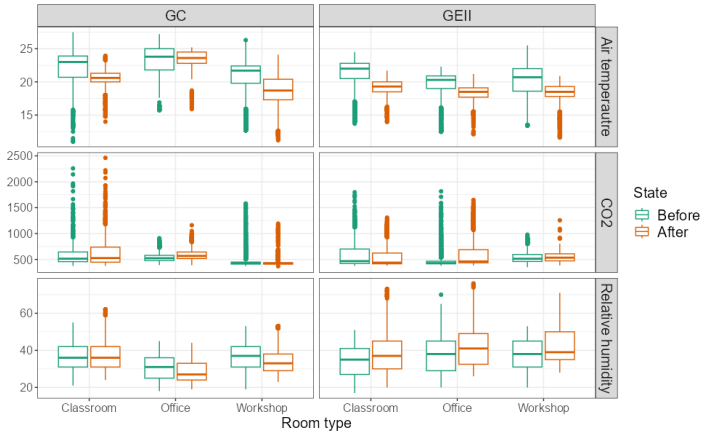

Fig. 0-1. *Boîte à moustaches du climat intérieur dans différents types de pièces en semaine pendant les heures d'occupation de 8h00 à 18h00*

La figure 0-1 présente un diagramme en boîte à moustaches des salles de classe, bureaux et ateliers, illustrant le climat intérieur pendant les heures de cours (8h00-18h00) en semaine. Selon la norme EN 15251 en France, les plages de température intérieure acceptables pour les bâtiments scolaires, catégorie II (rénovés) et catégorie III (existants), sont respectivement de 20°C à 24°C et de 19°C à 25°C. Les concentrations de CO_2 sont de 500 ppm et 800 ppm, avec une humidité relative de 25% à 60% et 20% à 70%. Un article récent du journal de l'ASHRAE remet en question la limite de 1000 ppm de CO_2 dans les environnements intérieurs [1]. Cependant, les valeurs moyennes de CO_2 et HR_{in} dans les bâtiments et les États respectent les recommandations.

Confort thermique

Pour une analyse comparative de la sensation thermique, les données d'enquête (TSV) et les votes moyens prédits (PMV) sont examinés en relation avec la température opérative (T_{op}), comme présenté dans la figure 0-2.

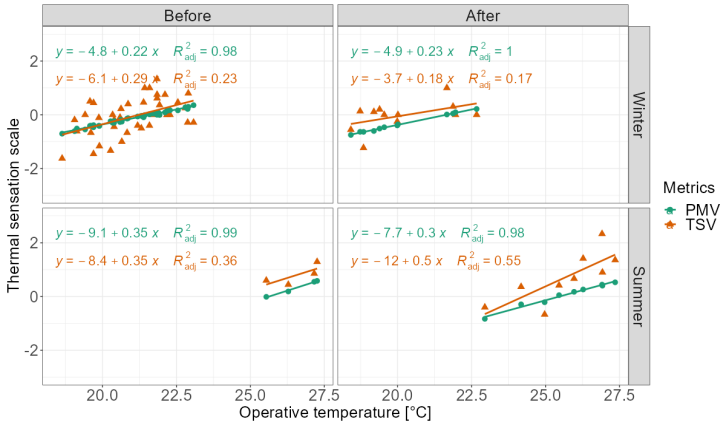

Fig. 0-2. *Vote sur la sensation thermique par rapport au vote moyen prédit*

Les lignes de régression proposées pour le vote moyen prédit (PMV) et le vote de sensation thermique (TSV) montrent une corrélation étroite avec la température opérative en hiver. Cependant, en été, un écart plus marqué entre les deux modèles apparaît, avant et après la rénovation. Ce résultat suggère que le modèle PMV est fiable pour estimer les sensations des occupants lors de conditions hivernales douces (18°C à 22,5°C). En revanche, avec des températures estivales dépassant 25°C, le modèle PMV a tendance à surestimer la sensation de fraîcheur, indiquant une possible surestimation de la tolérance à la chaleur des occupants.

Consommation d'énergie

La figure 0-3 montre la relation entre la consommation hebdomadaire d'énergie par surface utilisable et les degrés-heures de chauffage hebdomadaires des deux sections rénovées (bâtiments GC et GEII) et de la section non rénovée (bâtiment GMP) du 22 décembre 2023 au 7 janvier 2024. La pente moins accentuée de la ligne de régression du bâtiment GC (0,69) par rapport à celle du bâtiment GMP (1,15) indique une consommation d'énergie environ 40% moins élevée pour les bâtiments non-rénovés. Les pentes similaires des lignes de régression pour les bâtiments GC et GEII (0,69 contre 0,73, respectivement) suggèrent des niveaux de consommation comparables, compte tenu de leurs mesures de rénovation identiques.

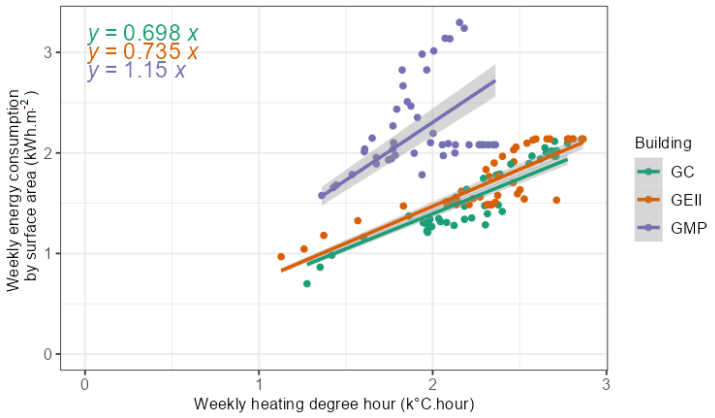

Fig. 0-3. *La relation entre la consommation hebdomadaire d'énergie par surface utile et les degrés-heures de chauffage hebdomadaires des sections d'enseignement GC, GEII et GMP du 22 décembre 2023 au 7 janvier 2024.*

Conclusion

En conclusion, la rénovation énergétique a considérablement réduit la consommation d'énergie du bâtiment, tout en ayant un impact légèrement négatif sur les paramètres du climat intérieur, notamment le CO_2. Bien que ces valeurs approchent la limite de la zone de confort recommandée, elles demeurent dans des fourchettes acceptables selon les normes de construction. Les ajustements mineurs dans le climat intérieur n'ont pas notablement altéré la satisfaction des occupants en termes de sensation, d'acceptabilité et de préférence. L'intégration de scénarios réels a fourni des informations précieuses sur les résultats de la rénovation, offrant une compréhension nuancée du comportement des occupants, des défis inattendus, et de la performance effective des mesures mises en œuvre. Cette perspective est importante pour affiner les stratégies d'efficacité énergétique et assurer leur succès dans des environnements variés et dynamiques.

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List of acronyms

Acronym	Description
ASHP	Air-Source Heat Pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BBC	Bâtiment Basse Consommation
BEPOS	Bâtiment à Energie POSitive
BPIE	Building Performance Institute Europe
CDD_{25}	Cooling Degree Day base 25°C (°C.d)
CPER	Contract Plan Etat Région
DH	District Heating
DJU	Unified Degree Day (°C.d)
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificates
GHG	Greenhouse Gas
HDD_{18}	Heating Degree Day base 18°C (°C.d)
HVAC	Heating Ventilation Air-Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
IUT	Institut Universitaire de Technologie
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
ML	Machine Learning
MLR	Multiple Linear Regression
MSE	Mean Square Error
nZEB	nearly Zero Energy Buildings
OEHM	Optimisation Energétique de l'Habitat Méditerranéen
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
R	Coefficient of determination

RE	Réglementation Energétique
RED	Renewable Energy Directive
REPOS	Régions à Énergies POSitives
RMSE	Root mean square error
RT	Réglementation Thermique
SBS	Sick Building Syndrome

List of symbols

Symbol	Unit	Description
b_i	-	Reduction factor of fabric's temperature
C	$W.m^{-2}$	Convective heat loss
C_{res}	$W.m^{-2}$	Respiration heat loss by convection
D	-	Number of days of the month
E_{res}	$W.m^{-2}$	Respiration heat loss by evaporation
$E_{rsw,req}$	-	Sweat flow
E_{sk}	$W.m^{-2}.k^{-1}$	Evaporating heat loss
F	-	Reduction factor of the insulation
f_{cl}	-	Clothing surface area factor
h_c	$m^2.K.W^{-1}$	Convective heat transfer coefficient
HR_{ext}	%	Outdoor relative humidity
HR_{in}	%	Indoor relative humidity
H	$W.K^{-1}$	Total heat loss coefficient of the building
H_T	$W.K^{-1}$	Specific transmission loss through each building fabric
H_V	$W.K^{-1}$	Specific heat loss through ventilation
I_{cl}	$m^2.K.W^{-1}$	Clothing insulation
K	$W.m^{-2}.^{\circ}C^{-1}$	Heat loss density
l	m	Transmission length
M	$W.m^{-2}$ or met	Metabolic heat production rate
N	-	Number of predictions
p_a	Pa	Vapor pressure of the surrounding air
Q_1	kWh	Total heat loss
Q_g	kWh	Total heat gain
Q_h	kWh	Total heat demand
Q_i	kWh	Internal heat gain
Q_s	kWh	Solar gains for each window
R	$W.m^{-2}$	Radiant heat loss

S	m^2	Transmission surface area
SR	$MJ.m^{-2}$	Solar radiation
t	h	Time constant
t_a	°C	Air temperature
t_{cl}	°C	Clothing surface temperature
Tej_{min}	°C	Minimum daily outdoor temperature
Tej_{max}	°C	Maximum daily outdoor temperature
T_{ext}	°C	Outdoor temperature
T_{in}	°C	Indoor temperature
t_{mr}	°C	Mean radiant temperature
$t_{sk,req}$	°C	Skin temperature
U_i	$W.m^{-2}.K.^{-1}$	Transmission coefficient
$\dot{V}$	$m^3.h^{-1}$	Air flow rate
V_{ar}	$m.s^{-1}$	Relative air velocity
W	$W.m^{-2}$	Mechanical work rate
x_1	-	Day index (weekday, weekend and vacation)
x_2	-	Time index (daytime, nighttime)
x_3	-	Orientation (North and South)
x_4	m^2	Surface area (Big, Small)
x_5	%	Outdoor humidity relative
x_6	%	Indoor humidity relative
x_7	°C	Outdoor temperature
x_8 to x_{13}	°C	Delayed of 2 to 7 hours of outdoor temperature
x_{14}	ppm	CO_2
x_{15} to x_{20}	ppm	Delayed of 2 to 7 hours of CO_2
x_{21}	$MJ.m^{-2}$	Solar radiation
x_{22} to x_{27}	$MJ.m^{-2}$	Delayed of 2 to 7 hours of solar radiation
$\hat{y}$	-	Rredicted value of y
$\bar{y}$	-	Mean value of y
y_i	-	Value of y at the ith*moment*
η	-	Utilisation factor for heat gain
γ	-	Relative heat gain
Φ_i	$W.m^{-2}$	Power density of internal heat gain
ψ	$W.m^{-1}.K^{-1}$	Thermal bridge coefficient

General Introduction

"If we knew what it was we were doing,
it would not be called research, would it?"

— ALBERT EINSTEIN

Motivation

In 2022, the building sector in France accounted for 18% of national emissions and consumed 45% of final energy, driving the need for transformative changes in energy efficiency [2]. To combat climate change, protect the French from rising energy prices, and improve their quality of life, many legislative and regulatory tools regarding building renovation have been implemented to change the approach to energy efficiency. Public buildings in the south of France face unique challenges due to climatic variations, including extreme heat conditions and heatwaves, coupled with mid-low adaptation capabilities, making the region particularly susceptible to the impacts of climate change [3].

Indoor environments significantly impact occupants, who spend over 80% of their time indoors [4]. Poor indoor climate quality has been linked to discomfort, health issues, and reduced productivity [5–10]. Existing buildings pose a challenge to achieving optimal Indoor Environmental Quality (IEQ) conditions, emphasizing the need for a comprehensive approach to support policies and guide investments in building refurbishments [11, 12].

However, attaining both energy efficiency and good IEQ simultaneously is a challenging task, as these two factors often work against each other. Furthermore, field studies concerning the evaluation of energy-efficient impact, IEQ, and users' comfort have yet to be extensively discussed in the current literature. This dissertation aims to address this gap by exploring the intricate relationship between energy-efficient renovations and occupants' comfort, particularly in Mediterranean weather conditions. The findings are anticipated to provide valuable evidence supporting further investments in renovation projects, emphasizing the importance of harmonizing energy efficiency and IEQ for sustainable building practices.

Background

This thesis is part of the OEHM project (Optimisation Energétique de l'Habitat Méditerranéen), which centers around enhancing the digital simulation of residential buildings by incorporating physical phenomena and user behavior. The goal is to improve the predictive accuracy of energy rehabilitation efforts in Mediterranean residences, particularly addressing the sensitivity to summer comfort and the crucial interplay of user behavior and building energy efficiency.

A thesis by Batier Cécile showed the effect of user behavior on their comfort in hot weather in residential buildings. This work made it possible to identify user behavior without going into detailed simulations. Another thesis by Abbas Abbas modeled an experimental building in as much detail as possible using the previously identified scenarios.

The University of Montpellier was funded by the CPER (Contract Plan Etat Région) 2015–2020 project to undergo a renovation to improve energy performance and reduce consumption. This priority aligns with the group's REPOS strategy of the Occitanie "Positive Energy Region" strategy. A BEPOS (Bâtiment à Energie POSitive - Positive Energy Building) objective will be sought for all suitable building projects.

In continuation of the OEHM project and in line with previous initiatives, this thesis seizes the opportunity to comprehensively investigate the renovated buildings on the IUT de Nîmes campus. The primary focus is identifying user comfort and energy efficiency, pre- and post-renovation, contributing to a broader understanding of Mediterranean building dynamics.

Research questions

This thesis asks three primary questions:

Q1: How does the interplay between IEQ, occupants' satisfaction, and energy consumption unfold in the context of energy-efficient renovations?

Q2: What are the critical factors in energy-efficient renovations that have been overlooked in simulation studies?

Q3: What insights does the real-world scenario provide into the outcomes of energy-efficient renovations?

Main objectives of the thesis

The main objective of this thesis is to formulate the relationship between occupants' comfort and heating energy consumption and to integrate occupants' thermal comfort in the design of energy-efficient buildings. The specific objectives are outlined as follows:

1. Investigate the indoor climate, considering elements that characterize thermal comfort and indoor air quality, in the buildings during pre- and post-renovation phases.

This objective is discussed in Chapter 3, Section 1 and Section 3

2. Assess the impact of energy-efficient renovations on occupants' thermal comfort.
This objective is discussed in Chapter 4, Section 3

3. Analyze the energy performance of buildings after the renovation.
This objective is discussed in Chapter 5

In pursuit of these primary objectives, the secondary aims of the thesis are to:

- Identify the most influential factors affecting indoor climate concerning building characteristics.
This objective is discussed in Chapter 3, Section 2 and Chapter 4, Section 1

- Evaluate thermal comfort in public buildings under Mediterranean weather conditions using rational and adaptive models.
This objective is discussed in Chapter 4, Section 3

- Apply a field study approach to transient conditions, enhancing conventional models in understanding and predicting indoor climate dynamics.
This objective is discussed in Chapter 4, Section 2

Research tools and methodology

To achieve the defined objectives, a diverse set of research tools was employed in this study:

- Climate sensors: Deployed to continuously monitor indoor temperature, humidity, and CO_2 levels; these sensors provided real-time data essential for understanding indoor environmental conditions.

- Door-to-Door Comfort Surveys: Conducted as an integral part of the research, these surveys involved direct interaction with occupants to gather firsthand insights into their comfort perceptions, acceptability, and preferences.

- IUT de Nîmes Buildings information and activities: An in-depth exploration of the campus buildings, including their structural details and diverse activities within, offered valuable context and contributed to a holistic understanding of the built environment under study.

Utilizing data from these tools, the following methods were employed to address specific research goals:

- Indoor Climate Analysis: Comparative methods, including direct observations and statistical analyses.

- Thermal Comfort Studies: The thermal comfort assessment relied on applying rational

(PMV) and adaptive (ASHRAE-55 and EN 15251) models.

- Energy Performance Evaluation: The evaluation of energy performance was conducted using a degree-day method to investigate the energy consumption patterns and efficiency of the studied buildings.

Research outline

Brief description of the contents of the following chapters:

Chapter 1: Literature review

This literature review chapter provides a comprehensive overview of key themes related to building renovation, energy efficiency, indoor environmental quality (IEQ), and the intricate relationship between energy usage, IEQ, and occupants' comfort. **The building renovation section** examines the motivation, emphasizing the global imperative to reduce energy consumption and greenhouse gas emissions. It explores the impact of legislation on renovation practices, highlighting advantages like energy savings and improved IEQ. Barriers to progress, such as high initial costs and the challenge of balancing energy efficiency with IEQ, are also addressed. **The energy efficiency section** defines and explores the concept, detailing strategies like optimizing the building envelope, upgrading HVAC systems, and promoting energy-efficient behaviors. It underscores the significance of precise measurement methods and introduces diverse approaches, from white boxes to gray boxes, for comprehensive before-and-after renovation modeling. **The IEQ section** defines concepts like thermal comfort and air quality, emphasizing the importance of evaluating thermal comfort for fostering a healthy and productive indoor environment. The chapter concludes by addressing the intricate relationship between energy usage, IEQ, and comfort, highlighting challenges and the need for broader research representation.

Chapter 2: Research methodology and tool

This chapter outlines a comprehensive research approach for studying indoor climate conditions, energy consumption, and occupant comfort in educational buildings, focusing on the IUT de Nîmes campus in the south of France. The methodology involves a dual data collection approach, combining real-time sensor technology to capture physical data on temperature, humidity, CO_2 levels, and energy consumption, with subjective data collected through surveys from occupants, including students and employees.

Chapter 3: Results of indoor climate

This chapter thoroughly explores the indoor climate in the investigated buildings and is organized into three distinct parts. **Part A** examines the pre-renovation conditions of IUT de Nîmes

buildings, offering a comprehensive overview of indoor climate profiles, influential factors, building characteristics, and usage. In **Part B**, the focus is on temperature prediction, aiming to establish a predictive model and understand the key factors influencing indoor temperature variations. This knowledge is essential for developing strategies to maintain a comfortable and energy-efficient indoor environment. **Part C** assesses the renovation performance of two recently refurbished IUT de Nîmes buildings, concentrating on the impact of these measures on air temperature, humidity levels, and CO_2 concentrations.

Chapter 4: Results of thermal comfort

This chapter is divided into three parts that address the thermal comfort and air quality votes in renovated and non-renovated buildings. **Part A** focuses on a field study of thermal sensation and acceptance in existing buildings before renovation. The chapter delves into a comfort/discomfort study, presenting an analysis and discussion of results from physical measurements and subjective assessments. In **Part B**, the field study evaluates thermal comfort under transient conditions. The aim is to understand how transitional periods impact occupants' thermal perceptions. This section also assesses the effectiveness of the Predicted Mean Vote (PMV) model in transient conditions and investigates thermal comfort in university buildings under both transient and steady-state conditions. **Part C** explores students' perceptions of the thermal environment and air quality, specifically in renovated and non-renovated buildings. The analysis encompasses thermal sensation, humidity sensation, and air quality sensation votes, along with thermal acceptability, humidity acceptability, and air quality acceptability votes. By comparing occupants' votes, the chapter analyzes the impact of renovation on students' satisfaction with thermal comfort and air quality in different building conditions.

Chapter 5: Results of building energy performance

This chapter conducts a comprehensive analysis of energy consumption at IUT de Nîmes, focusing on evaluating the buildings' energy performance pre- and post-renovation. Historical records of electricity and heating energy consumption from EDF and NIMERGIE companies are scrutinized to understand overall energy dynamics. The study also explores the influence of the COVID-19 pandemic on energy reduction. Using the degree-day method, the chapter estimates the heat demand of each building. The final step involves assessing measured heating energy consumption to quantify the reduction in energy consumption for renovated buildings.

Chapter I

Literature review

"Like what you do, and then you will do your best"

— KATHERINE JONHSON

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I.1 Introduction

In response to the escalating challenges of climate change and energy security worldwide, renovating existing buildings for enhanced energy efficiency has garnered significant attention as an effective solution. The built environment plays a crucial role in energy consumption and, thus, presents a major opportunity for carbon reduction and sustainability. In Europe, the building sector represents a significant portion of the total primary energy consumption. Moreover, 35% of this building stock was built before 1960 [13], resulting in poor energy performance. The energy-efficient renovation of these buildings is not only a matter of compliance with environmental regulations to achieve the European Union's energy target but also to improve the overall indoor environmental quality (IEQ) of the building.

Renovation strategies, such as enhancing the building envelope, upgrading HVAC systems, and implementing advanced control strategies, result in significant energy savings. However, these improvements also impact IEQ, encompassing factors like thermal comfort, indoor air quality, acoustic comfort, and visual comfort. The relationship between energy efficiency renovations and IEQ requires a delicate balance to ensure reduced energy consumption and optimal IEQ. This chapter explores this complex interplay, offering a comprehensive understanding of renovation strategies and IEQ evaluation based on previous works.

I.2 Building renovation

I.2.1 Motivation behind building renovation

Over the past two decades, energy security has emerged as a significant concern within the energy paradigm [14, 15]. Based on data from the U.S. Energy Information Administration in 2013 [16], global primary energy consumption and CO_2 emissions have significantly increased, with growth of 85% and 75%, respectively, between 1980 and 2012. Notably, the energy production sector is accountable for 87% of worldwide greenhouse gas (GHG) emissions, and the most significant emissions arise from the wealthiest nations.

In March 2007, the European Union (EU) embraced an all-encompassing climate and energy strategy. It aimed to combat climate change and improve energy security in the EU by reducing 20% of energy consumption and 20% of CO_2 emissions compared to 1990 levels. Following the 2007 strategy package, new targets have been introduced by the 2030 Climate and Energy Framework, updated in 2020 [17], which seeks to reduce GHG emissions by 55% compared to 1990 levels.

In Europe, buildings contribute to around 40% of total energy consumption and are

responsible for approximately 36% of energy-related GHG emissions [18, 19]. Prioritizing the building sector is crucial for effectively addressing climate change and achieving energy-related goals [20]. To realize the energy target set by the 2030 Climate and Energy Framework, the directive commission has introduced its renovation wave strategy, aiming to double the annual rate of energy-efficient building renovations by 2030 and promote the development of deep renovation [21].

European buildings account for 25 billion m^2 total floor area, with approximately 75% of this space allocated to residential buildings [22] and 25% of non-residential buildings [23], as illustrated in Figure 1-1.

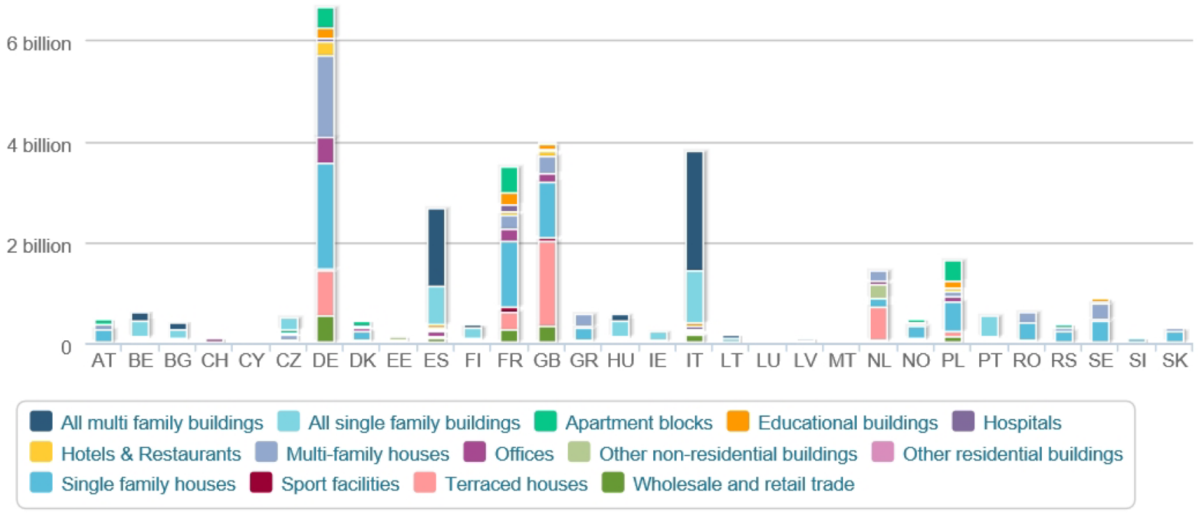

Fig. 1-1. *Building stock floor area (m^2) per building type per Member State [13]*

Nevertheless, 35% of buildings in Europe are more than 50 years old [22]. Educational buildings are found to constitute the predominant proportion of the oldest buildings, as indicated by Figure 1-2. According to Schimschar et al., [24], a significant proportion of public and office buildings were constructed throughout the 1990s.

Roughly 75% of existing buildings are energy inefficient, and the rate of new building construction is modest at around 1% per year. This highlights the crucial role of rehabilitating existing buildings to reduce energy consumption in the built environment.

According to "Renovation tracks for Europe up to 2050 – Building renovation in Europe – what are the choices" [25], it is suggested that a deep renovation of the current building stock, along with the construction of nearly zero energy buildings (nZEB), has the potential to reduce 80% of the final energy consumption for space heating by 2050, in comparison to the levels observed in 2012. Implementing a deep renovation plan targeting 3% per year of the existing building stock, which amounts to a total area of 25 billion m^2, is projected to result in energy savings of around 100 TWh/y by 2020.

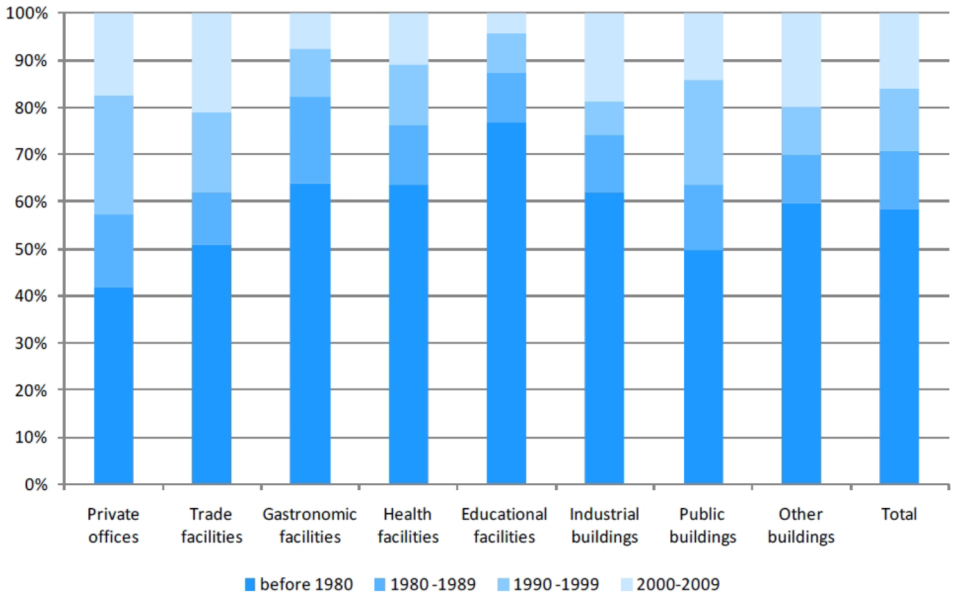

Fig. 1-2. *Age profile non-residential buildings EU [24]*

Simultaneously, better and more energy-efficient buildings will also improve people's overall well-being, mitigate energy poverty by enhancing health and indoor comfort, and create green jobs, contributing positively to the economy and society.

I.2.2 Legislation and regulations

I.2.2.1 In Europe

The EU has implemented a legislative framework consisting of various directives and certifications to enhance the energy efficiency of buildings in Europe. These include the Energy Performance of Buildings Directive (EPBD) 2010/31/EU [26], the Energy Efficiency Directive (EED) 2012/27/EU [27], the Renewable Energy Directive (RED) [28], the Ecodesign Directive [29], and Energy Performance Certification (EPC).

The EPBD was initially implemented in 2002 through Directive 2002/91/EC [30] and subsequently revised in 2010 (Directive 2010/31/EU) [26] and again in 2018 (Directive 2018/844/EU) [31]. This 2018 directive aims to improve the energy efficiency of EU buildings by incorporating external and local factors, addressing indoor climate demands, and cost-effectiveness.

According to the EED [27], every member state must develop a comprehensive strategy or roadmap to attract investments to enhance the energy efficiency of both public and private residential and commercial buildings within their respective countries. Additionally, it is crucial to establish policies and measures that encourage investments in energy-efficient building renovations while also developing projections for anticipated energy savings. One of the requirements

outlined in the EED is that EU member states are obligated to undertake energy-efficient repairs on a minimum of 3% of the overall floor area of buildings owned and occupied by central governments [32].

The primary objective of the RED is to facilitate the attainment of both EU and national energy targets by utilizing renewable energy sources [28]. Including integrated renewables, such as photovoltaic systems, solar thermal technologies, and biomass boilers, is widely recognized as a crucial component in pursuing these objectives. However, it is worth noting that the document does not explicitly address the topic of energy-efficient building renovations.

The Ecodesign Directive (2009/125/EC) [29] establishes a framework for regulating the efficiency requirements of several technologies utilized in the building sector, including but not limited to boilers, hot water generators, pumps, ventilation systems, and lighting. This directive mandates minimum efficiency standards for these technologies. The Energy Labeling Directive [33] mandates that member states implement energy efficiency labeling schemes for various products utilized within the building sector.

The EPC is responsible for incorporating energy demands for the buildings and reference values, including prevailing standards and benchmarks. Its introduction can be traced back to 2002 when the EPBD established it (Directive 2002/91/EC [30]). The development of the EPC continued throughout the years, as depicted in Figure 1-3. In addition, the certificate is expected to be accompanied by recommendations for energy improvement strategies that are either cost-optimal or cost-effective.

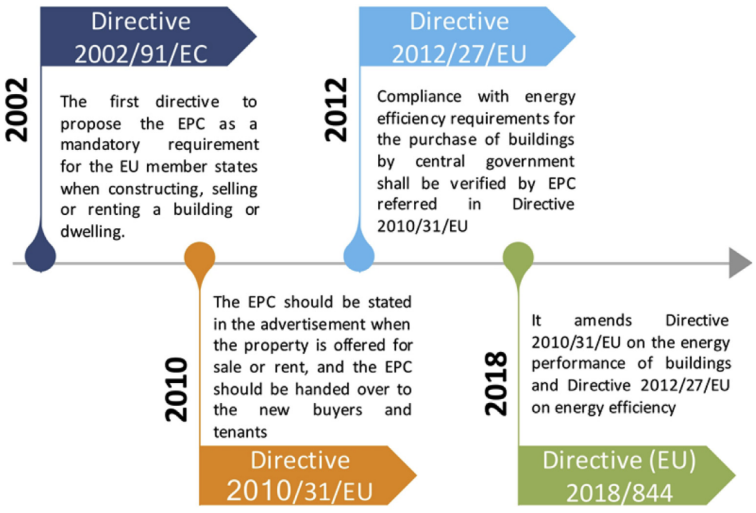

Fig. 1-3. *Timeline for EU Directives related to the Energy Performance Certificates (EPC) [34]*

Each member state has devised its strategies for EPCs to facilitate their implementation. However, the main goal remains to enhance building energy efficiency and mitigate carbon emissions. The European Parliament and Council have influenced the choice to undertake build-

ing renovations [35, 36]. According to a study conducted in 12 EU countries, it was shown that 73% of the participants perceive EPC as a significant catalyst for building refurbishment [35]. Using energy labels enables individuals to assess and compare energy savings levels before and after retrofitting. Hence, the EPC can be a valuable tool for decision-making and strategic planning, aiming to incentivize individuals to engage in building refurbishment activities [34].

I.2.2.2 In France

The concept of renovating buildings to meet the Bâtiment Basse Consommation (BBC) standard in France has been legally established since 2007 by the Effinergie Association to advocate for advancing comfort and environmental sustainability in newly constructed and refurbished buildings [37]. The comprehensive scope of the BBC-Effinergie rénovation label includes the totality of the project, with a specific focus on achieving a yearly energy performance level of 80 $kWh.m^{-2}$ of primary energy [37]. The project participants are given the autonomy to select their technical solutions. The designation is derived from the thermal regulations and incorporates additional stipulations into the content of the 2009 legislative decree.

In 1974, the thermal building code was implemented in response to the 1973 oil shock [38]. Since then, six updates have strengthened the code, and still, 55% of residential buildings were built without energy building requirements [39]. To improve this, the Law on Energy Transition for Green Growth (LTECV), published in the Official Journal on August 18, 2015 [40], and the accompanying action plans for various measures, including buildings [41]:

- All buildings will be low-energy, following the BBC standard by 2050;
- 60% reduction in energy consumption in the tertiary sector by 2050;
- 500,000 homes renovated per year by 2017, including 250,000 occupied by low-income households (Art. 3);
- All private residential buildings with primary energy usage over 330 $kWh/m^2/year$ must undergo energy renovation by 2025 (Art. 5).

To meet these targets, several regulations are being implemented, starting with the building thermal regulation code, which, as of 2013, requires all new buildings to meet nearly zero energy building standards (nZEB) set by the EU. Regarding building renovation, the building code requires buildings with a surface area of more than 1000 m^2 and built after 1948 to meet a global energy performance target of 80–165 $kWh.m^{-2}$ per year since 2010, compared to 240 $kWh.m^{-2}$ per year for the existing stock. The savings for non-residential structures should be 30%. In other residential buildings under 1000 m^2, thermal regulation specifies a minimum performance level for insulation, heating, cooling, hot water, and ventilation [39].

I.2.3 Advantages and barriers of renovation projects

I.2.3.1 Benefits of energy-efficient renovation

The set of publications by Building Performance Institute Europe (BPIE) [42] comprised two targeted papers (policy and market) and is based on more than 400 academic articles that have stated that the impact of building renovation could improve the lives of more than 200 million Europeans. Furthermore, these energy-efficient and low-carbon renovations contribute to co-direct benefits that enhance the well-being of occupants, drive economic prosperity, and elevate the overall quality of buildings, as summarized in Table 1-1. This multifaceted approach to building renovation is a response to global challenges and a driver of comprehensive and positive change within communities and societies.

Key benefits of energy renovation		
Environmental	**Economic**	**Social**
- Energy savings & GHG emissions reduction - Reduced usage of materials	- Employment - GDP and public budgets - Innovation - Sectoral modernisation - Energy Security - Productivity benefits	- Health benefits - Reduction energy poverty - Wellbeing / Comfort benefits - Energy bill savings - Increase in property value & tenant satisfaction

Table 1-1. *Summary of the benefits of renovating a building [42]*

The most apparent benefit of renovation is energy savings [43], which in turn lowers the demand for fossil fuels, electricity, and other energy sources [44–46]. Renovation projects often include upgrades to building envelopes, HVAC (heating, ventilation, and air conditioning) systems, and lighting. These improvements enhance buildings' energy efficiency, reducing the energy required for heating, cooling, lighting, and other operations.

Improved HVAC systems also increase the overall well-being [47] and reduce the risk of respiratory problems, allergies, and other health issues among occupants [48, 49]. Renovation may address health hazards such as lead-based paint or asbestos. Removing or mitigating these hazards protects occupants from exposure, especially in older buildings. Conventional renovation strategies such as improving insulation and heating systems can contribute to better thermal comfort, resulting in a comfortable indoor temperature, essential for overall health and productivity levels [50].

Besides, energy-efficient retrofitting benefits property owners by reducing energy bills [51]. This can positively impact households, businesses, and public institutions, as it frees up funds for other purposes. Energy savings from renovation projects contribute to a positive feed-

back loop. The spending on materials, labor, and services associated with renovations adds to the overall economic output. Simultaneously, refurbishment projects often drive innovation in construction materials, technologies, and methodologies [52, 53]. This innovation can impact other industries, fostering technological advancements that lead to economic growth and competitiveness, which leads to the modernization of entire industries.

Reduced energy consumption means lower GHG emissions, which, in turn, helps mitigate global efforts to limit temperature rise and combat climate-related challenges [54, 55]. The reduced GHG emissions over the lifecycle of renovated buildings contribute to a more sustainable and resilient built environment. Very often, retrofitting projects involve reusing and repurposing existing materials and structures, reducing the demand for new resources [56]. This promotes resource conservation and reduces the environmental footprint of extracting, manufacturing, and transporting new materials. Refurbishment extends the lifespan of conventional buildings, generating less construction and demolition waste compared to new construction projects [57].

I.2.3.2 Barriers and challenges of renovation projects

Decades of experience have shown many obstacles that can be classified into five macro-groups: financial, technical, process, regulatory, and awareness, detailed in Table 1-2.

Key barriers to energy renovation				
Financial	**Technical**	**Process**	**Regulatory**	**Awareness**
- Renovation cost - Access to finance - Low energy prices	- Lack of technical solutions - Cost of technical solutions - Lack of knowledge of construction professionals	- Fragmentation of the supply chain - Burdening of home owners	- Varying ambition of performance requirements - Multiple definitions for renovation	- Lack of awareness

Table 1-2. *Key barriers and challenges of energy-efficient renovations [13]*

Renovations to satisfy nZEB, or deep renovation, are too expensive for many owners and investors. According to recent research on 120 retrofitted houses in Alsace, deep energy renovation (BBC level) costs approximately €465/m^2 [58]. However, the energy renovation investment in France in 2015 was only €314/m^2 [59], which falls short of the energy renovation goal. Governments typically face two options when addressing financial constraints in promoting building renovation. They can either support a substantial quantity of renovations with moderate energy efficiency goals or a smaller number of highly ambitious renovations. The EnergieSprong program [60], introduced in France in 2016 and funded by national and European sources, with oversight by public authorities since 2019, takes a different approach. Its vision is to facilitate more exceptionally ambitious but cost-effective energy-efficient renovations to alleviate energy-related hardships.

I.3 Energy efficiency

I.3.1 Definition and concept

There is no standard energy efficiency definition, but according to the European Parliament and Council of the EU, it is characterized as controlling and limiting the rise in energy consumption [61], which is also crucial to decarbonization. The French energy-efficient policy encompasses two primary measures: thermal regulation and energy-performance diagnosis [62]. Energy efficiency regulations for new buildings have been updated approximately every decade since the 1970s. In 2020, the introduction of RE2020 (Environmental Regulation 2020) to replace RT2012 (Thermal Regulation 2012) [63]. This new regulation emphasizes energy efficiency and includes environmental considerations [64]. The French government has launched a major initiative for energy refurbishment in residential and commercial buildings [62], aiming for carbon neutrality by 2050 and addressing social concerns related to decreasing energy insecurity.

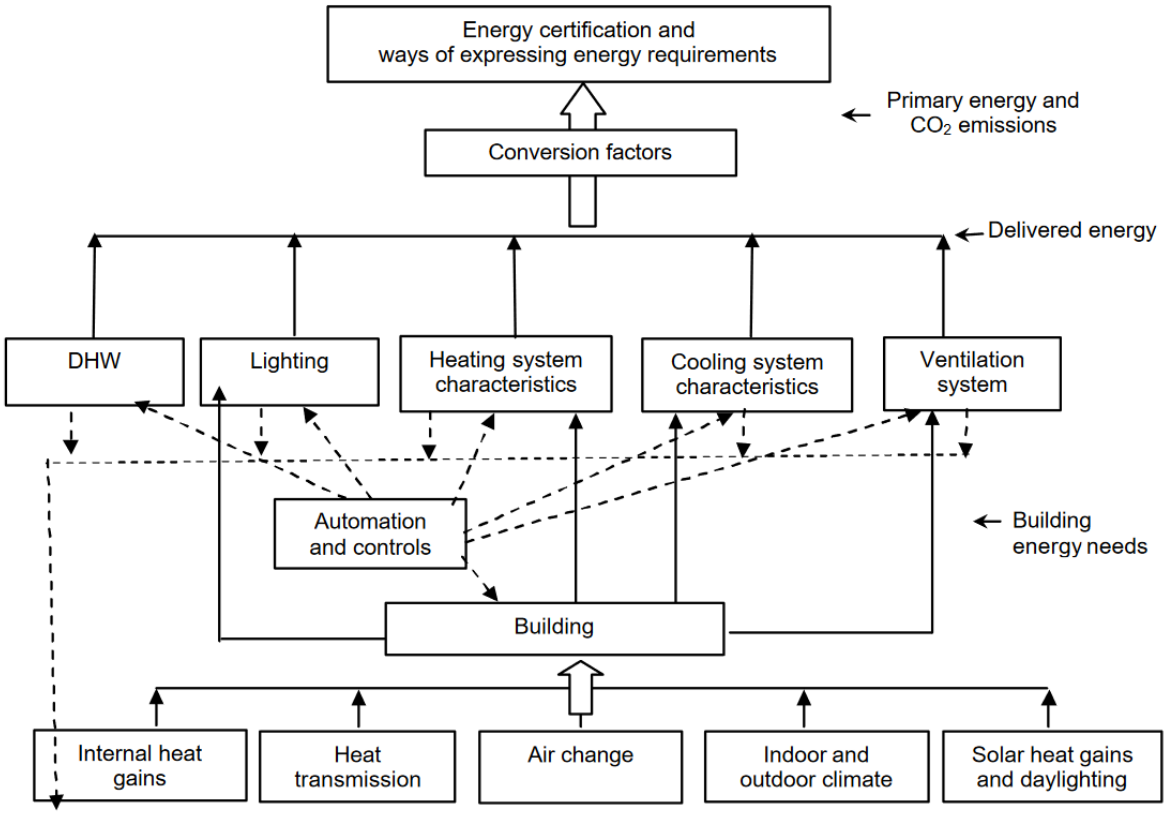

Fig. 1-4. *Energy flows and their links. The bottom row indicates the input data comprising the building characteristics, usage, and climatic parameters. Recovered losses from systems contribute to the heat gains [65]*

The energy efficiency of buildings is assessed through an EPC, which quantifies the

net energy consumption of the building. The calculation is derived from an analysis of the building's characteristics and the equipment that has been installed. It can be structured in three levels, as shown in Figure 1-4:
i) calculation of the building's energy needs for heating and cooling, together with those for ventilation, domestic hot water, and lighting;
ii) calculation of the building's delivered energy;
iii) calculation of the overall energy performance indicators (primary energy, CO_2 emissions, etc.).

To carry out this computation, one requires data on indoor climate standards, internal heat emissions, building characteristics, and external climate conditions. These data are acquired by adhering to established standards. EN ISO 13790 provides instructions on how to divide a complicated building into distinct zones to facilitate the computation process [65].

I.3.2 Renovation strategies

Given the age distribution of buildings in the EU as discussed in Section I.2.1 and the relatively slow renovation rates, it is evident that there is substantial potential for renovation of buildings within the EU. It is estimated that as many as 110 million buildings may require renovation, based on calculations considering a total of 210 million buildings in the EU [13]. The realization of the potential to decrease energy consumption in existing buildings depends on the number of buildings undergoing renovation and the depth of the refurbishment.

The concept of energy-efficient renovation exhibits variations between EU legislation and practical implementation, wherein several levels of renovation are established and executed [13]. The BPIE (2011) [22] provided a comprehensive set of definitions for renovation levels, accompanied by an estimation of the market share represented by each level in relation to all renovations as follows:

• Minor renovations, which constitute approximately 85% of the market, involve implementing one or two measures, such as installing a new boiler. These measures typically result in energy consumption reductions ranging from 0% to 30%, with average costs of around €60/m^2.

• Moderate renovations, which make up about 10% of the market, encompass three to five improvements, such as insulating relevant parts of the dwelling and installing a new boiler. These improvements typically lead to energy reductions between 30% and 60%, with average costs of about €140/m^2.

• Extensive renovations, which represent approximately 5% of the market, entail a comprehensive package of measures that work together to achieve energy reductions ranging from 60% to 90%. The average cost for these renovations is about €330/m^2.

• Renovations aiming to transform buildings into almost zero-energy buildings involve replacing or upgrading all elements affecting energy use and incorporating renewable energy technologies to achieve energy consumption and carbon emissions levels close to zero. These renovations have an average cost of approximately €580/m^2.

Papadakis et al. [66] extensively reviewed renovation strategies and categorized them into three primary levels: technical, operational, and behavioral. Table 1-3 offers a comprehensive summary of these strategies, highlighting their core objectives, the challenges they entail, and the potential opportunities they offer [66].

Intervention category	Focus	Challenges	Opportunities
Technical	Improving the efficiency of the building's systems and equipment.	Expensive to implement	Can lead to significant energy savings
Operational	Changing the way that the building is operated.	May require changes to building operating procedures	Can be more cost-effective
Behavioral	Changing the way the building occupants use energy	More challenging to implement	Can be the most effective in the long run

Table 1-3. *Categories of energy-saving interventions in buildings [66]*

I.3.2.1 Technical

Energy optimization through technical measures encompasses numerous components, as depicted in Figure 1-5. Nevertheless, it can be subdivided into three primary categories: the building's envelope, systems, and equipment.

Enhancing a building's envelope through improved insulation of walls and roof methods is a fundamental technical intervention that can frequently yield substantial improvements in the building's overall energy efficiency [67]. This is achieved by minimizing heat loss during cold periods and reducing heat ingress in warm periods [68, 69]. Such adaptive improvements consequently result in reduced dependence on HVAC systems and contribute to an enhanced sense of indoor comfort.

Thermal insulation comprises a material or a combination designed to slow heat flow through conduction, convection, and radiation when applied correctly [70]. The required level of insulation becomes evident when contemplating the U-values to increase the thermal resistance specified in different European countries for the building envelope [71] to reduce energy consumption for heating or cooling [72]. Commonly used thermal insulation materials are glass and rock wool, polystyrene, sheep wool, spray foam, polyurethane, and fiberboard that can be categorized into four groups—namely, inorganic, organic, combined, and gaseous—based on their chemical composition [73].

Another technique is window glazing, which is often identified as a critical point for

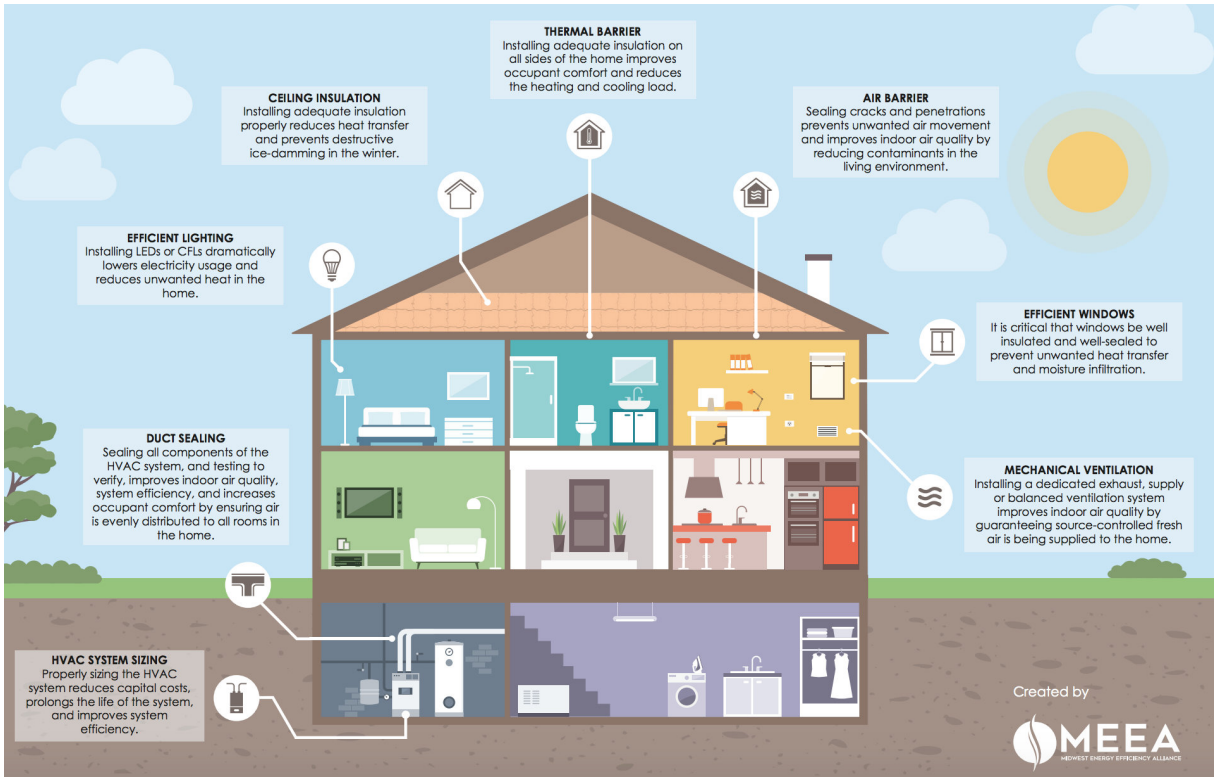

Fig. 1-5. *Energy renovation through technical intervention (Source: MEEA)*

thermal control within buildings and can account for up to 60% of energy loss. Glazing design is associated with many parameters such as heat transfer, thermal comfort, light transmission, and aesthetics [74]. Increasing window area and/or transmittance to enhance daylighting savings often reaches a threshold contingent upon climate and orientation, at which point overall energy consumption rises due to increased cooling demands [75]. To address this issue, low-emission windows are employed to mitigate thermal losses during the winter and limit solar heat gain in the summer. Additionally, they offer ample fenestration to optimize the benefits of natural lighting, thereby reducing the need for artificial lighting and electricity consumption [76]. A common approach during renovation is to replace the single-glazed windows with low-emissivity double- or triple-glazed windows.

In France, space heating and cooling have the highest energy consumption at 60%, followed by water heating at 20%, lighting and auxiliaries at 10% each [77]. That is why systems such as ventilation and hot water production have a major impact, and focusing certain measures on these technologies can have a considerable effect on achieving the nZEB target, being therefore aligned with circular economy principles [73].

Several methods can enhance heating systems, such as district heating (DH) for buildings within a DH grid, offering cost savings during elevated fuel prices. DH substations, requiring minimal space, can repurpose existing boiler flues for ventilation [78]. Without a district

heating connection, heat pump systems, including Air-Source Heat Pumps (ASHP) and others, can be alternative solutions. A simulation study in an Italian university building revealed that replacing an existing system with a ground source heat pump and underground water storage tanks reduced primary energy use for heating and cooling by 64% and 69%, respectively [79]. Modern HVAC systems, including these heat pumps, can efficiently control air circulation, preventing energy waste in specific zones within a building.

Additionally, the adoption of energy-efficient lighting, such as LEDs, not only consumes less energy but also has extended lifespans, reducing energy and maintenance costs [80]. Another issue in existing buildings is the inefficient systems and appliances contributing to energy waste in modern buildings. Thus, integrating modern, energy-efficient appliances can contribute to more energy-saving [81].

A well-designed ventilation system, crucial for indoor air quality, prevents mold growth and decay by removing moisture [82]. Maintaining relative humidity within a specific range is essential for building conservation [83]. Given the COVID-19 pandemic, increased attention to ventilation is crucial for better airflow in poorly ventilated spaces. Renovation strategies may involve modern ventilation and heat recovery systems, contingent upon a properly sealed and well-insulated building envelope.

Alongside active solutions, passive design options like building orientation, natural ventilation, and efficient use of thermal mass play a crucial role in reducing energy consumption and improving thermal comfort. Smart metering systems have the potential to enhance control over services, inform occupants about their behavior, and encourage energy conservation measures [84].

I.3.2.2 Operational

Operational interventions redefine building functions, distinct from technical strategies focusing on system efficiency. Despite potential challenges, these changes often prove more cost-effective than technical alternatives. Optimizing daily routines holds the potential for significant energy savings without major building modifications. Efficient maintenance schedules, like regular HVAC cleaning and calibration, can reduce energy consumption and operational costs [66].

Previous studies [85–88] have identified the operational techniques as follows:
• Thermostat: Lowering the thermostat temperature threshold in winter and raising it in summer can minimize heating and cooling energy.
• Occupancy sensors: Turning off lighting and HVAC systems when rooms are empty reduces energy use.
• Lighting controls: Lighting controls to dim or switch off lights when not in use can reduce

energy usage.
• Optimized Scheduling: adjusting lighting, heating, and cooling hours according to occupancy.

I.3.2.3 Behavioral

Behavioral approaches aim to alter the energy usage behaviors of building occupants, differing from technical and operational solutions. Based on a review paper [66], these approaches consist of:
• Educational and energy awareness Campaigns: Providing occupants with energy conservation education and guidance to foster a deeper understanding of energy-saving practices. Some buildings offer energy efficiency training or presentations.
• Incentive programs: Rewarding residents for adopting energy-saving habits, such as turning off lights, with incentives like gift cards or reduced utility bills.
• Real-time energy consumption feedback: Offering real-time energy consumption feedback to building occupants, either through displays or intranet platforms, to encourage responsible energy use.
• Social norms: Emphasizing energy conservation as a social norm, showcasing how much energy tenants save compared to others.
• Nudges: Implementing subtle environmental cues, such as stickers on light switches, to remind individuals to turn off lights when not in use.

These behavioral strategies play an important role in shaping energy-efficient behaviors among building occupants, contributing to a more sustainable and energy-conscious built environment.

I.3.3 Measurements and evaluations

Energy efficiency is achieved through good energy management, which is a broad concept that includes the planning, monitoring, control, and optimization of an organization's or facility's energy resources. Based on a previous study, energy-efficient buildings can save 30% of the annual energy cost of buildings [89].

One prevalent technique within energy management is energy prediction, a collection of methods used to anticipate the impact of hypothetical energy-efficient measures on individual buildings or facilities. These predictive results guide recommendations for selecting specific energy-efficient measures, enabling the planning of optimal energy retrofit scenarios.

Through prediction and recommendation techniques, various critical questions can be addressed, such as determining the return on investment for specific energy-efficient measures, identifying the most suitable measures for a given building's characteristics, selecting low-

capital-cost measures to enhance energy performance, targeting buildings for energy renovation programs, and projecting energy savings over a 30-year timeframe.

Traditionally, engineers address these questions following a building energy audit, although the audit results may exhibit significant uncertainty [90]. The current trend of energy-efficient measures is categorized into three categories [91]: the white, the black, and the grey boxes, as shown in Figure 1-6.

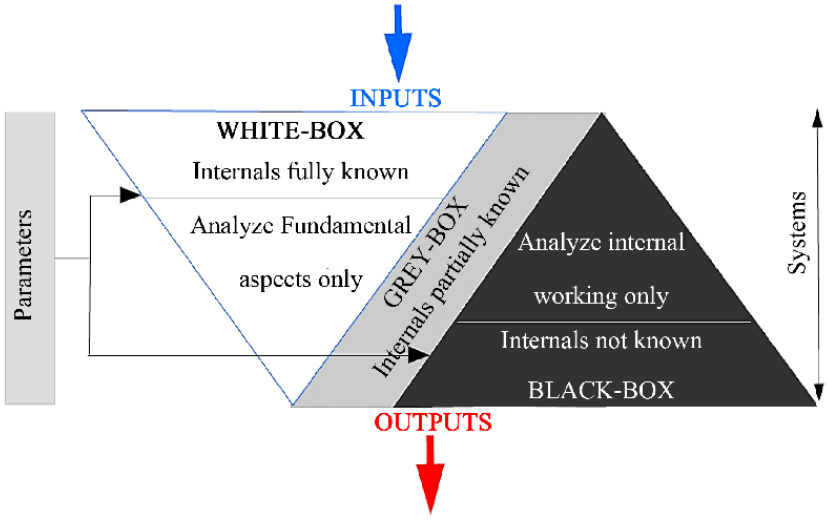

Fig. 1-6. *Black box, white box and grey box behavior [92]*

White-box models, often called physics-based models, are a category of predictive models in which the internal mechanisms are explicitly defined. These models require comprehensive knowledge of a building's characteristics and systems, resulting in a more time-consuming modeling process due to the many necessary model parameters. However, the simulation outcomes tend to exhibit higher accuracy compared to other model types [93].

Conversely, black-box models, also known as data-driven models, are empirical models that lack physically significant parameters. These models are employed when limited information is available about the inner workings of the building system, which is often the case with existing buildings where comprehensive building data may be absent [92]. Nevertheless, black-box models typically necessitate lengthy training and validation periods and are constrained by the specific operating conditions encountered during the training phase. Additionally, reliance on closed-loop data, where only limited data points are accessible, can complicate system identification [94].

Gray-box models represent a hybrid approach that combines elements of both white-box and black-box models. They are most suitable when the physical data are not entirely transparent, and substantial empirical data is available, yet certain critical information still needs to be discovered [95].

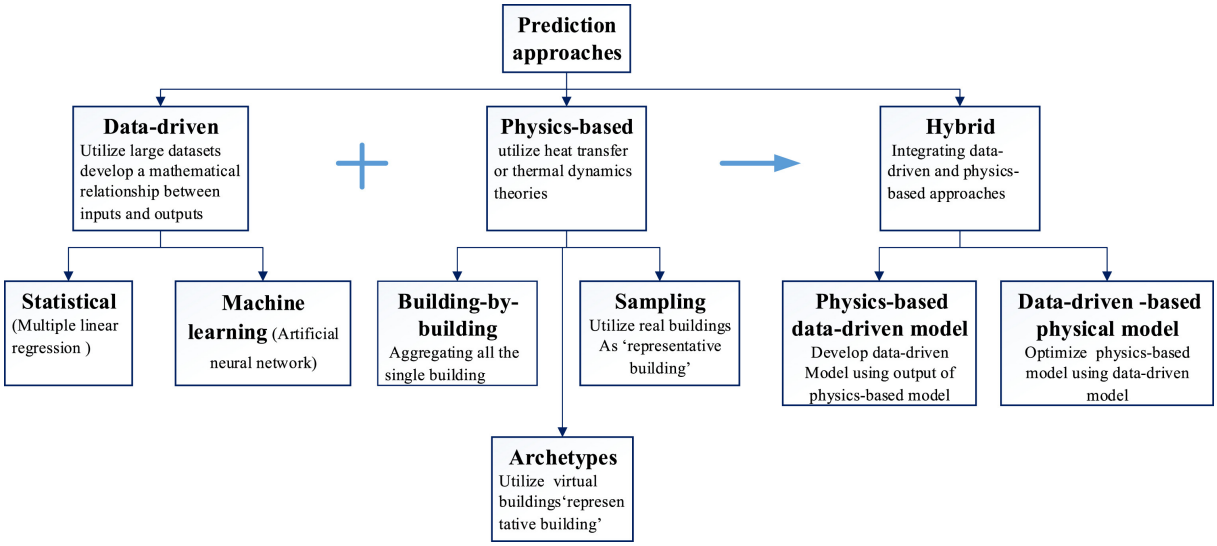

Fig. 1-7. *Approaches for estimating the energy-saving effect of building on large-scale [96]*

The details of each approach are presented in Figure 1-7 for building energy-efficient assessments.

I.3.3.1 White box

Numerous comprehensive building energy simulation software packages are available, including EnergyPlus [97], eQUEST, DOE-2 [98], ESP-r [99], BLAST, HVAC-SIM+, and TRNSYS [100]. These tools enable the modeling and assessment of the thermodynamic characteristics and energy performance of various retrofit measures. It has become common practice to employ these building energy simulation packages to quantify energy consumption and explore potential energy-saving strategies. For instance, TRNSYS, recognized for its flexibility in simulating transient systems, is frequently used in research and applications [101].

These simulation engines are primarily based on thermal heat balance equations, which, in their most simple form, could be written as follows:

$$Q_{heating\ or/and\ cooling} = \sum Q_{tran} + Q_{vent} + Q_{int} + Q_{sol} \tag{I.1}$$

where:

$Q_{heating\ or/and\ cooling}$ is the energy required for space-heating or cooling;
Q_{tran} is the transmission heat loss or gain through opaque building elements like walls;
Q_{vent} is the ventilation and infiltration heat loss or gain;
Q_{int} is the heat gained through internal elements like occupants and appliances;
Q_{sol} is the heat gained through direct or diffused solar radiation.

These methods for calculating energy consumption and the associated software are eas-

ily adaptable to conform to local and national requirements, rendering them versatile and suitable for application in various climate zones [101].

I.3.3.2 Black box

A black-box model does not rely on any prior understanding of the system's characteristics or underlying physics [102]. The primary objective of algorithms within this domain is to create a mathematical model that effectively fits the available data. Once this model accurately represents the known data, it can be used to make predictions with new data. This learning process involves two key steps: estimating the unknown parameters within the model based on a given dataset; and making output predictions using new data and the previously acquired parameters. Consequently, data-driven strategies seek to establish models that connect input and output variables, even when representing system dynamics and their relationships, which proves challenging [103].

The most commonly known techniques in black-box models are statistical analysis and machine learning (ML). Most ML algorithms fall into two broad categories: supervised learning and unsupervised learning. These terms refer to whether the user supervises the program when making its predictive algorithm. In supervised learning, information on the predicted outputs is provided to label the training set and is used for the model training. Unsupervised learning did not provide information about the desired output to label the training data. Consequently, the learning algorithm must find patterns to cluster the input data [104].

Data-driven models of a type building for retrofit analysis based on large data sets can be presented in Figure 1-8.

The literature reviewed, as outlined in the work by Cifuentes et al. [103], has delved into a wide array of data-driven methods for forecasting purposes. In particular, various approaches have been extensively utilized in analyzing time series data related to air temperature. These encompass Multiple Linear Regression (MLR), Artificial Neural Networks (ANN), and Support Vector Machines (SVM). A substantial portion of ANN models focuses on Multi-layer Perceptron Neural Networks (MLPNN) and Radial Basis Function Neural Networks (RBFNN). When it comes to SVM models, researchers frequently opt for the use of Radial Function Base Kernels. When evaluating their performance on a global scale, SVM models have demonstrated superior performance metrics compared to traditional ANNs for forecasting over horizons ranging from 1 to 20 steps into the future. In contrast, at a regional level, recent advancements in Deep Learning (DL) techniques have gained prominence due to their capacity to provide highly accurate predictions. More specifically, Convolutional Neural Networks (CNN) and Long Short Term Memory (LSTM) Recurrent Neural Networks (RNN) have been employed to forecast hourly energy consumption, resulting in remarkably minimal errors in 1-step-ahead predictions.

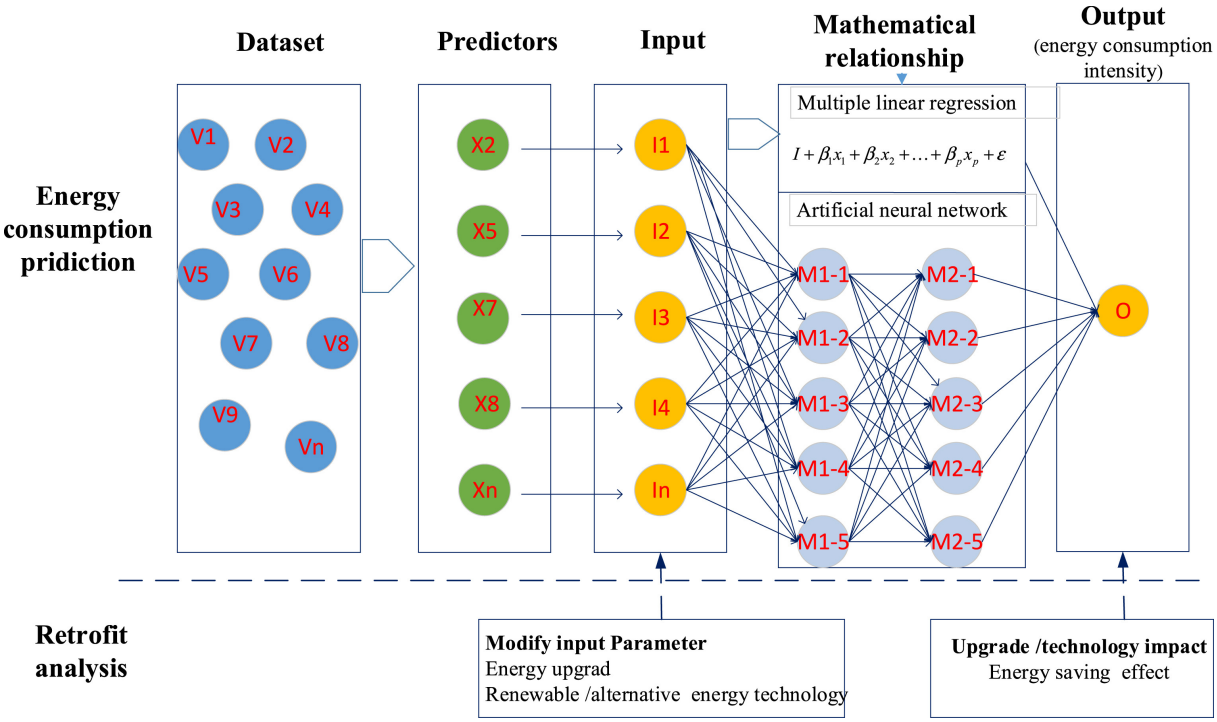

Fig. 1-8. *The steps involved in developing a data-driven model for building retrofit [96]*

I.3.3.3 Gray box

Gray-box models are constructed based on physical knowledge and data, using the advantages of white-box and black-box models. They have gained importance in industrial processes due to their low modeling effort and improved transparency compared to pure data-driven models. The novel techniques in this model are gray-box neural network models (GBNNM), including Multi-layer Perceptron (MLP) Neural Network (NN) and integrators, and are proposed for a Model Identification and Fault Estimation (MIFE) scheme [105].

I.4 Indoor Environmental Quality

I.4.1 Definition and concepts

Indoor Environmental Quality pertains to the overall environmental conditions within a building, encompassing many elements that impact the occupants' well-being, satisfaction, and productivity level. Individuals may have varying comfort preferences even when exposed to the same IEQ conditions. Comfort is a composite outcome influenced by numerous factors, making it evident that individuals of the same geographical location, age group, and time frame might exhibit divergent perceptions of comfort.

Sick Building Syndrome (SBS) is a range of health issues that result from insufficient or suboptimal indoor comfort [106–112]. Unfavorable temperature and humidity levels, chemical and biological contaminants, physical conditions, and psychosocial factors are among the root causes of SBS. Individuals suffering from SBS commonly experience eye, nose, and throat irritation, headaches, coughing, wheezing, cognitive disturbances, depression, sensitivity to light, gastrointestinal discomfort, and flu-like symptoms [113].

Factors influencing IEQ and occupant satisfaction can be categorized into two main groups, physical and non-physical, as depicted in Figure 1-9. Physical factors typically contain four key aspects: thermal comfort, indoor air quality (IAQ), lighting, and acoustic conditions, each of which can be assessed using measurable parameters. On the other hand, non-physical factors pertain to indoor attributes that are challenging to assess with instruments. These include space layout, privacy, furnishings, cleanliness, available facilities, and external views [114]. It is worth noting that, in previous studies, physical factors have been the primary focus due to their quantifiable nature, while non-physical factors have received less attention.

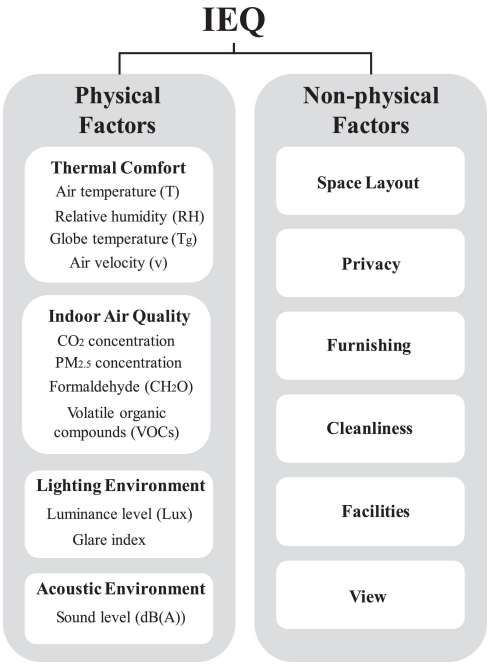

Fig. 1-9. *Physical and non-physical factors in IEQ studies [115]*

The measurement of physical factors can be categorized into two primary forms [116]: first, the measurement of physical environmental parameters that can be objectively quantified through the use of monitoring equipment, and second, the collection of subjective data related to how occupants perceive their indoor environments. The latter involves surveys and self-reporting and is often referred to as "comfort factors".

IEQ can exert both positive and negative influences on an occupant's health, and the interplay between its sub-factors is intricate, as shown in Figure 1-10. For example, sub-optimal

IEQ can adversely affect an individual's physical health, potentially exacerbating conditions like asthma and respiratory allergies due to poor air quality, extreme temperatures, humidity imbalances, and inadequate ventilation. It can also impact psychological well-being, potentially leading to issues like depression and stress, often due to insufficient lighting, acoustics, and ergonomic design. In office settings, employees working in spaces with suboptimal IEQ tend to exhibit higher absenteeism rates, experience more lost work hours, and display reduced productivity compared to their counterparts in environments with high indoor environmental quality [117].

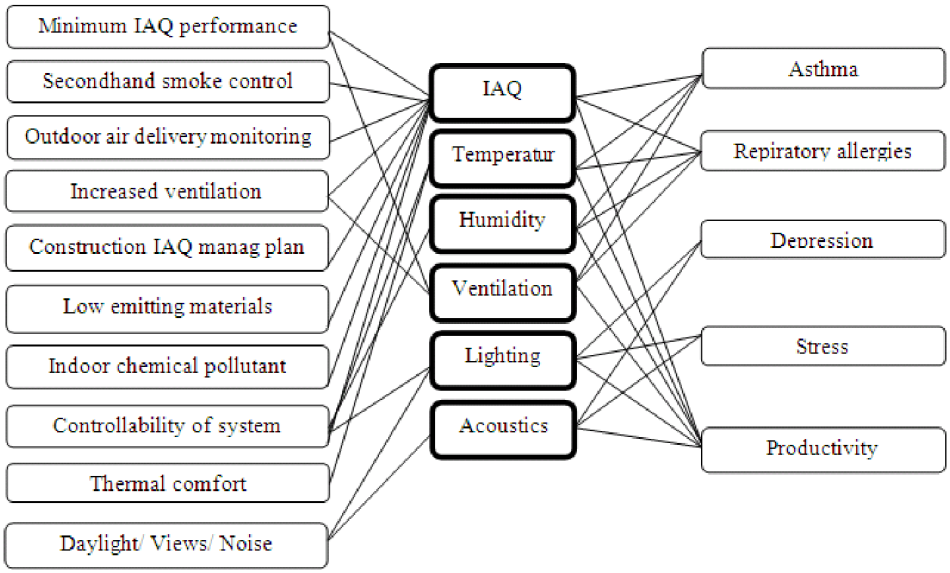

Fig. 1-10. *IEQ occupant well-being and productivity structure [117]*

Each of these IEQ factors uniquely impacts the quality of the indoor environment and the well-being of the occupants. The harmonious interplay of all these IEQ factors results in a built environment that promotes occupant health, comfort, and satisfaction. Therefore, building renovation projects should prioritize these aspects to create sustainable and high-performing indoor environments that benefit both the occupants and the environment.

I.4.2 Components of IEQ physical factors

I.4.2.1 Indoor air quality

The concept of indoor air quality (IAQ) covers various aspects, including indoor air movement, obstructions to airflow, odors, and the presence of indoor air pollutants. While CO_2 is just one of the air pollutants in indoor environments, it is commonly used to assess IAQ and ventilation efficiency within buildings. Elevated indoor CO_2 levels, typically exceeding 1000 ppm, often

suggest inadequate ventilation. However, CO_2 concentrations below this threshold do not consistently ensure sufficient ventilation for eliminating air pollutants from other indoor sources. It is important to note that characterizing indoor CO_2 concentrations is challenging due to their variability, dependent on factors like occupancy and ventilation rates, which change over time. Thus, relying on small samples or short-term measurements may not comprehensively understand the long-term ventilation conditions in educational facilities, such as schools [118].

Poor IAQ can harm building occupants in the short and long term. Building design usually addresses IAQ in two ways: increasing ventilation rates, which results in lower indoor air pollution, and reducing pollution sources within and outside the building to reduce indoor contamination. Research shows that increasing outside air supply rates in non-industrial environments improves air quality and reduces pollution. Outdoor air supply should match building contaminant levels. The nature of pollutants and occupant density affect interior pollutant levels, so the building must have a method to evaluate them and modify external air intake [113].

I.4.2.2 Visual comfort

Visual comfort, defined as the subjective state of visual well-being within a given visual environment, is critical in enhancing the productivity and overall well-being of indoor building occupants [106]. Visual comfort is influenced by several factors: the physiology of the human eye, the physical parameters defining light quantity and distribution, and the spectral characteristics of the light source. Researchers have evaluated visual comfort by examining various factors that describe how well the light environment meets human visual needs [119], such as:

• Adequate lighting: Good visibility during tasks that avoid discomfort from insufficient or excessive illumination. Illuminance, a measure of light reaching a point or surface, is commonly used for lighting quantification.

• Light uniformity: Even distribution over a task area minimizes visual stress caused by shifts between overly and underly lit areas, thus reducing discomfort.

• The quality of light in rendering colors: Natural light is preferred for enhanced satisfaction, productivity, improved color rendering, connection to the time of day, and reduced electricity consumption. It impacts occupants' health, well-being, perception, physiology, psychology, and economics.

• Glare: Glare results from excessive light reaching an observer's eyes or a wide luminance range in their visual field. These issues can be addressed by adjusting retinal illuminance or reducing luminance contrast.

I.4.2.3 Acoustic comfort

Acoustic comfort within buildings is the ability to shield occupants from noise while providing an acoustic environment suited to the building's intended purpose. Acoustic quality primarily depends on two factors: sound insulation and sound absorption. Sound insulation protects the interior from external noise, addressing elements like the building's façade, roof, windows, floors, wall partitions, and doors if indoor noise sources are present. Once the room is adequately insulated, the focus shifts to room acoustics. Multiple reflections can impact the sound generated within enclosed spaces, like restaurants or classrooms, potentially leading to reduced speech clarity and unwanted noise levels [120]. According to Kockat et al., [42], renovation efforts, coupled with the strategic application of insulation, can effectively mitigate external noise, substantially enhancing the internal acoustic environment.

I.4.2.4 Thermal comfort

"Thermal comfort" denotes a satisfactory and comfortable thermal environment within buildings, shaped by socially constructed norms and expectations. This concept has evolved, varying across locations, periods, and seasons [121].

Thermal comfort is influenced by two primary factors: person-related aspects, where the average body temperature remains near 37°C, and environment-related factors, including conditions like air temperature, mean radiant temperature, relative humidity, and air velocity, collectively shaping an individual's thermal comfort [122].

Amongst other IEQ factors, thermal comfort is often the most popular among researchers as it has the most direct and immediate impact on occupants in terms of well-being and energy usage [123–126]. Consequently, the current study also incorporates methodologies for assessing thermal comfort, as detailed in Section I.4.3.

I.4.3 Evaluating thermal comfort

The concept of thermal comfort, which evolved in the 20th century, originated from HVAC industry needs. HVAC engineers aimed to define precise conditions for sizing systems, transforming "comfort" into an HVAC product. The industry redefined comfort in IEQ physical factors, leading to a complex study area for researchers. Assessing thermal comfort can be done through rational and/or adaptive methodologies.

I.4.3.1 Rational model

In 1962, Macpherson outlined six factors influencing thermal sensation, comprising four physical variables (air temperature, air velocity, relative humidity, and mean radiant temperature) and two personal variables (clothing insulation and metabolic rate). Fanger's comfort model integrates these six factors with the two-node model developed by Gagge [127]. This heat-balance approach is rooted in Fanger's experiments in controlled climate chambers involving 1296 young Danish students, utilizing a steady-state heat transfer model [128]. During these studies, participants wore standardized clothing and engaged in predetermined activities while exposed to diverse thermal conditions [129]. In certain tests, participants self-reported their thermal sensations on the seven-point ASHRAE scale, which ranged from cold (-3) to hot (+3), with a neutral rating (0) at its center. The scale included the following categories:

i) 1: slightly warm (+) or cool (-);

ii) 2: warm (+) or cool (-);

iii) 3: hot (+) or cold (-);

iv) 0: neutral (neither cool nor warm)

Considering the thermal interaction between the human body and its surroundings, one can formulate the familiar energy balance equation [130]:

$$S = (M - W) - (R + C + E_{sk}) - (C_{res} + E_{res}) \tag{I.2}$$

S accounts for heat storage in the body, M represents the metabolic heat production rate, W signifies the rate of mechanical work performed, R and C represent radiant and convective heat losses from the outer surface of a confined body, E_{sk} is the rate of evaporating heat loss from the skin, C_{res} indicates the rate of convective heat loss from respiration, and E_{res} represents the rate of evaporative heat loss from respiration. Each term in this fundamental heat balance equation is expressed per unit of the body's exposed surface area ($W.m^{-2}$) and is defined as follows:

- *Metabolic* varies according to the activity performed; it is often measured in met (1 met = 50 $kcal.h^{-1}.m^{-2}$).

- *Mechanical work rate* is the mechanical work done by the muscles for a given task, which is often expressed in terms of the body's mechanical efficiency $\mu = W.M^{-1}$ and typically assumed to be zero for most activities.

- *Radiant heat loss* is the energy exchange between the human body and its environment and may be expressed as:

$$R = 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (t_{mr} + 273)^4] \tag{I.3}$$

- *Convective heat loss* is a flow rate from the body to the environment given by:

$$C = f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \tag{I.4}$$

- *Evaporating heat loss* is made up of two terms: heat loss by water vapor diffusion through the skin (E_d) and heat loss due to the regulatory sweat secretion from the skin (E_w).

$$E_{sk} = E_d + E_w \tag{I.5}$$

- *Respiration heat loss* is the body exchanging sensible heat and latent heat by evaporation (E_{res}) and convection (C_{res}) with exhaled air during respiration. As it leaves the lungs, the exhaled air is at a temperature close to the body's internal temperature and is almost saturated. Breathing is accompanied by a transfer of heat and mass. These exchanges depend on differences in temperature and humidity between exhaled air and ambient air and the ventilation rate.

$$E_{res} + C_{res} = 0.0173 \cdot M \cdot (P_{ext} - P_a) - 0.0014 \cdot M \cdot (t_{exp} - t_a) \tag{I.6}$$

where P_{ext} and t_{ext} are water vapor pressure in exhaled air (kPa) and exhaled air temperature ($°C$), respectively.

Fanger's method consists of analytically determining the heat exchanges between the subject and the environment. In addition to maintaining a balanced heat balance in the human body for thermal comfort, Fanger considers two additional conditions for thermal comfort concerning the limitation of sweat flow ($E_{rsw,req}$) and skin temperature ($t_{sk,req}$) within the limits of comfort [131].

$$t_{sk,req} = 35.7 - 0.0275 \cdot (M - W) \tag{I.7}$$

$$E_{rsw,req} = 0.42 \cdot (M - W - 58.15) \tag{I.8}$$

On substituting the appropriate formulae for heat exchange between the body and environment in the heat balance equation (I.2) as well as the skin temperature equation (I.7) and sweat flow equation (I.8), the "PMV" index is established and expressed in equation (I.11) [128, 130]. It is now a well-known thermal comfort model that predicts a group of people's average thermal sensation vote on the ASHRAE thermal sensation scale.

$$PMV = [0.303 \cdot e^{-0.036 \cdot M} + 0.028] \cdot L \tag{I.9}$$

where L is the difference in the heat balance between heat produced and heat loss $(W.m^{-2})$

$$L = M - W - E_{sk} - E_{rsw,req} - E_{res} - C_{res} - R - C \tag{I.10}$$

Thus:

$$\begin{aligned} PMV = \quad & [0.303 \cdot exp(-0.036 \cdot M) + 0.028] \cdot \\ & \{(M-W) - 0.35 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M-W) - p_a] - 0.42 \cdot [(M-W) - 58.15] \\ & - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) \\ & - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (t_{mr} + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \end{aligned} \tag{I.11}$$

where:
p_a (P_a) is the vapor pressure of the surrounding air, which can be calculated from the following correlation using air relative humidity HR (%) and air temperature t_a (°C) [132]:

$$p_a = 1000 \cdot HR \cdot exp\left(18.6686 - \frac{4030.183}{t_a + 235}\right) \tag{I.12}$$

The clothing surface temperature, t_{cl} (°C), is expressed in equation (I.13) [124] in function of clothing insulation I_{cl} ($m^2.K.W^{-1}$), clothing surface area factor f_{cl}, air temperature t_a (°C), and mean radiant temperature t_{mr} (°C).

$$t_{cl} = 35.7 - 0.028 \cdot (M-W) - I_{cl} \cdot \{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl}+273)^4 - (t_{mr}+273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \tag{I.13}$$

The equations of convective heat transfer coefficients h_c ($W.m^{-2}.K^{-1}$) for free and forced convection modes [124, 130], respectively, are denoted by:

$$h_c = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} & \text{for} \quad 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} & \text{for} \quad 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1 \cdot \sqrt{v_{ar}} \end{cases} \tag{I.14}$$

The clothing surface area factor f_{cl} is directly related to the thermal resistance of clothing [124, 128], expressed as:

$$f_{cl} = \begin{cases} 1.00 + 1.290 \cdot I_{cl} & \text{for} \quad I_{cl} \leq 0.078\, m^2.K.W^{-1} \\ 1.05 + 0.645 \cdot I_{cl} & \text{for} \quad I_{cl} > 0.078\, m^2.K.W^{-1} \end{cases} \tag{I.15}$$

The Predicted Mean Vote (PMV) index has an optimum value equal to zero, but according to ISO Standard 7730 [124], the range of thermal comfort is typically considered to be between -0.5 and +0.5. The PMV index is recommended within the range of +2 to -2. The Predicted Percentage of Dissatisfied (PPD) predicts the percentage of individuals who feel more than slightly warm or slightly cold, meaning those inclined to complain about the environment. Following Fanger's seven-point thermal sensation scale, which ranges from -3 to +3, it is considered uncomfortable for those who respond with ±3. Respondents who answer ±1 and 0 are considered comfortable [129]. PPD is determined by calculating the percentages of individuals who respond with ±2 and ±3 for each class of PMV. The relationship between PPD and the PMV index is expressed as follows:

$$PPD = 100 - 95 \cdot exp(-0.0335 \cdot PMV^4 - 0.2179 \cdot PMV^2) \quad \text{(I.16)}$$

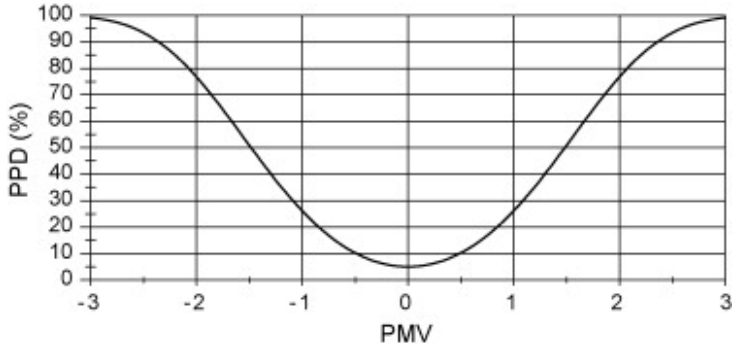

Fig. 1-11. *Relationship between PMV and PPD*

This relationship exhibits a noteworthy symmetry concerning thermal neutrality (PMV = 0). As illustrated in Figure 1-11, it is evident that even when the PMV index is 0, there are occasional dissatisfaction with the temperature level. This occurs despite individuals being similarly attired and engaged in similar activities. These variations in evaluating thermal comfort from one person to another account for these discrepancies. It is demonstrated that at PMV = 0, a minimum dissatisfaction rate of 5% exists [129].

The global scope of the PMV/PPD model was solidified through its incorporation into multiple comfort standards, notably, ISO 7730-1984 [133] and ASHRAE 55-1992 [134]. This inclusion has granted the model the credibility of HVAC engineers in ensuring thermal comfort within buildings [135].

Following the introduction of the PMV model, extensive research has been conducted on thermal comfort, both in real-world scenarios and in controlled climate chamber experiments. While many studies have validated the PMV model, some have revealed inconsistencies. Critiques have addressed multiple facets of the model, including its overall applicability, geographic limitations, suitability for different building types, and the model's input parameters [136]. The PMV index is primarily designed for use with healthy adults and may not be suitable for children, the elderly, or individuals with disabilities. Research has indicated that the responses to the PMV index range is broader for disabled respondents, particularly within the PMV range of "1.5" to "0' [136]. Field studies have demonstrated that the PMV model performs effectively in air-conditioned spaces but may not be as reliable as in naturally ventilated buildings. In warmer climates, the PMV tends to overestimate the perceived warmth in the indoor environment [137].

I.4.3.2 Adaptive model

In developing the adaptive model, accuracy stresses incorporating parameters like clothing level and metabolic rate from the PMV model. The adaptive model should also include non-thermal parameters such as demographics, contextual factors, seasonal variations, environmental aspects, and cognitive elements. Preferences and expectations are shaped by current and past thermal experiences, cultural practices, and technical norms [138].

The adaptive approach to thermal comfort assessment originated in the mid-1970s in response to oil shocks. This approach takes into account the individual's interaction with the environment and involves thermal adaptation occurring on three distinct levels [139]:

• Behavior: Individual factors include clothing, physical activity, body posture, beverage consumption, and room changes. Technological factors involve adjusting heating, cooling, and window settings. Cultural factors related to working schedules and breaks influence individuals' adaptation to the thermal environment;

• Physiological: Long-term exposure to specific environmental conditions can lead to increased tolerance and reduced stress as individuals adapt and acclimatize genetically and physiologically over time;

• Psychological: It is related to an individual's thermal comfort preferences based on their past experiences, expectations, and perceived control over the microclimate, establishing a direct connection between the ideal internal temperature and the external reference temperature.

The fundamental concept of adaptive comfort theory is that occupants adjust their behavior or environment to mitigate thermal discomfort, seeking their preferred conditions [140]. Research confirms that individuals can self-adjust to a wide range of indoor temperatures [141]. However, integrating adaptability into building design and implementing adaptive principles in the design process and operation strategies require further development.

Auliciems first discussed the correlation between thermal perception and indoor and outdoor conditions [142, 143], Nicol and Humphreys [144] and Humphreys [145, 146] and later included in the international standard such as ASHRAE 55-2004 [147] and EN15251 [148].

The equation can be expressed as:

$$T_c = a \times T_{ext} + b \tag{I.17}$$

where:
- T_c is the comfort temperature (°C)
- T_{ext} is the outdoor temperature (°C)
- a and b are dimensionless constants

As depicted in Figure 1-12, both adaptive comfort charts show significant similarity,

differing mainly in selecting outdoor temperatures. ASHRAE 55-2004 comfort standard [123], based on de Dear and Bragers' adaptive comfort model (1998) [149], computes the comfort temperature as a function of the monthly outdoor temperature. On the other hand, the EN15251 standard [148], developed by CEN (Comité Européen de Normalisation), is designed to support the European Performance of Buildings Directive (EPBD), which aims to reduce the energy consumption of the built environment in Europe. This standard employs an exponentially weighted running mean of the external temperature to determine the comfort temperature.

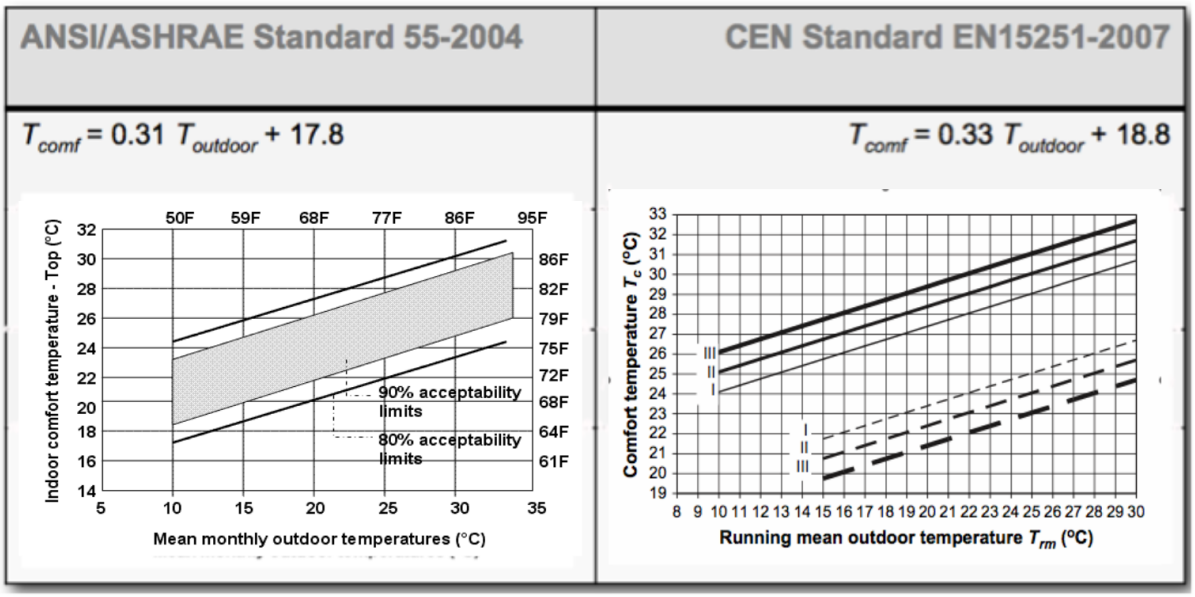

Fig. 1-12. *The ASHRAE 55 (2004 & 2010) [123] and European EN15251 (2007) [148] adaptive comfort charts*

While the adaptive approach offers energy-efficient solutions that align more closely with occupants' thermal sensations in naturally ventilated buildings than the PMV model, it raises several questions about the underlying principles of various factors that influence actual environmental conditions. One key concern with adaptive models is their reduction of multiple influential parameters to just one (outdoor air temperature), which can oversimplify the complexities of human thermal perception. Additionally, predictive equations are derived from specific datasets, meaning that an equation suitable for one context may not be effective in another [150].

I.5 Relationship between energy usage, IEQ, and occupant satisfaction

The intersection of energy consumption, IEQ, and human comfort is a multifaceted aspect that presents a considerable challenge. It is a complex issue because these three elements are interrelated, and changes or improvements in one domain can affect the others. Achieving optimal conditions in all three areas simultaneously is a difficult task. For instance, the level of occupant satisfaction, specifically in terms of comfort concerning IEQ, predominantly hinges on the choices made by building designers, owners, and end users [151]. Moreover, attaining good IEQ is often facilitated through HVAC systems. The balance of these factors not only contributes to occupants' well-being but also directly impacts energy consumption [106].

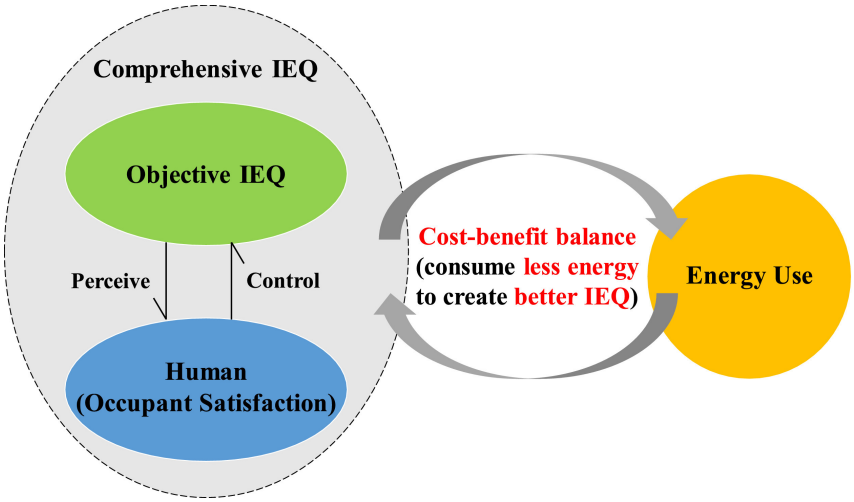

Fig. 1-13. *The relationship between energy use, IEQ, and occupant satisfaction [115]*

Figure 1-13 demonstrates the dynamic interaction between objective IEQ, occupant satisfaction, and energy usage. Initially, objective IEQ performance is closely tied to human factors, particularly occupant satisfaction. Occupants are the direct recipients of the indoor environment, and their instinctive perceptions determine the comfort level of IEQ conditions. Consequently, occupant satisfaction with the indoor environment can be employed as an evaluation criterion for IEQ. If IEQ conditions are unsatisfactory, adjustments or controls on lighting and HVAC systems can be implemented based on human feedback, thus affecting energy usage [115].

I.5.1 Building energy consumption elements

A study by Rashed Alsharif [152] summarizes the principal elements that primarily influence energy consumption in buildings. These critical elements include occupant behavior, the build-

ing envelope, and the building energy systems, as illustrated in Figure 1-14.

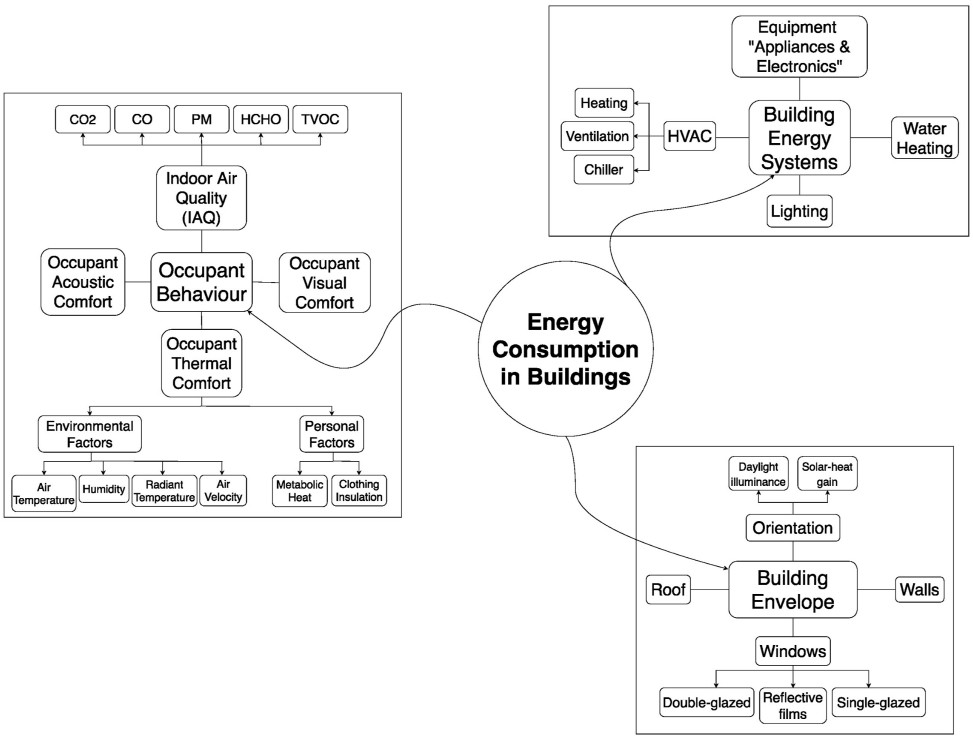

Fig. 1-14. *The main elements in building energy consumption [152]*

I.5.1.1 Building envelope

Building energy consumption is influenced by climatic factors like solar radiation, weather conditions, and wind patterns, varying across regions and seasons [153]. Materials with higher thermal effusivity can efficiently store and release thermal energy [154]. Components like solid external walls, vertical glazing, and roofs with high thermal properties manage heat effectively, aligning indoor temperatures with comfort standards. This reduces reliance on heating and cooling systems, enhancing overall energy efficiency [153].

Moreover, solar radiation greatly influences energy consumption through building orientation and design. In the northern hemisphere, orienting buildings southward to optimize exposure to solar heat and radiation is advisable. A suitable orientation angle allows buildings to receive minimal solar radiation in the summer and maximize it in the winter [155].

I.5.1.2 Building energy systems

In building control, maintaining proper temperature and humidity is essential. According to ASHRAE-55 [123], the temperature range of 20°C-24 in winter and in summer with a relative

humidity range of 30-60% should be maintained. In commercial buildings, a significant portion, approximately 50%, of the energy demand is allocated to the task of ensuring comfortable indoor temperatures.

Ventilation systems are essential in maintaining IAQ by removing contaminants and promoting a healthy environment within buildings [156]. Notably, the energy consumption required for moving air in and out of mechanically ventilated buildings is generally lower than what is needed for thermal conditioning. To further enhance energy efficiency, electricity usage for fans can be minimized by reducing pressure drops in the ventilation system and selecting high-efficiency equipment [157]. When retrofitting buildings to improve IAQ, it is recommended that energy-efficient ventilation systems be implemented. This may include a mechanical supply and exhaust system with heat recovery, which transfers heat from outgoing air to preheat incoming air, or a variable air volume (VAV) ventilation system that tailors fresh air supply to occupants' needs [156]. Since a significant portion of people's time is spent indoors, developing energy-efficient HVAC systems is crucial in reducing overall energy consumption and lowering greenhouse gas emissions [61].

I.5.1.3 Occupant behavior

Buildings themselves do not consume energy; instead, it is the occupants who influence energy usage. As the occupancy level rises, the energy demand for HVAC, lighting, elevators, and other plug loads also increases. Achieving energy savings in energy-efficient buildings relies on advanced building technology and the role of human factors, which carry equal significance alongside technological innovations [158, 159].

Building occupants play a crucial, often underestimated role in the indoor environment. Their behaviors, especially concerning HVAC systems to achieve a specific range of indoor climates, significantly impact energy consumption. These behaviors include actions such as managing building openings (e.g., opening or closing windows), controlling lighting and solar shading (e.g., adjusting blinds), operating HVAC systems (e.g., turning air-conditioning on or off and modifying thermostat settings), and using hot water and electrical appliances [160].

I.5.2 Energy efficiency's impact on IEQ

I.5.2.1 Risk factors of energy-efficient renovation

Neglecting the interplay between energy consumption and IEQ poses risks and challenges regarding occupants' health and productivity levels. For instance, prioritizing reduced air leakage and improved thermal insulation for energy conservation in renovation may lead to health-

related risks like internal condensation, excess moisture, increased pollutants, radon gas concerns, and potential overheating [161].

Another example is the negative impact of heating and ventilation systems on noise comfort, which is often caused by fans, airflow, and pumps and disrupts residential environments. It is crucial to make suitable design decisions for both the systems and the environment in which they are installed to prevent the generation of such noises. Thus, analyzing design solutions during renovation is essential to assessing advantages and potential drawbacks.

I.5.2.2 Balancing comfort and energy efficiency

To date, many strategies have been employed to optimize both comfort and energy usage. One potential strategy is to implement occupancy-responsive control, which involves integrating the subjective responses of inhabitants into the control loop. This approach has attracted considerable attention from researchers, device manufacturers, and building operators.

In contrast to conventional practices that adhere to fixed pre-set ranges for indoor temperature and humidity, typically defined by building standards, occupancy-responsive control adopts a dynamic approach by gathering real-time feedback from occupants to assess the thermal environment. Subsequently, it adjusts the control target settings based on this feedback. This method involves the integration of various thermal responses from occupants, which can include feedback such as expressions of feeling too hot or too cold [162], real-time thermal votes [163], and more. The incorporation of these responses has demonstrated the potential to enhance thermal comfort while achieving notable energy savings, often ranging from 20% to 40%, particularly in office settings, as supported by studies such as [164–166].

Another strategy is incorporating automated building systems, paired with sensors, to regulate heating, CO_2-controlled ventilation and lighting based on occupant preferences and environmental conditions. Infrared sensors detect occupant presence, enhancing overall system efficiency [161].

Successfully deploying automated control systems to monitor indoor environments while adhering to regulations can enhance the flexibility of built environments. This adaptability is crucial for meeting evolving performance needs, responding to changing climatic conditions, and shaping the future of building design.

I.6 Conclusion

This section has highlighted the critical role of Indoor Environmental Quality in influencing occupants' well-being, health, and productivity levels. One of the well-known IEQ factors is

thermal comfort, which is evaluated through a rational model or adaptive models.

In response to climate change and energy security, building renovation is found to be a key solution. Subsequently, many studies have extensively analyzed the effectiveness of energy-efficient buildings through different techniques (black box, white box, and grey box) to evaluate the energy reduction in new and renovated buildings.

Though progress has been made in understanding the interplay between building energy efficiency and good IEQ and its effects on occupants, there are still research gaps. The current rate of building renovation is relatively low at 1% per year due to numerous challenges and barriers; subsequently, field studies evaluating the impact of energy-efficient measures on IEQ performance in real building settings are limited. Moreover, there is still a lack of diversity in the representation of technologies and building types. Most studies focus on residential and commercial buildings, leaving areas like healthcare and schools less explored.

Chapter II

Methodology

"However difficult life may seem, there is always something you can do and succeed at"

— STEPHEN HAWKING

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II.1 Introduction

The comprehensive study of indoor climate conditions, energy consumption, and occupant comfort in buildings necessitates a research approach that integrates quantitative and qualitative data. This chapter presents the methodology and tools employed in this dissertation.

The case study is based on IUT de Nîmes campus buildings, which are situated in the south of France in Mediterranean weather. This chapter delves into the details of these school buildings, providing insights into their physical characteristics, climate control systems, and historical context. The physical data collection involves using sensor technology to capture real-time data on temperature, humidity, CO_2 levels, and energy consumption. This data is essential for understanding the building's performance, its response to climatic conditions, and the effectiveness of any renovation measures.

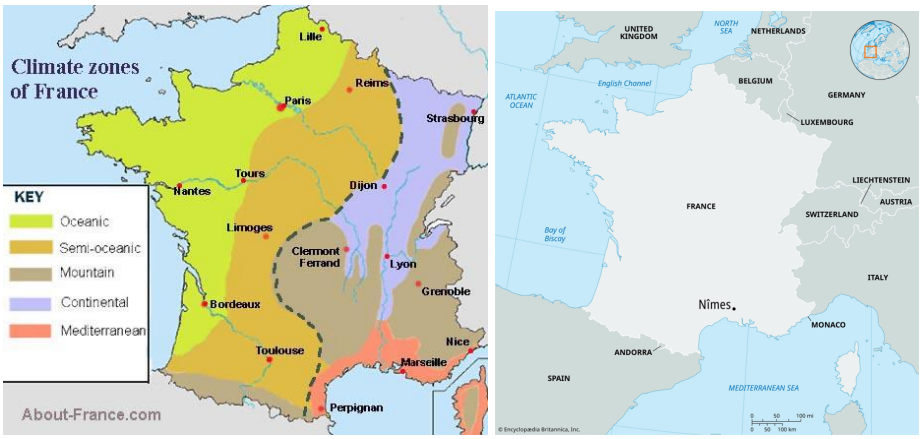
In conjunction with the physical data, the study also relies on subjective data collected through questionnaire surveys assessing students and employees. The surveys aim to gather opinions, experiences, comfort, and preferences related to indoor climate and adaptive behaviors. These subjective insights provide a holistic view of the occupants' perspectives and their interaction with the built environment.

II.2 Case study buildings

II.2.1 Climatic conditions

France is known for its diverse and varied climate (see Figure 2-1A), influenced by its geographical location and the surrounding bodies of water, which profoundly impact people's adaptations and lifestyles. There is a drastic difference between the northern and southern weather. In northern of France, where the oceanic climate prevails, residents have adapted to a climate characterized by mild temperatures all year round. The relatively cool summers and winters mean that households and buildings are equipped to handle moderate temperature variations. People in this region may not experience extreme heat or cold, influencing their clothing choices, building designs, and energy consumption. In the southern regions of France, particularly in areas like Provence and the French Riviera, the Mediterranean climate presents different challenges and adaptations. The extremely hot summers, with average temperatures exceeding 30°C, require people to adjust their daily routines.

The case study is located in Nîmes city at 43,49°N longitude and 4,19°E latitude (Figure 2-1B). Nîmes is a city located in the south of France, within the Occitanie region, close to the Mediterranean Sea, which influences its climate and weather patterns. The concept of



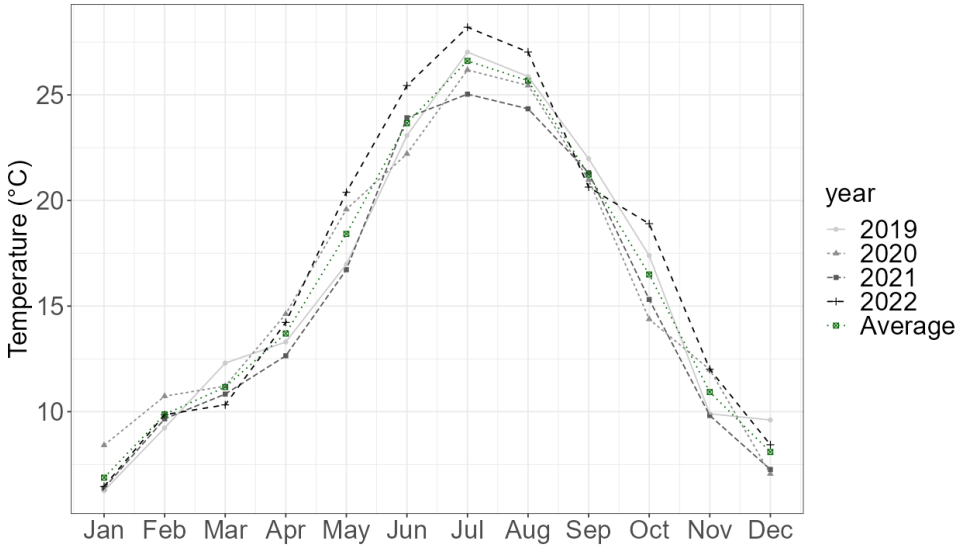
(A) French climate map (B) French world map

Fig. 2-1. *Geography of Nîmes city on the (A) climate zone map and (B) world map*

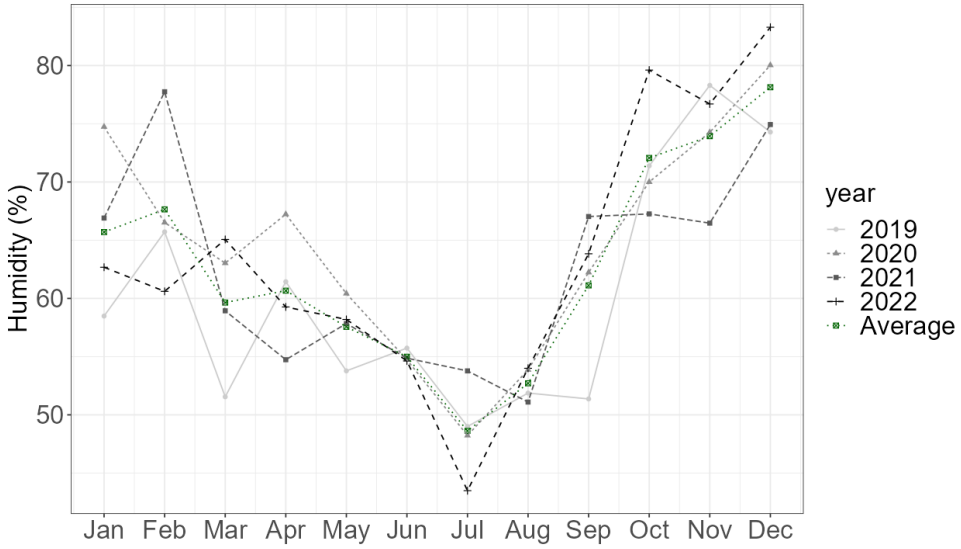
"Mediterranean" climate is classified as Csa according to Koeppen and Geiger [167] and is characterized by mild, wet winters and warm to hot, dry summers. Heat waves in this region have been perceived as a significant health danger since the 2003 episode that hit central Europe, heavily affecting northwestern Mediterranean countries such as Spain, France, and Italy. The extremely high temperatures in early August 2003 were responsible for about 30,000 casualties in Western Europe, half of these in France alone, about 4,200 in Spain, 4,000 in Italy, 2,000 in Portugal, and 1,000 in Switzerland [168]. Recently, another heat wave was marked with the highest temperature at 45.9°C on June 28, 2019, in Gallargues-le-Montueux, near the city of Nîmes [169]. Therefore, naturally ventilated buildings in this region are susceptible to the indoor temperature during the summer.

The meteorological data is taken from the nearest weather station, Nîmes Courbessac, which is situated at 43,86°N and 4,41°E, approximately 5 km from Nîmes city. According to Figure 2-2A, which displays monthly outdoor temperature data over four years from 2019 to 2022, the mean annual temperature was 16.1°C. The hottest months were July and August, with a mean temperature of 26.6°C and 25.7°C, respectively. The coldest months were December and January, with a mean temperature of 8.1°C and 6.8°C, respectively. The average annual humidity (see Figure 2-2B) of the four mentioned years was 63%. The driest month was in July at 49%, and the most humid was in December at 78%. In particular, the year 2022, which was the most commonly used data in the current study, tends to have the highest temperature.

Figure 2-3 illustrates the distribution of hourly temperature (panel A) and hourly humidity (panel B) in each month throughout 2022. Although the average temperature was 28°C in July, the highest temperature reached up to 35°C, which corresponded to the afternoon at 14h00. Respectively, the average humidity in this month was also the lowest at 43% (with 28% minimum and 60% maximum).



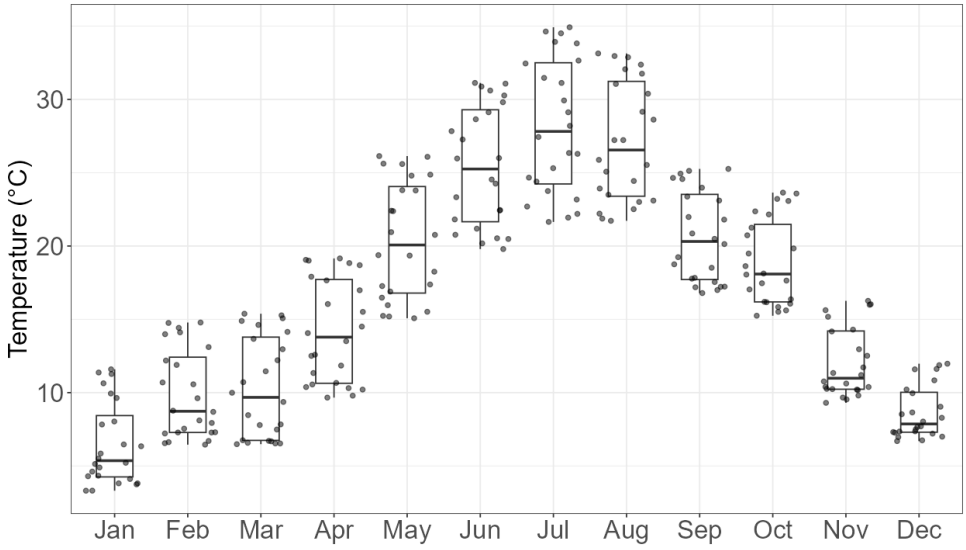
(A) Monthly temperature



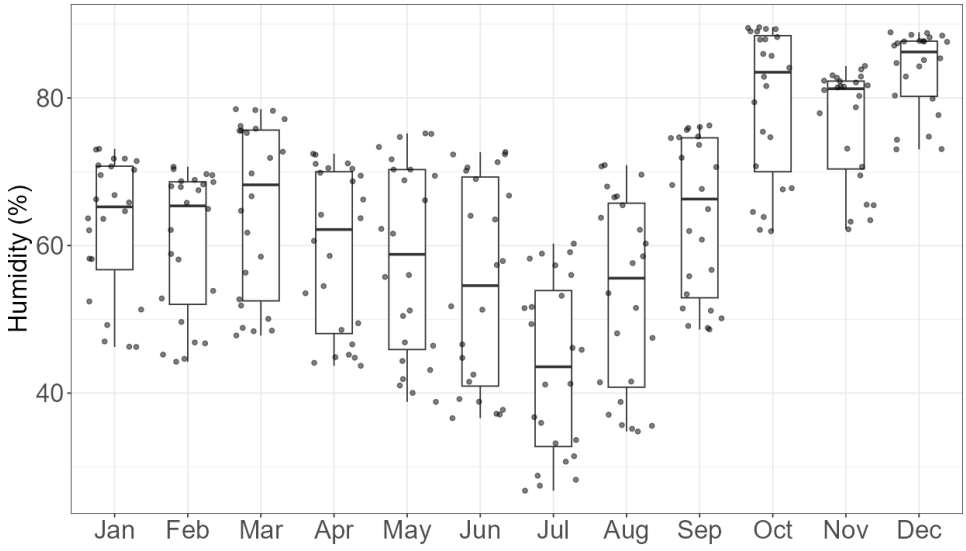
(B) Monthly humidity

Fig. 2-2. *Monthly outdoor (A) temperature and (B) humidity from the Nîmes Courbessac weather station during four years: 2019, 2020, 2021, and 2022*

Another factor contributing to the heat accumulation in the summer of 2022 was the long duration of solar radiation, shown in Figure 2-4, especially in July, which was close to 400 hours per month. The duration of solar radiation indicates a sufficient intensity of more than 120 $W.m^{-2}$ to produce distinct shadows. Although the outdoor temperature was the lowest in January at 6°C on average, the solar duration was 208 hours per month, which was more important than in December. Intense radiation in the winter months can effectively contribute to reducing heating costs.



(A) Average hourly temperature in 2022



(B) Average hourly humidity in 2022

Fig. 2-3. *Average hourly outdoor (A) temperature and (B) humidity from Nîmes Courbessac in 2022 (the 24 dots in the individual boxplot represent the 24 hours per day of the month)*

Unified Degree Day (DJU) plays a pivotal role in building operations, for they are quantifiable metrics that enable building managers to assess and manage energy consumption, a critical component of operational budgets. By tracking the DJU of heaters (also known as heating degree days HDD) and air conditioners (also known as cooling degree days CDD), building operators gain valuable insights into the heating and cooling demands of their buildings, which, in turn, contribute to estimating energy costs more accurately. HDD represents the accumulation of positive deviations of average daily temperatures over a given period, which qualifies the



Fig. 2-4. *Monthly duration of radiation in 2022 (time during which solar radiation has sufficient intensity* $> 120W.m^{-2}$ *to produce distinct shadows in the previous hour)*

local winter climatic rigor (where outdoor temperatures are lower than 18°C). Meanwhile, CDD measures the local summer climate over a specified period, identified by outdoor temperatures higher than 25°C.

Equation (II.1) and Equation (II.2) define HDD_{18} and CDD_{25}, respectively :

$$\begin{aligned} &If \quad \frac{Tej_{max}(t)+Tej_{min}(t)}{2} < 18 \\ &then: \quad HDD_{18} = \int \left[18 - \frac{Tej_{max}(t)+Tej_{min}(t)}{2}\right] \cdot dt \qquad \text{(II.1)} \\ &If \quad \frac{Tej_{max}(t)+Tej_{min}(t)}{2} > 25 \\ &then: \quad CDD_{25} = \int \left[\frac{Tej_{max}(t)+Tej_{min}(t)}{2} - 25\right] \cdot dt \qquad \text{(II.2)} \end{aligned}$$

where HDD_{18} is the heating degree day with a 18°C threshold, CDD_{25} is the cooling degree day with a 25°C threshold, Tej_{max} is the maximum daily outdoor temperature (°C), Tej_{min} is the minimum daily outdoor temperature (°C), and t is time (day).

Table 2-1 presents the monthly and annual heating degree days and cooling degree days for the Nîmes region from 2018 to 2023. The annual average of HDD was 1459°C.day, with a reference temperature for heating of 18°C. Among the months within this time frame, the highest monthly average demand for heating, as reflected by the HDD, was observed in January, with a value of 318°C.day. This indicates that January typically experiences the coldest temperatures, necessitating more heating to maintain indoor comfort. Following closely behind, December exhibited the second-highest heating requirement, with an HDD of 294°C.day.

Year	DJU	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2018	HDD	239	351	236	91	28	0	0	0	0	54	180	291	**1469**
	CDD	0	0	0	0	0	3	65	57	2	0	0	0	**127**
2019	HDD	355	225	172	142	55	3	0	0	3	24	232	251	**1461**
	CDD	0	0	0	0	0	29	81	49	4	0	0	0	**162**
2020	HDD	292	206	202	93	13	0	0	0	18	102	166	339	**1430**
	CDD	0	0	0	0	0	7	49	48	4	0	0	0	**108**
2021	HDD	353	227	214	158	56	0	0	0	0	75	231	321	**1634**
	CDD	0	0	0	0	0	18	35	26	0	0	0	0	**80**
2022	HDD	343	224	233	123	2	0	0	0	7	4	171	290	**1397**
	CDD	0	0	0	0	0	35	104	79	3	0	0	0	**221**
2023	HDD	326	255	193	96	13	0	0	0	0	6	202	274	**1365**
	CDD	0	0	0	0	0	16	57	53	2	0	0	0	**127**
Average	***HDD***	***318***	***248***	***208***	***117***	***28***	***1***	***0***	***0***	***5***	***44***	***197***	***294***	***1459***
	CDD	***0***	***0***	***0***	***0***	***0***	***18***	***65***	***52***	***2***	***0***	***0***	***0***	***138***

Table 2-1. *Monthly heating degree day (HDD) and cooling degree day (CDD) of Nîmes from 2018 to 2023*

The cumulative CDD at a reference temperature of 25°C showed significant variation from year to year, primarily influenced by high temperatures from June to August. Among the years provided, CDD was at its lowest in 2021 (80°C.day) and reached its highest in 2022 (221°C per day).

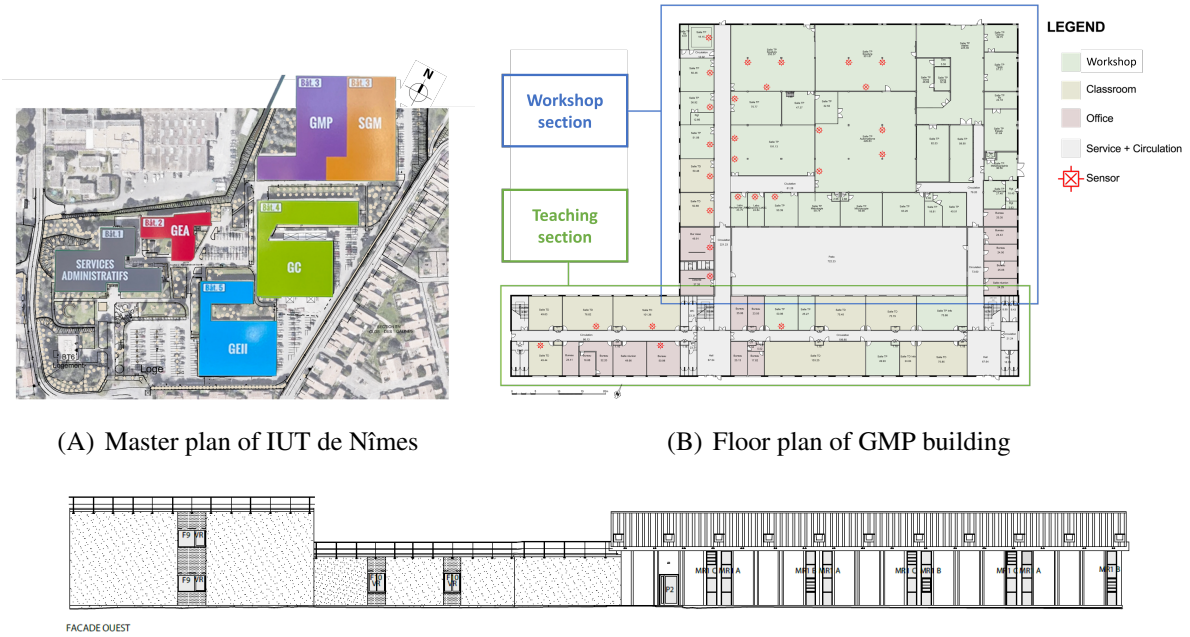
II.2.2 Overview of investigated buildings

This study investigates existing school buildings on the IUT de Nîmes campus. This institution is part of the French higher education system and offers a variety of undergraduate programs with five professional degrees for students, mainly aged between 19 and 22 years old. Each year, this campus hosts 1,200 students, and 30% of them come from different parts of France.

II.2.2.1 Building design and layout

The IUT de Nîmes campus comprises six independent buildings built in the late 1960s with a total usable area of 23,217 m^2 as presented in Figure 2-5A. They are one administrative building (BC), four teaching buildings (GMP/SGM, GC, GEII, GEA), and a housing building. The BC, GMP/SGM, GC, and GEII buildings account for 91% of this floor space. The GMP/SGM building is later referred to as "GMP".

The administrator building, covering an area of 5,509 m^2 and featuring three floors, each



(A) Master plan of IUT de Nîmes

(B) Floor plan of GMP building

(C) West elevation plan of GC building

Fig. 2-5. *Architecture drawings of the IUT de Nîmes campus: (A) Master plan of the campus; (B) Floor plan of a teaching building (GMP building) on the ground floor; and (C) West elevation plan of a teaching building*

with a height of 2.6 m, primarily accommodates offices, two lecture halls (amphitheaters), and a few classrooms. The teaching buildings, namely Mechanical and Production Engineering (GMP), Civil Engineering (GC), Electrical Engineering and Industrial Computing (GEII), and Management Companies and Administration (GEA), encompass 7,294 m^2, 5,670 m^2, 4,279 m^2, and 1,547 m^2, respectively. These buildings share a similar architectural layout, as shown in Figure 2-5B, facing the north-west and south-east directions. Each building accommodates two distinct sections: *teaching* and *workshop*. The 2-story teaching building, as seen in the elevation plan (Figure 2-5C), is primarily designated for classrooms and offices, with each floor having a height of 2.5 m. In contrast, the technical section stands at 3.5 m in height and predominantly contains spacious workshops for practical work and laboratories with various mechanical machines.

Each room type within all the buildings varies in floor area and can be classified into three size categories: small ($x < 50m^2$), medium ($50m^2 < x < 150m^2$), and big ($x > 150m^2$). In the teaching section, classrooms and offices are equipped with operable windows and blinds, accounting for 27% of the total envelope area. On the other hand, in the technical section, there is fixed glazing extending from the floor to the ceiling, covering 15% of the entire envelope. Additionally, most workshop halls are situated in the central areas of the buildings, and they lack accessible windows.

II.2.2.2 Building usage schedule

IUT de Nîmes, like other universities across France, follows a general academic schedule and annual calendar that aligns with the country's higher education system. The academic year typically spans from early September to late June and is divided into the fall and spring semesters. The first semester usually commences in early September and runs through December with lectures, workshops, and practical training sessions. Following the winter break in late December, the second semester starts in early January and extends through late June. It is important to note that late June typically marks the end of the academic period (which usually consists of internships and other project defenses), during which classrooms are not fully occupied, allowing students to focus on their self-study and defense preparation. Starting in July, campus buildings often remain unoccupied as students are either on a break or engaged in internships.

The study period typically starts at 8h00 and ends at 18h00, with a one-hour lunch break between 12h00 and 13h30. During these study periods, students assist in lectures held in larger halls with gatherings of 100 to 150 students or practical training sessions conducted in classrooms accommodating 14 to 28 students. Workshop sessions occupy the least number of students, around 15 per hall.

Typically, each session for one course spans 2–3 hours, and students move to the next class for their next course. This rotation can occur multiple times daily, depending on a student's timetable.

II.2.3 Renovation measures

II.2.3.1 Objectives of IUT de Nîmes's renovation project

The University of Montpellier is an educational institution in the Hérault department in the south of France. Its campus is spread across multiple locations within Montpellier and Nîmes. In recent years, the University of Montpellier has been carrying out major refurbishments of its buildings, including the IUT de Nîmes. This renovation is to satisfy the thermal regulations (RT) for existing buildings over 1000 m^2 as mentioned in Section I.2.2.2. The requirements of RT for renovated buildings are:
- Energy consumption not to be exceeded: $C_{ep} \leq C_{ep_{ref}}$ and $C_{ep_{project}} \leq C_{ep_{initial}} - 30\%$
- Well-insulated building overall: $U_{bat} \leq U_{bat_{max}}$
- Comfortable building in summer: $T_{ic} \leq T_{ic_{ref}}$

The RT Global Thermal Study compares the actual building with the initial building and a "reference" building with fixed thermal characteristics. The project's conventional primary energy consumption (C_{ep}) and conventional summer indoor temperature (T_{ic}) must be lower

than the reference consumption and temperature.

The main aim of the renovation projects of IUT de Nîmes is to improve the energy efficiency of buildings, which includes the following works:
- Install external insulation on the building envelope
- Replace windows
- Replace lighting
- Install a single-flow mechanical ventilation system
- Improve control and energy consumption monitoring by building

The primary objective of the renovation is to enhance the energy performance of the buildings, focusing on improvements to both the building envelope and its systems. The anticipated benefits are multifold, with a direct and immediate reduction in energy consumption and lower operational costs for the campus. However, these improvements have far-reaching implications for the buildings' indoor quality.

One such impact is an enhancement in air quality, resulting from improvements in the air renewal system and the buildings' increased air tightness. Additionally, refurbishment measures aimed at achieving thermal comfort address issues such as mitigating the impact of cold walls during winter and minimizing heat infiltration during summer. This involves the enhancement of air tightness through the replacement of joinery and regulating the heating system to reduce overheating in the colder months.

Lastly, improvements in visual comfort were achieved by implementing low-luminance lighting, creating an environment that is more conducive to work and study. In sum, while the primary aim is energy efficiency, the anticipated benefits are expected to extend to encompass a range of factors, including air quality, thermal comfort, building durability, and visual appeal, all of which will contribute to a more conducive and sustainable educational environment for the IUT de Nîmes buildings.

II.2.3.2 Pre-renovation conditions

Building envelope

The teaching sections are constructed with prefabricated concrete elements resting on a main concrete framework and are built over a crawl space. They have inaccessible, waterproofed flat roofs on concrete slabs. The elastomer waterproofing under heavy protection was renovated in 2013 and is in good condition. This work involves installing a minimum of 40 mm of thermal insulation (Eurothane BR BIO) on the roof. Regarding windows, rooms on the south side are protected with natural aluminum roller shutters integrated into the outside of the joinery. They have single-glazed bay windows, and some are renovated to have double-glazed sliding windows. Some windows in the north are not covered with shutters.

On the other hand, the workshop sections are constructed from prefabricated concrete elements on a grid of load-bearing posts, wall elements, and a median strip. They are made of Vulcasteel sandwich panels 120 mm thick (polyurethane). Between each sloping panel, waterproofed valleys collect rainwater. Part of this roof comprises translucent Isoclair polycarbonate sheets to allow natural light into the workshops. On the roof of the GEII building, there are a large number of these, covering around 25% of the surface area. There are also opening skylights used to clear smoke from large workshops (surface area $> 300\ m^2$). The glazing in this section is full-height glazed bands without spandrels.

Building systems

All the buildings are connected to the district heating system via a primary loop, as illustrated in Figure 2-6. The urban substation is located to the north of the campus. Each building has a dilapidated substation in the basement (easily accessible). Moreover, the pumps and flanges are corroded, and no regulation exists. The circulators, three-way valves, and sectional valves are generally in poor condition, and numerous leaks appear at the various connections, including the circulators. Old, inefficient finned convectors heat classrooms and administrative offices, while air heaters heat workshops. At the same time, there is no energy metering on the site apart from the concession meters, so it is impossible to monitor the installations' consumption separately.

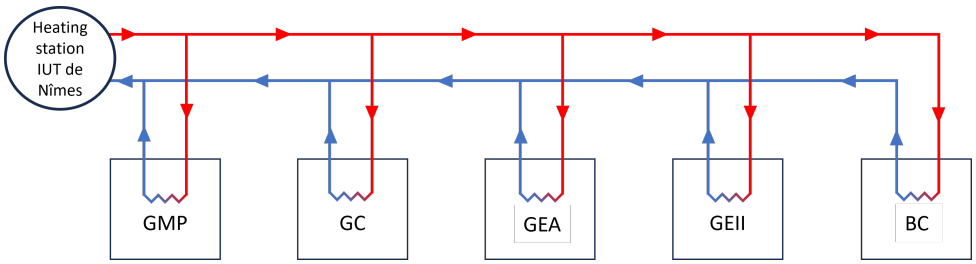


Fig. 2-6. *Schema of the sub-station heating system within the IUT de Nîmes campus*

The renovated heating system follows the 90°/70°C temperature regime, which implies high heat losses over the length of the network. This is all the more true when the network's insulation is in a poor general state or even non-existent. The design of substations is also penalizing, as they are not fitted with "heat exchangers" but with "decoupling cylinders". As a result, the same fluid circulates through the heating network and the radiators in each building. Moreover, each building has only one circuit, with no differentiation of zones or orientation, leaving almost no possibility of optimizing heating curves, which is essential in this type of building.

Most buildings are not equipped with centralized cold production and distribution. The BC, GMP, and GC buildings are equipped with many individual split systems. These were developed gradually, without any effort being made to rationalize energy use. This has resulted

in a significant impact not only on electricity consumption but also on the power demand in the summer (and therefore on the cost of the site's energy bills).

II.2.3.3 Renovation works

Within the IUT de Nîmes campus, the GEII building underwent an energy-efficient renovation in 2021, followed by the GC building in 2022. Each building has gone through construction work for five months, from May to November. The renovation covers fixtures and fittings on all levels of the building, in all rooms, including classrooms, workshops, administrative offices, corridors, and all facades.

The objective of the renovation is to achieve the BBC Effinergie Renovation level for both GC and GEII buildings, to get closer to the requirement of heating consumption < 15 $kWhEP.m^{-2}$ per year and $C_{ep_{project}} \leq C_{ep_{initial}} - 40\%$ without the installation of photovoltaic solutions. To achieve this objective, the renovation cost is estimated to be 426 000 € excluding taxes total (GEII of 208 500 € excluding taxes and GC of 217 500 € excluding taxes), as presented in Table 2-2.

	GEII building	**GC building**	**Total**
Heating system	145 000 € excl. taxes	154 000 € excl. taxes	299 000 € excl. taxes
Ventilation system	63 500 € excl. taxes	60 500 € excl. taxes	124 000 € excl. taxes
Others	-	3 000 € excl. taxes	3 000 € excl. taxes
	208 500 € excl. taxes	217 500 € excl. taxes	**426 000 € excl. taxes**

Table 2-2. *Summary of estimated renovation costs*

Building envelope

This case study adopts a technical renovation strategy by adding external insulation with 12 cm of rock wool while covering the teaching sections (see Appendix E.2 for more detailed information on insulation work). Figure 2-7 shows the changes between the before (panel A) and after (panel B) renovation of the north façade. The doors are also upgraded to the aluminum frame with thermal break and 16 mm low-emissivity double glazing argon blade Uw = 1.80 $W.m^{-2}.k^{-1}$ and the windows changed to PVC frames with low-emissivity double glazing and 16 mm argon blade Uw = 1.50 $W.m^{-2}.K^{-1}$ (see Appendix E.3 for more detailed information on upgraded windows information and positions).

Roller shutters, seen in Figure 2-7C, initially made of metal, are replaced with PVC material on the south-facing facades of the ground and first floors. Overhangs in powder-coated galvanized steel with an 80-cm-wide canopy with PVC slats spaced 10cm apart.

Systems improvements

The buildings of IUT de Nîmes utilize two heating sources, with district heating as the primary



(A) Pre-renovated façade on the north side

(B) Post-renovated façade on the north side



(C) Post-renovated façade on the south side

Fig. 2-7. *IUT de Nîmes façades: (A) Pre-renovated north side; (B) Post-renovated north side; and (C) Post-renovated south side*

source. The main purpose of district heating is to effectively generate, distribute, and deliver heat from a central source to various end-users via a network of insulated pipes. Nevertheless, the campus's network pipes are poorly insulated, featuring 30 mm rock wool with a metal coating.

The secondary heating source, an air heater, is independently managed yet remains connected to the primary source, resulting in continuous operation. These sources are handled by the urban heating network, which is operational during the heating season from November to April and consists of two function modes. The first mode, referred to as *"Comfort"*, maintains an average indoor temperature of 21°C, operating from 7h00 to 19h00, Monday to Friday. The second mode, known as *"Eco"*, is designed for nighttimes, weekends, and holidays to keep the indoor temperature at an average of 18°C.

Before the renovation, the substation was configured as follows: it included a high-temperature network that was uncontrolled and directly connected to the primary loop, supplying heat to the unit heaters in the workshops. Additionally, a regulated 3-way valve network was equipped with a KSB ETATHERM circulator, which was responsible for providing heat to the radiators. The substation also housed a protection cabinet and a SIEMENS RVL 480 controller, which adjusted water flow based on outdoor temperature and followed a specific water law (Table 2-3).

Outdoor temperature	**Network departure temperature**
-5°C	78°C
+15°C	40°C

Table 2-3. *Water law for heating system*

The building system renovation focuses on enhancing heat production, heat distribution, and ventilation. The key improvements in the heat production of the substation heating system following the refurbishment are outlined in Figure 2-8. The hydraulic separation of the primary and secondary systems is achieved by installing a plate heat exchanger, eliminating interferences (leaks) between buildings, and facilitating better control of heating water quality for the restructured networks. Furthermore, a radiator-controlled heating network is established, featuring a high-efficiency variable flow circulator and a hydraulic decoupling cylinder. A constant temperature network is also created for workshops and is equipped with high-efficiency variable flow circulation. Finally, a protection and control cabinet is implemented to enhance the system's overall functionality.

As for heat distribution, the existing distribution networks are to be retained. However, isolation valves and a solenoid valve (in a metal box) whose opening and closing are controlled by an adjustable room thermostat (+/- 2°C) were installed. The building system was also changed by adding a room thermostat or thermostatic valve to hot water radiator emitters with water control according to the outside temperature.

Before the renovation, due to the absence of controlled mechanical ventilation, the air renewal of the buildings is ensured by high and low vents in the rooms (without controlling the hygienic flow rates, minimum 18 $m^3.h^{-1}$per person). To assist with these problems, single-flow mechanical ventilation is also integrated into the building following the renovation of the teaching section with air inlets in the joinery, extract units served by presence detection, extraction flow rate according to the number of air inlets, a galvanized network, and an extractor in the terrace. For more information on the newly installed ventilation system, refer to Appendix E.1. The natural ventilation of the workshops is maintained by high and low air intakes, allowing for free cooling.

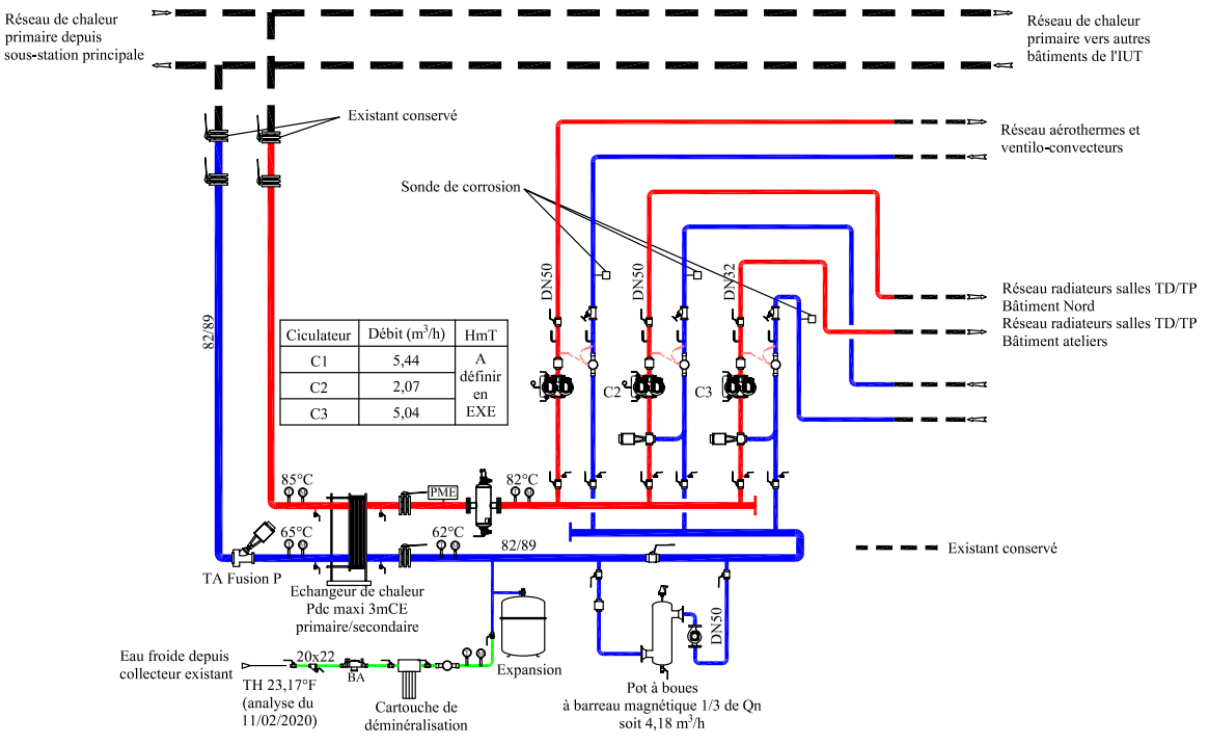


Fig. 2-8. *Upgraded district heating system in renovated buildings*

II.2.3.4 Renovation summary

Table 2-4 displays the U-values of the building envelope, along with a short description of the ventilation and heating system, for both the pre-building and post-building phases. Installing mechanical ventilation and thermostats is limited to the *Teaching* section. Before the refurbishment, the heating system was controlled manually, in contrast to its current state of operation, which is managed and operated through a computer program.

II.3 Physical data collection

The collection of physical data covered a range of objective measurements and assessments. This involved utilizing specialized sensors and monitoring equipment to quantify various parameters. Measurements such as monthly energy consumption and heating system efficiency were recorded to assess energy performance. Simultaneously, the climate sensors measured temperature, humidity, and CO_2 levels.

Element		Materials		U-value ($W.m^2.K^1$)	
		Before	After	Before	After
Floor		Concrete	Unchanged	3.08	3.08
Roof	Teaching	Concret + polyurethane foam 40 mm	Unchanged	0.51	0.51
	Workshop	Concrete + mineral wool 120 mm	Unchanged	0.25	0.25
Wall		Hollow brick	Hollow brick + rock wool insulation 120 mm	3.52	0.27
Window		Single-glazed / Double-glazed	Double-glazed argon 16mm + Overhang on the south	3.6	1.5
Building information				**Program**	
Ventilation	Teaching	Natural (0.5 vol/h)	Mechanical extract ventilation (0.23 vol/h)	Permanent	6h00-20h00
	Workshop		Air blower		
Central heating system	Teaching	District heating + Convection heater	District heating + Radiator + Thermostat control	7h00 - 18h00	7h00 - 18h00
	Workshop	District heating + Air heater	Unchanged		

Table 2-4. *Thermal properties of the building envelope and a short description of ventilation and heating systems before and after renovation*

II.3.1 Energy measurement

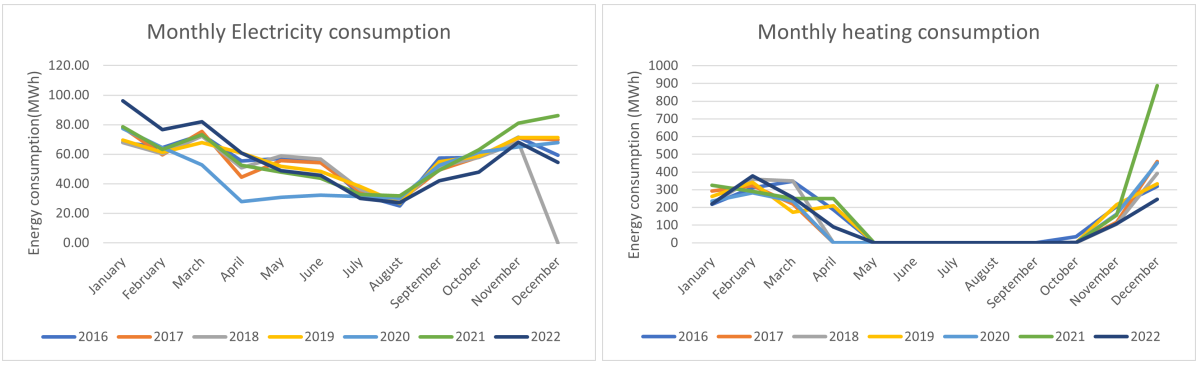
The energy consumption at the IUT de Nîmes campus is categorized into two types: heating for primary and secondary space heaters and electricity, which serves other demands within the campus, including lighting, building appliances, servers, and others.

The campus has been equipped with real-time electric measurement systems for monitoring and managing electricity consumption since 2016. These sensors record and capture the total hourly electricity consumption of each building. The recorded data are stored in the Socomec IG61 memory system, facilitating ongoing analysis and tracking of electricity usage trends. Unfortunately, a period of missing data from March to October 2020 was attributed to technical issues. To complement this real-time data, an alternative source for assessing electric-

ity consumption is the monthly energy bills for the entire campus, which are provided by the ENGIE company.

In the case of heating consumption, no heater meters were installed on campus before the renovation. However, for a comprehensive view of the total campus heating consumption, the monthly heating bills provided by the NÎMERGIE company are relied upon. This data allows for understanding the overall heating consumption trends and patterns across the entire campus.

The electricity and heating consumptions of the IUT de Nîmes campus from energy bills can be summarized in Figure 2-9.



(A) Electricity bill (B) Heating energy bill

Fig. 2-9. *History of the monthly IUT de Nîmes campus's energy consumption from energy bills: (A) Electricity and (B) Heating*

II.3.2 Environmental measurement

II.3.2.1 System LoRa

The Internet of Things (IoT) is becoming increasingly significant across diverse sectors, including business, industry, consumer electronics, automotive, and more. IoT facilitates the connection of various entities like sensors, actuators, electronics, and network connectivity, enabling seamless data exchange and connectivity among these objects. IoT forms a network of tangible objects, and this interconnectivity is made possible through technologies such as GSM, ZigBee, Wi-Fi, and Bluetooth. However, it is worth noting that power requirements and battery life pose substantial challenges in deploying IoT solutions. In the contemporary landscape, the majority of applications involve embedded systems that operate under stringent power constraints, primarily relying on batteries for their power source rather than external power supplies [170]

LoRa, short for Long Range, represents a novel wireless IoT connectivity solution

that has emerged recently and is swiftly becoming a preferred choice for low-power, battery-operated embedded systems. These systems necessitate the transmission of small data packets at frequent intervals across extended distances. LoRa serves as a physical layer, facilitating long-distance communication links. To enhance its capabilities, a standardization process has led to the introduction of LoRaWAN (Long Range Wide Area Network), which incorporates a MAC (Medium Access Control) layer. LoRaWAN is responsible for defining the network architecture and the communication protocol associated with LoRa technology [171].

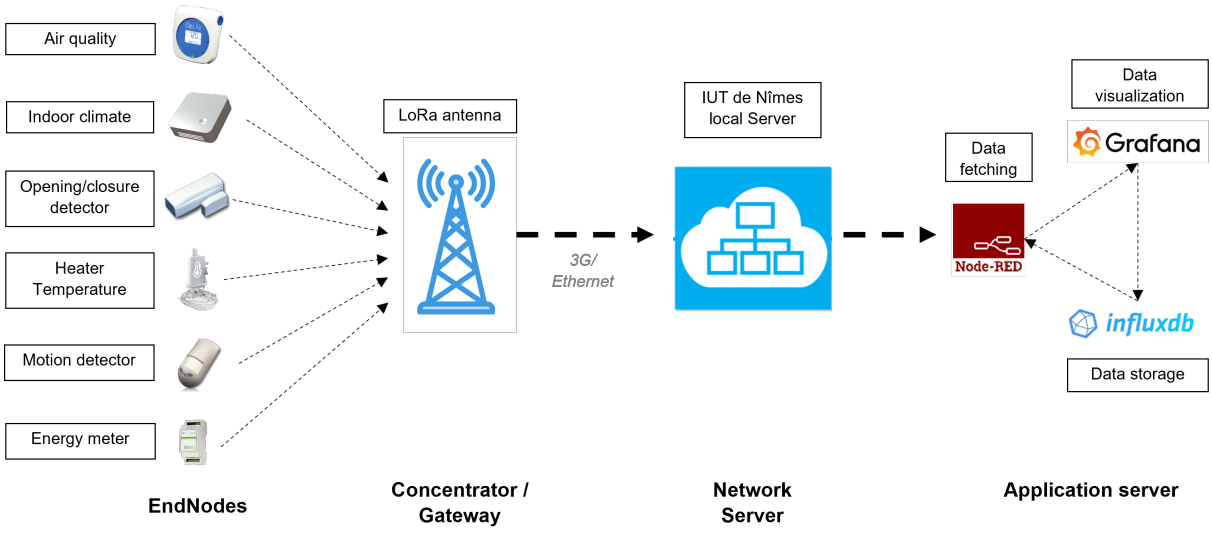


Fig. 2-10. *LoRaWAN network architecture*

The LoRa network consists of four basic elements: the LoRa node or endpoints, the gateway, the network server, and the application server. LoRaWAN ensures that all the components, devices, features, and functions of any building (or outdoor space) communicate instantly and remotely via a common language. As illustrated in Figure 2-10, LoRa connects sensors everywhere installed within the campus to generate insight and communicate with the IUT de Nîmes local server through the LoRa antenna network. Data are then transmitted to the Node-RED/python application, which interprets the encrypted data and sends the data to a database to be stored and used. InfluxDB is deployed to store the sensor data, and Grafana is used to display the data.

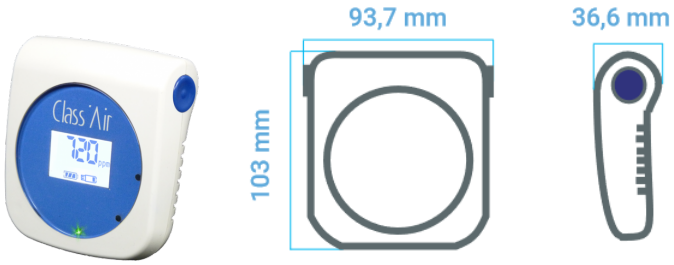
II.3.2.2 The LoRa Node or End Points

The endpoints, or LoRa nodes, comprise sensors or applications where sensing and control occur, such as sensors and tracking devices. On the IUT de Nîmes campus, 338 sensors of six types (Class'Air, Elsys, CM868LR, IR868LR, BT1-L, and Adeunis) have been placed on four buildings, namely, GC, GEII, GMP, and BC, to measure continuously since 2020. In this

study, only Elsys, Class'Air, and the CM868LR (opening/closing detector) sensors are taken into account.

Class'Air sensor

The Class'air sensor (Figure 2-11) measures indoor air quality and raises awareness of room ventilation according to the CO_2 level, designed under a CSTB (French Scientific and Technical Centre for Building) license. The Class'Air sensor measures and records in its function Datalogger the CO_2 rate, temperature, humidity, and pressure. The sensor uses 3 LEDs (green, orange, and red) to indicate the level of confinement in the measurement zone as a function of CO_2 level. The sensor runs on a lithium-ion 3.7V/2600mA battery. The sensor display shows the measured values within the design range, detailed in Table 2-5. The acquisition period is over 10 minutes by default per 1 point averaged. For more detailed information on this sensor, refer to Appendix B.



(A) Front side (B) Dimensions

Fig. 2-11. *Class'Air sensor (A) the front view and (B) dimensions*

CO_2	Part Per Million (PPM) ratio	From 0 to 5,000 ppm
	Resolution	1 ppm
	Accuracy at 25°C and 1013 mbar	$\leq, \pm$ (50 ppm + 3% of measured value)
Temperature	Measurement range	from -10 to +50°C
	Resolution	0,1°C
Humidity	Measurement range	from 0 to 100% HR
	Resolution	1 % HR
Pressure	Measurement range	300 to 1100 hPa
	Resolution	1 hPa

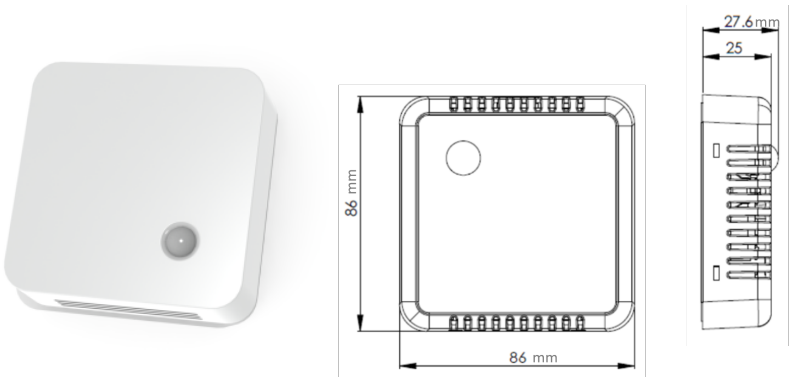
Table 2-5. *Class'Air measured parameters*

Elsys sensor

Elsys ERS CO_2 sensor measures (Figure 2-12) the indoor environment, including CO_2 levels, temperature, humidity, and light, and detects motion given in Table 2-6. It is enclosed in a room sensor box and is designed to be wall-mounted. ERS CO_2 is entirely wireless and

powered by two 3.6V AA lithium batteries. When the PIR is triggered, room occupancy is set to 1. The sensor captures a heat map image if no other motion is detected within 5 minutes. Room occupancy is set to 2 if heat signatures are detected; otherwise, room occupancy is set to 0, and a new background image is calibrated.

The ERS2 Eye will trigger a transmission whenever the occupancy value changes. No triggered transmission will be done if the occupancy value remains unchanged. Periodic transmissions will send all values, including occupancy. The occupancy values are 0 for unoccupied, 1 for motion (entering or leaving the room), and 2 for occupied. For more detailed information on this sensor, refer to Appendix B.



(A) Front side (B) Dimensions

Fig. 2-12. *Elsys sensor (A) the front view and (B) dimensions*

CO_2	Part Per Million (PPM) ratio	From 0 to 1000 ppm
	Resolution	1 ppm
	Accuracy at 10 - 40°C and 0-60% RH	$\leq, \pm$ (50 ppm + 3% of measured value)
Temperature	Measurement range	from 0 to +40°C
	Resolution	0.1°C
Humidity	Measurement range	from 0 to 80% RH
	Resolution	0.1 % RH
Light	Measurement range	4 to 2000 LUX
	Resolution	1 LUX
Motion	There is a blanking time of 30 seconds of the PIR triggering after each PIR trig and after each transmission	

Table 2-6. *Elsys measured parameters*

Sensor positioning

In late 2019, sensors were starting to be mounted on the wall, both Class'Air and Elsys. However, it was not until March 2020 that all sensors were completely installed in the

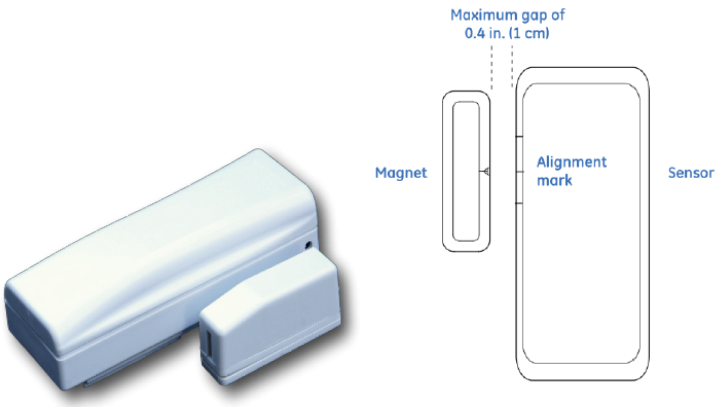
selected classrooms, workshops, and offices. In total, 21 Class'Air sensors are installed in BC and GC buildings, and 131 Elsys sensors are installed across all four buildings. Each building has different rooms, ranging from 45 (GEII) to 110 (BC). However, the number of sensors was limited. The concept of sensor positioning is to capture essential rooms that can represent different conditions, such as different floor levels (ground floor, first floor, second floor), different orientations (south, center, and north), and different room sizes (small, medium, and large). More importantly, rooms were selected based on their level of occupancy.

To adhere to the ISO standard for sensors [172], they are installed on the wall at heights of 0.6 *m* and 1.1 *m* above the ground. These heights correspond to the center of gravity of a seated person in classrooms and a standing person in workshops. Ideally, one room is equipped with one sensor, either Class'Air or Elsys. However, some exceptions exist where both sensors are installed in the same room to compare their precision and differences directly. Moreover, due to the large volume of workshops, sensors ranging from 2 to 4 can be installed in one workshop to capture the data evolution best.

CM868LR (Opening/Closing detector)

The CM868LR is a magnetic contact sensor for indoor applications. This type of sensor is specifically designed to detect the opening or closure of an object, like a door or a window, without any cable and is entirely battery-powered. An opening or closing object is detected using two reed contacts. CM868LR is supplied by one 3.6V AA battery.

The best configuration for the sensor is to immediately fix the magnet directly on the door or window (or, more generically, on the moving part) and the sensor on the door frame or window frame (or the fixed part) next to the door or window. The magnet is on the moving object, and the sensor is fixed to the wall. The maximum gap between the sensor and the magnet should be 1 cm; a bigger gap could prevent the sensor from detecting an opening or a closure.



(A) Front side (B) Dimensions

Fig. 2-13. *Opening/closing sensor (A) the front view and (B) dimensions*

II.3.2.3 The Gateway

The gateway is a critical component within the LoRa network. Multiple gateways are typically deployed, with each gateway connected to all end nodes. When a node transmits data, it is broadcast to all the gateways. Each gateway that receives the signal then relays it to a cloud-based network server using various communication methods like cellular, Ethernet, satellite, or Wi-Fi [170].

The LoRa antenna receives the radio waves emitted by various connected objects within a theoretical radius of 10 to 15 km. Two LoRa antennae are installed on the GC building of IUT de Nîmes, which communicate with the six types of sensors installed within the building.

II.3.2.4 The Application Server

Node-RED

Node-RED, a visual programming tool based on NodeJS and influenced by flow-based programming, develops IoT systems using nodes and flows. Nodes in Node-RED represent device or system service logic. Whenever nodes must cooperate or communicate to perform tasks, they compose flows, which logically aggregate sequences of functions. New Node-RED nodes based on upcoming technology are supplied every day by an active community. There are nodes for reading database values, implementing Javascript functions, receiving Twitter feeds, communicating between devices using MQTT, and more [173].

Node-RED IoT runs on multiple operating systems since it is platform-independent. Some hardware platforms with preloaded Node-RED environments can handle it. The multiplicity of hardware modules and networking options makes physical support assurance easy. These qualities include scalability, portability, data writing, compression, access efficiency, information security, and implementation costs.

InfluxDB

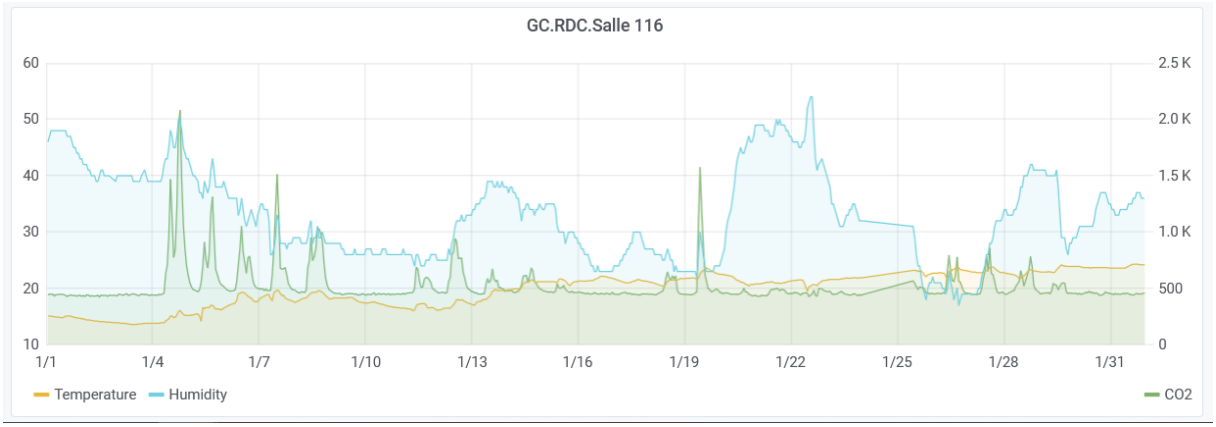
InfluxDB is an integral component of a comprehensive platform that facilitates the acquisition, retention, surveillance, representation, and notification of time series data. The InfluxData platform is constructed on an open-source foundation, built from scratch as a time series database [174].

The data obtained from the characteristic registries will be stored in a database. In light of the challenges posed by the IoT field, InfluxDB was chosen due to its ability to write and retrieve data efficiently within a minimal timeframe. In contrast to the conventional database structure that employs tables for data storage, InfluxDB adopts an alternative approach by utilizing measurements as the primary unit for data organization. A measurement comprises a

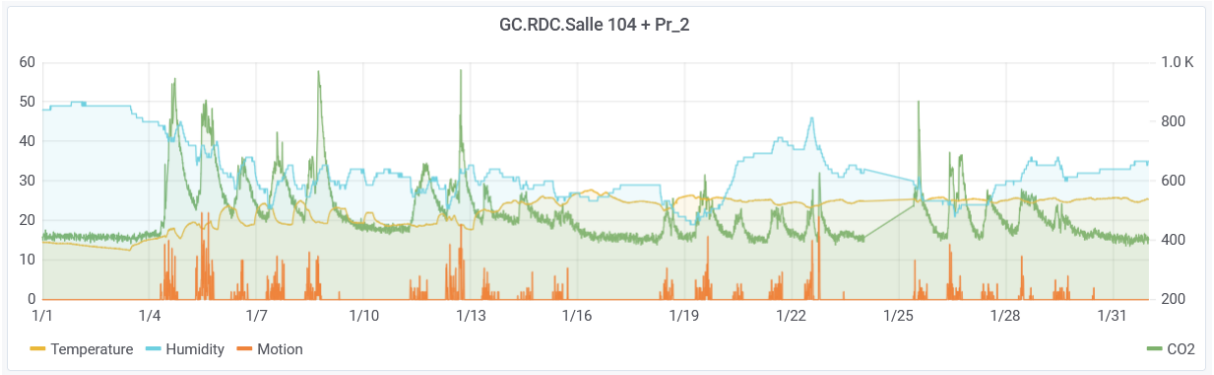
recorded data point accompanied by a timestamp assigned to each data series [175].

Grafana

Grafana, an open-source software that analyzes data and creates embedded images and alerts, was used to improve metrics visualization and enable data monitoring in a single interface. To encapsulate the visualizations, Grafana settings had to allow embedding and anonymous access (security was not addressed since this implementation aims to use protocols and build an IoT network that allows intercommunication) [175].



(A) Class'air sensor



(B) Elsys sensor

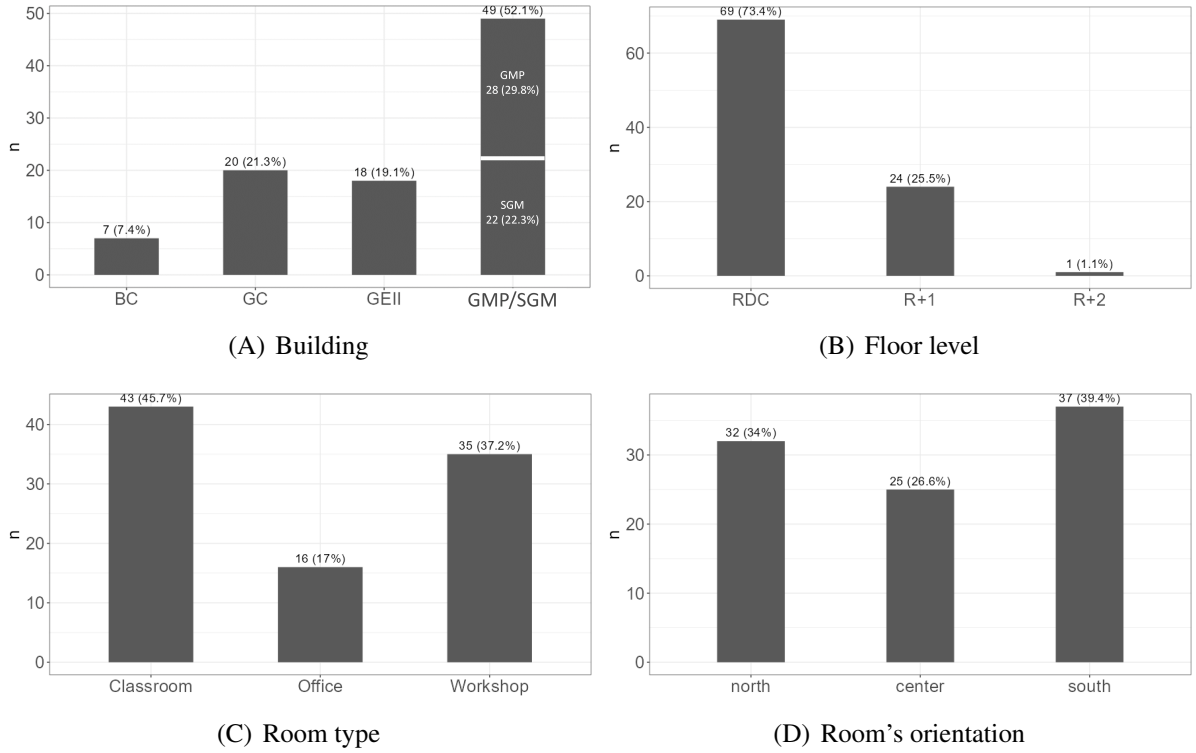
Fig. 2-14. *Monitoring platform - Grafana of (A) class'air sensor and (B) elsys sensor*

Each visualization panel offers a distinct range of capabilities that can be adjusted to accommodate the requirements of the intended application. In this case, the dashboard consists of two visualization panels: Class'Air and Elsys sensors, grouped by building and floor categories. Figure 2-14 presents the Grafana dashboard of (A) Class'air with three parameters and (B) Elsys with four parameters. The creation method was identical for all the panels. Each panel can be exported to a CSV file for data analysis.

II.3.3 Physical measurement analysis

II.3.3.1 Sensor counts

The exported CSV files from the Grafana platform are then imported to Rstudio, a data management and analysis programming language. As detailed in Section II.3.2.2, the combined count of the two sensors totals 152 objects. Notably, some rooms, particularly workshops, exhibit the installation of 2 to 4 sensors within a single room. After eliminating duplicates, the number of distinct rooms with at least one mounted sensor is 94.



(A) Building (B) Floor level

(C) Room type (D) Room's orientation

Fig. 2-15. *Number of sensors based on different categories: (A) Building; (B) Floor level; (C) Room type; and (D) Orientation*

When comparing the distribution of sensors among the various buildings on the IUT de Nîmes campus (as depicted in Figure 2-15A), a notable observation is that approximately 50% of the sensors are concentrated within the GMP building. This concentration is mainly due to the GMP building, which is comprised of two departments, GMP and SGM (as mentioned in Section II.2.2.1), each serving different functions and users. GC and GEII buildings have a similar number of sensors, totaling 20 and 18 devices, respectively, that contribute to 40% of the overall sensor.

Moreover, when considering the distribution of sensors across different floor levels (Figure 2-15B), it can be seen that the majority, approximately 73%, of the sensors are positioned

on the ground floor, which is often referred to as RDC (Rez-de-chaussée). This is because this level hosts all three types of rooms, accommodating various functions and activities. In contrast, the first floor, R+1, is primarily designated for classrooms.

Amongst the three room types and the distribution of sensors across all four buildings collectively, it becomes evident that classrooms are the most extensively equipped with sensors, constituting approximately 45% of the total sensors, as depicted in Figure 2-15C. In contrast, workshops and offices account for 37% and 17% of the sensors, respectively.

Furthermore, Figure 2-15D shows a relatively balanced number of sensors installed in rooms in the north, the south, and the middle. This suggests a consistent environmental quality across spaces exposed to different orientations. In essence, the four panels of Figure 2-15 shows a diverse distribution of sensors in different room conditions, ultimately contributing to a more comprehensive understanding of the campus's environmental conditions.

II.3.3.2 Evaluation of Class'Air and Elsy's accuracy

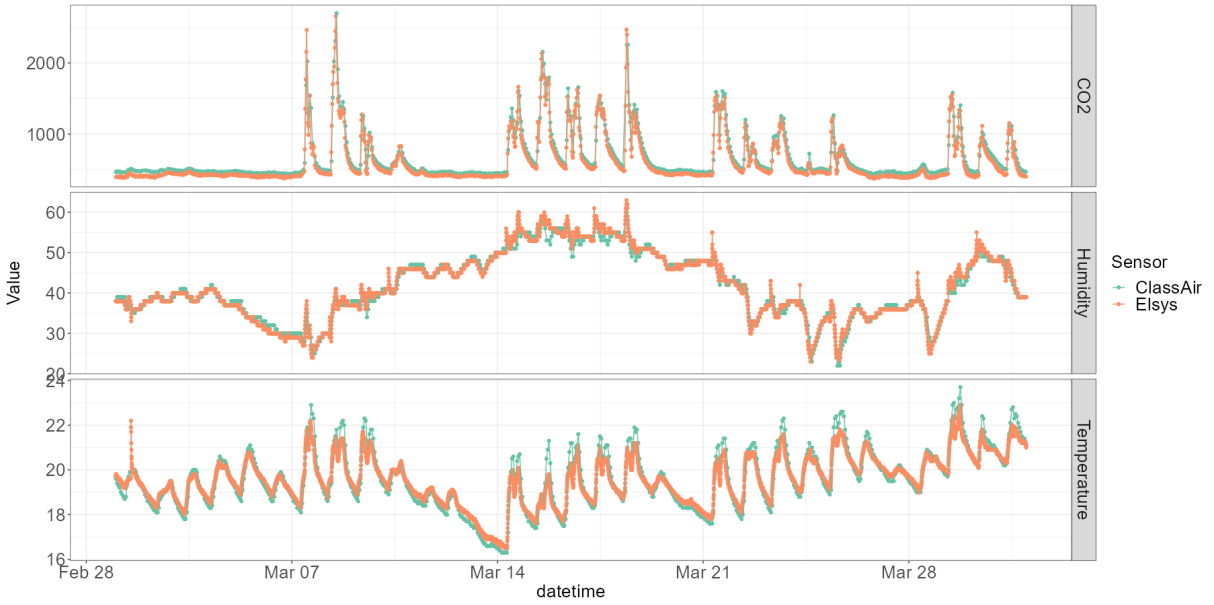
As the data analysis is based on two different sensors, comparing data evolution is critical in ensuring the accuracy and dependability of the data collected between the two sensors. This comparison involves an in-depth examination of how the data generated by these sensors evolves to determine whether they consistently report the same values or, at the very least, exhibit similarity in their trends.

The sensors' time intervals differ, with Elsys every 15 minutes and Class'Air every 60 minutes. Thus, to initiate this comparison, it is crucial to ensure that the data from both sensors is synchronized to the same time base for a direct point-by-point comparison. This entails aligning the timestamps for the data readings to establish a common time reference through data interpolation.

Figure 2-16 depicts data comparison in different duration lengths: (A) during a month-long period for a broader perspective of trends, and (B) during a day-long period to allow for a closer examination within a shorter timeframe. In general (panel A), the trends between the two sensors are practically identical. However, in the granular view (panel B), it can be seen that there is a slight difference. The average difference between the two values is 55.27 ppm, 7% HR, and 0.03°C.

To statistically compare the two datasets, one common approach used is the paired t-test, which determines whether there is a significant difference between the means of two related groups. The result of this test is expressed as a p-value, which quantifies the likelihood of observing such a difference if there is no real distinction between the datasets.

An additional metric known as Cohen's d is employed to gain a deeper understanding



(A) One month long



(B) One day long

Fig. 2-16. *Compared data evolution of the Class'Air and Elsys sensors of one classroom in different duration lengths (A) a month-long and (B) a day-long*

of the difference between the two datasets. Cohen's d is a formula for calculating the effect size, which provides insight into the magnitude or practical significance of the observed difference [176]. The effect size for a paired-sample t-test can be calculated by dividing the mean difference by the standard deviation of the difference:

$$d = \frac{M_1 - M_2}{S_{pooled}} \tag{II.3}$$

where d is the differences of the paired samples values; M_1 is the mean of group 1; M_2 is the mean of group 2; S_{pooled} is the pooled standard deviations for the two groups. The formula is: $\sqrt{[(S_1^2 + S_2^2)/2]}$

Upon comparing the datasets generated by the two sensors, the statistical results are summarized in Table 2-7:

Variable	Pair	Mean difference	P-value	Effsize	Magnitude
CO_2	Class'Air, Elsys	55.27 ppm	5.55e-24	0.68	moderate
Humidity		7%	0.0009	0.06	negligible
Temperature		0.03 °C	3.94e-06	0.08	negligible

Table 2-7. *Summarize the statistically comparison of Class'Air and Elsys sensors*

Statistical significance has been established over one month for humidity and temperature parameters, as evidenced by p-values < 0.05. However, their effect sizes suggest that their difference is minor and may be considered negligible in practical terms. On the contrary, the CO_2 parameter exhibits substantial disparities in effect size. However, the range of CO_2 level is between 300 ppm and 3000 ppm, ultimately showing the sensors present low measurement deviations. Different positioning in the tested rooms can explain the observed deviations from the maximum values in amplitude or time.

II.3.3.3 Missing data

The occurrence of missing data is a prevalent and inherent challenge when conducting long-term studies that involve continuous monitoring. In this case study, the collection of data extended over multiple years. During this prolonged data collection process, various factors can contribute to the emergence of missing data, impacting the completeness and reliability of the dataset.

One of the primary reasons for missing data in long-term monitoring studies is sensor-related issues. Over time, sensors and data collection equipment can experience wear and tear. They may develop technical problems, experience malfunctions, or degrade in performance. Sensors may temporarily stop providing accurate or consistent readings when these issues arise. These sensor failures can result in gaps in the data record where certain time intervals need more measurements. This is a common challenge in long-term studies, and it necessitates regular maintenance, sensor replacement, and monitoring of sensor health to minimize data losses.

Data transmission issues also play a role in creating missing data points. In long-term monitoring setups, data is often transmitted to central servers or storage locations. Network connectivity problems, issues with data transfer protocols, or failures in the data transmission

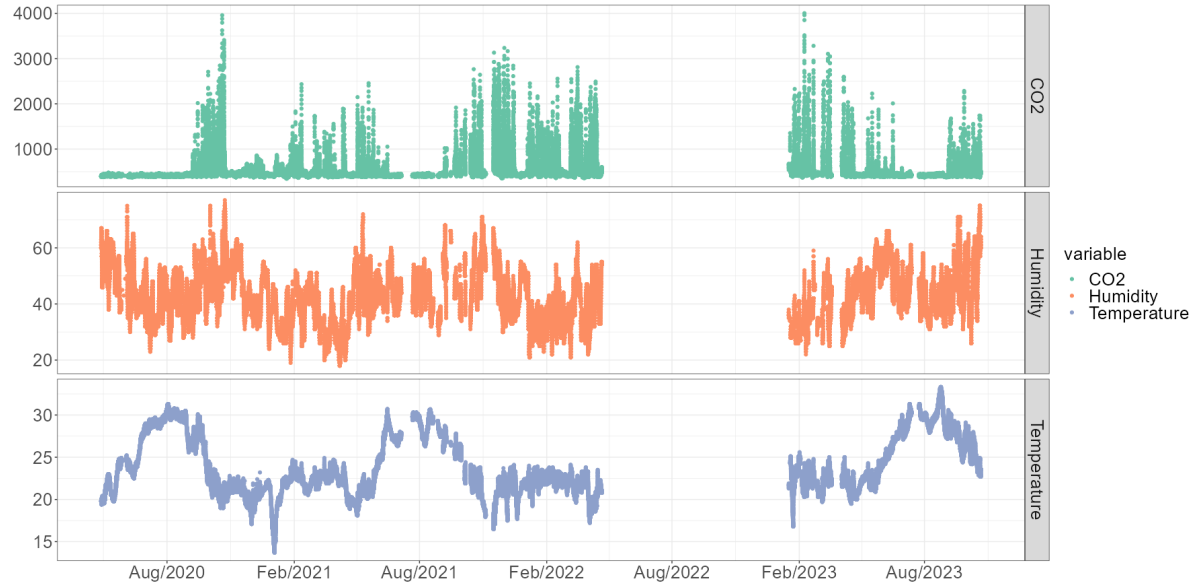


Fig. 2-17. *The entire data collection shows missing periods*

process can lead to incomplete or delayed data. When data cannot reach its intended destination, it contributes to data gaps in the overall dataset. As shown in Figure 2-17, several short, missing lengths often last for days or weeks. However, from April 2022 to late January 2023, a vast segment of data was missing due to transmission issues.

The occurrence of missing data for an entire year was primarily attributed to the expiration of the sensor contract (LoRaWAN system) in early 2022. Unfortunately, efforts to negotiate the renewal of this contract were unsuccessful. The team undertook a comprehensive data retrieval and decryption to address this data void. This initiative aimed to recover and restore the missing data, enabling the resumption of data acquisition from late January 2023 to the current date.

This effort to reclaim and resume data acquisition stresses the importance of proactive data management and recovery strategies in ensuring the completeness and reliability of long-term datasets, even in the face of unforeseen challenges like the ones mentioned.

II.4 Subjective data collection

In addition to the physical data, a subjective assessment was carried out to comprehensively study the impact of energy-efficient renovation on users' comfort. This involved gathering feedback from the building's occupants through a door-to-door survey. Occupants' perceptions and experiences are invaluable in understanding the real-world impact of renovations. They can highlight aspects of indoor comfort and air quality that might not be fully captured by physical

measurements alone.

The survey was based on a closed and open questionnaire to gather the occupants' opinions of both IUT employees (teachers, administrators, technicians, etc.) and students. The survey approach differs between the two groups, with students being more complicated as they were accessed four times (each lasting over five consecutive days) versus one time for the employees.

During an initial students' survey campaign, an online survey through Google Forms was officially launched on November 26, 2021, for 250 students of GC and GEII buildings. However, after five consecutive days, the total number of responses was only 34, with 12 students in different classrooms. This very low response rate led us to conduct a door-to-door survey with room selection strategies.

II.4.1 Survey assessment of IUT de Nîmes employees

The dynamics of indoor climate sensation and perception at IUT de Nîmes exhibit a degree of complexity due to the continuous influx of new students each year. Under their academic schedules, these students frequently shift between different classes after each session. Consequently, their experiences and perceptions of the indoor climate are subject to change, influenced by various factors such as outdoor climate conditions and the specific rooms they occupy.

In contrast, school employees tend to remain in the same office for an extended duration, leading to distinctions in their indoor climate sensations and perceptions compared to students. Their occupancy's enduring and consistent nature permits a comprehensive evaluation of their indoor climate experiences. This assessment is not confined to a specific moment but provides a broader overview of their sensations and perceptions throughout the year.

To capture this contrast in experience and gather insights into the indoor climate from students and employees, a survey for each group was designed slightly differently. One of the survey phases was accessed in June 2022, during the missing physical data period. However, the analysis in this section aims to understand the general habits of the employees during the heating and non-heating periods.

II.4.1.1 Questionnaire design

The questionnaire survey for IUT employees (teachers, administrators, and technicians) has two main parts: winter and summer. The questions within the two parts are identical, having two sections, with the first one being "*The overview of your office usage*", to find out their usual usage of windows, doors, shutters, and reversible air conditioners. The second section is "*Vote*

your comfort" regarding temperature, humidity, and air movement for each season's sensation, acceptability, and preference level.

However, there is an additional section (third part) to the survey questionnaires for teachers which asks about their classroom usage while teaching, specifically before and after COVID-19. This thesis spanned a significant duration, including the challenging period marked by the COVID-19 pandemic. As such, it was inevitable that the research and data collection processes would be impacted by the extraordinary circumstances brought about by the pandemic. The emergence of COVID-19 had far-reaching consequences that extended to various aspects of life, including how buildings were used.

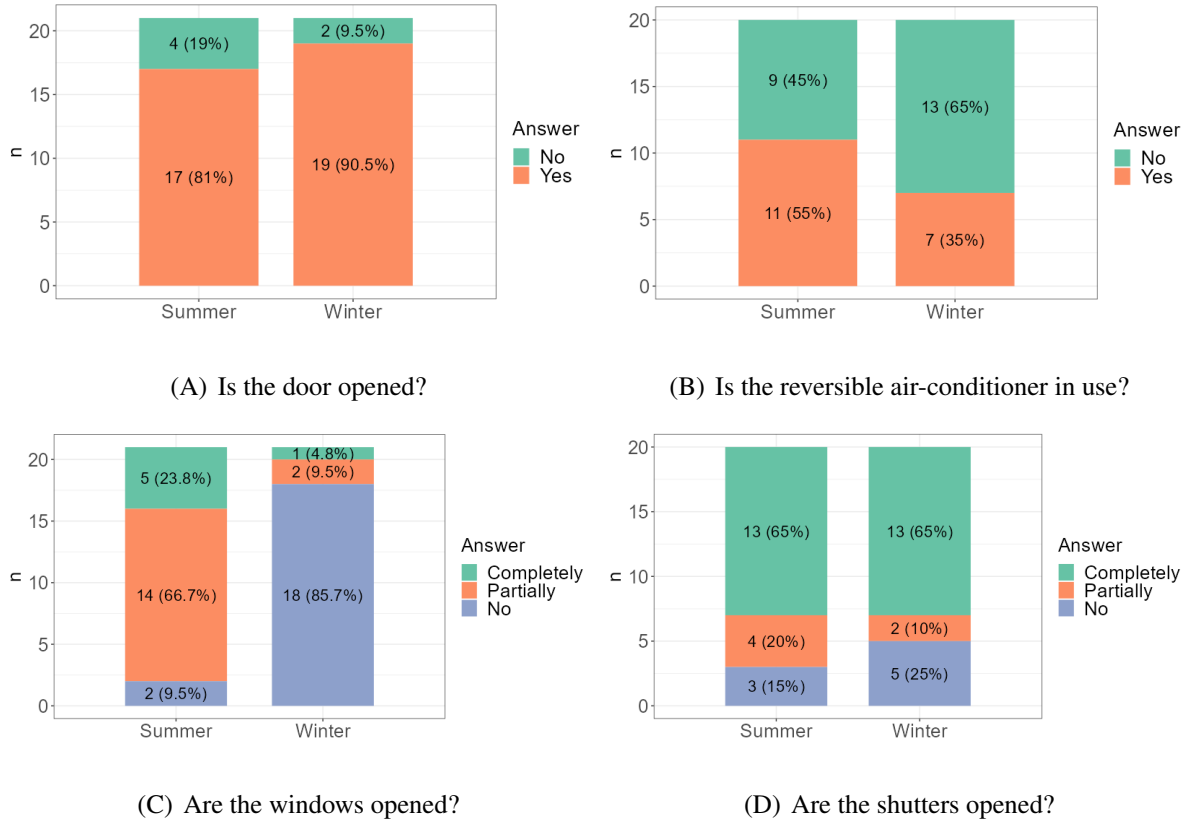
The building usage patterns, typically stable and well-established in pre-pandemic times, underwent a substantial shift in response to the health and safety measures necessitated by COVID-19. IUT de Nîmes strictly implemented COVID-19 measures from March 16 to June 15, 2020, following the first lockdown. The second lockdown lasted from November 01, 2020, to January 15, 2021. These measures included lockdowns, social distancing, remote work and learning, and the reconfiguration of indoor spaces to reduce transmission risks. Consequently, the data collected during this period would naturally differ from those obtained in more typical, non-pandemic conditions.

To comprehensively grasp the changes in building usage, especially their impact on classroom utilization, a questionnaire survey targeted teachers. This survey aimed to collect information on their typical classroom usage behavior before, during, and after the COVID-19 pandemic. The third part of the survey focused on any changes in teachers' behavior regarding pauses during teaching sessions and their use of classroom windows and doors. The obtained data provides insights into the lasting effects of the pandemic on educational institutions and the adaptability of teaching staff to the challenges, offering a unique perspective in consideration of the exceptional circumstances during the COVID-19 era.

II.4.1.2 Survey response from administrators and technicians

The survey for IUT employees, encompassing both online and offline components, was conducted over two consecutive working days in June 2022. This dual approach was designed to maximize participation and gather responses through both digital and in-person using door-to-door survey sheets. Despite the concerted effort to engage a broad spectrum of respondents, the overall number of participants remained remarkably limited. The survey yielded a total of 21 responses, a combination of different individuals from three buildings: GC, GEII, and BC.

The working spaces allocated to the employee members are typically characterized by their compact size, around 20 m^2 on average. These offices are usually shared, accommodating either one or two colleagues. The survey results shed light on several key aspects of how



(A) Is the door opened?

(B) Is the reversible air-conditioner in use?

(C) Are the windows opened?

(D) Are the shutters opened?

Fig. 2-18. *IUT employees' responses in their general adaptive behavior during the summer on thermal comfort to the following questions: (A) Is the door opened?; (B) Is the reversible air conditioner turned on?; (C) Are the windows opened?; and (D) Are the shutters opened?*

the employees interact with their office spaces. Based on Figure 2-18A, it is found that a substantial proportion of respondents, specifically 80%, tend to keep their office doors open for a significant part of the time. This practice may indicate a preference for open and accessible work environments, promoting collaborative interaction and collaboration.

During the winter months, most respondents (85.7%), opt to close their windows (see Figure 2-18C), likely to retain warmth and reduce heat loss. In contrast, during the summer, 90.5% of them choose to open their windows, partially and fully. This practice is indicative of a strategy to ventilate and cool the space, responding to warm weather conditions.

Furthermore, when it comes to window shutters, as seen in Figure 2-18D, 25% of the survey participants reported closing them in the winter, possibly to minimize heat loss or improve thermal insulation. Similarly, 15% mentioned closing the shutters in the summer, which might be aimed at blocking out excessive sunlight and heat.

The survey data, presented in Figure 2-18B, also reveals that a notable portion of the respondents, comprising 35%, resort to using electric heaters, particularly reversible air-conditioning

units, during the winter months. This behavior stems from perceived inefficiencies in the radiator heaters supplied by the district heating system. During the summer, 55% of the respondents opt for air-conditioning systems to combat the discomfort associated with high temperatures. This preference for air conditioning highlights the employees's reliance on cooling solutions during warm seasons.

Despite the availability of an additional reversible air-conditioning system, the survey results indicate that a large portion of the respondents, specifically 55%, experienced what can be categorized as "cold discomfort" during the heating period. This observation highlights the challenges of maintaining an optimal and comfortable indoor temperature during the colder season, even with the heating and cooling equipment at their disposal. The occurrence of cold discomfort suggests that these individuals might have been exposed to lower temperatures than their preferred or comfortable range.

Conversely, during the summer, a significant proportion of the respondents, constituting 50%, reported experiencing "hot discomfort". This finding indicates that a considerable number of respondents struggled with elevated temperatures and warmth in their indoor spaces despite the availability of air-conditioning systems.

The presence of an additional reversible air conditioner, while offering a degree of control over indoor temperature, does not entirely mitigate the challenges of maintaining optimal thermal comfort. In addition, employing an air conditioner contributes to the overall energy consumption within the campus, reflecting the employees' adaptive behaviors to ensure indoor comfort in their shared and relatively small office spaces.

II.4.1.3 Survey response from teachers

The issue of limited participation in the survey extends to the group of teachers, where only 12 responses were obtained. This relatively low number of respondents reflects the challenges often encountered when seeking active engagement in research surveys. However, the results from these respondents remain valuable and provide a perspective on the experiences of the teaching employees on the IUT campus.

Teachers and other employees (administrators and technicians) show similar patterns in their responses regarding actions taken for thermal comfort management, such as opening or closing doors, windows, shutters, and reversible air conditioners. This indicates that these groups share common behaviors and adaptive strategies for managing indoor climates.

As illustrated in Figure 2-19, the change in patterns of taking pauses between 2 hours or more teaching sessions does not differ drastically when comparing the pre- and post-COVID periods. This implies that adaptive behaviors related to the timing and duration of breaks do not

undergo substantial changes due to the pandemic.

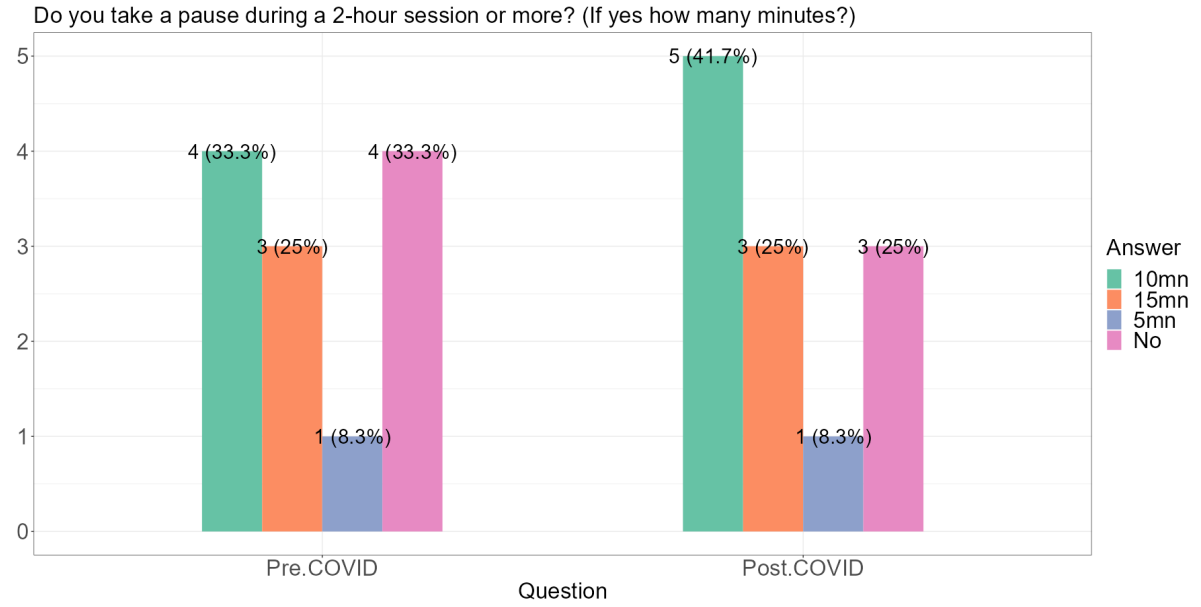
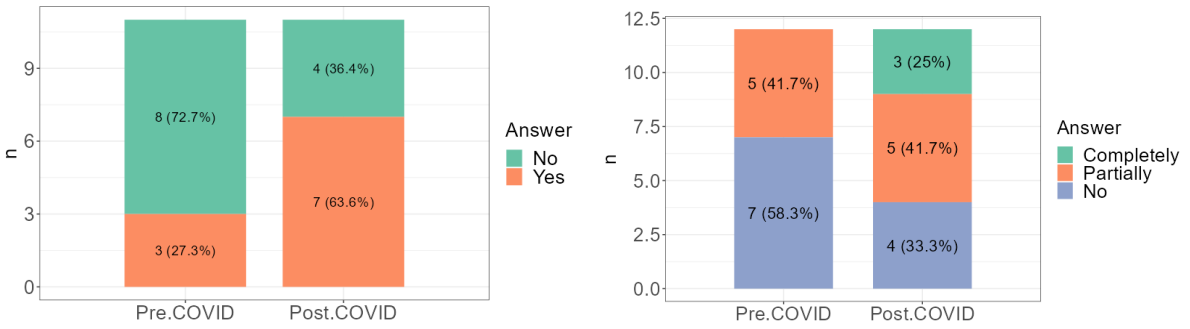


Fig. 2-19. *Teachers' habit of taking a small break during teaching sessions of 2 hours before and after COVID-19*



(A) Do you open the door during class?

(B) Do you open the windows during class?

Fig. 2-20. *Teacher responses to using adaptive strategies in the classroom during the heating period: (A) Is the door open? and (B) Is the window open?*

Figure 2-20 depicts passive comfort strategies employed by teachers during the heating period within classrooms before and after the COVID-19 pandemic. The shift in behavior toward increasing ventilation by opening door (panel A) and windows (panel B) may be attributed to the increased awareness of indoor air quality and safety during the COVID-19 pandemic. Adequate ventilation is crucial to mitigate the potential spread of airborne particles, including viruses. As such, the pandemic has likely emphasized the importance of maintaining good air quality and circulation within enclosed spaces.

II.4.2 Student survey process

II.4.2.1 Survey procedure

The successful execution of the door-to-door questionnaire survey was facilitated by a combination of key factors and logistical considerations. One fundamental criterion is the presence of physical sensors installed within the room, as they provide an additional layer of data for contextual analysis and validation. Second, the occupancy status during the survey period spanned five consecutive days for each phase. The survey selected rooms that were occupied during the study period based on accessible study schedules.

Another consideration is to choose rooms that best represent various conditions within the building. This included considering factors such as floor level, room size, and room orientation. The study aimed to capture the nuances and variations in student experiences across different conditions by including a diverse range of room types in the survey. Lastly, the survey was contingent on the cooperation and permission of the teachers, who determined when the questionnaires could be distributed. They decided that the questionnaire sheets should be handed out at the start or end of their teaching sessions. Teacher involvement was crucial to the smooth execution of the survey.

The subjective evaluation comprised four distinct phases: winter 2022, summer 2022, winter 2023, and summer 2023. During the first phase of a survey conducted in the winter of 2022, the chosen classrooms were assessed as often as they were occupied within the survey period. However, after multiple survey repetitions, a challenge arose when students began to lose interest in providing accurate responses to the questionnaires. The survey approach was adjusted to ensure the reliability of occupant responses and prevent inaccuracies. This adjustment entailed expanding the number of rooms selected for the survey while restricting each room to a single survey, thus avoiding the need for repetitive surveys in the same rooms by distinct groups.

Another challenge is the absence of data from physical sensors, as outlined in Section II.3.3.3, which corresponds to summer 2022. Consequently, survey responses collected during this period have been excluded from further discussion.

II.4.2.2 Ethics risk and data protection

This study involves student volunteers, so ethics must be considered. The ethical process requires justification for two key objectives. First, weigh the research's social benefits against participant risks. Second, keep monitored data confidential during and after the research endeavor. To meet ethical approval requirements, the IUT de Nîmes approved this project before

it began. Additionally, ethical considerations relate to obtaining informed consent from study participants and the potential use of deception in the study. Protocols must ensure the confidentiality of data collected during and after the study, including storage and protection measures. Providing incentives to participants is a potential motivating factor for their involvement in the study.

Efforts have been made not to alter students' indoor comfort perception while gaining ethical authorization. To do this, participants were told that their information would be kept private. If people want more information about the study or its results, they can get it thereafter. Participants were randomly selected and voluntarily participated in this study. All study participants were over 18 years old.

II.4.2.3 Survey questionnaires

The survey, which typically takes about five minutes to complete, encompasses 15 questions divided into four primary sections (refer to Appendix C for a full-form questionnaire survey sheet). The first section, labeled *"Inquiries about room overview"*, comprises five questions designed to gather information about the respondent's seating position and whether windows and shutters are opened or closed. The second section, titled *"Questions on your perception"*, includes four questions with a consistent format to assess the respondent's perceptions of indoor climate. The third section, denoted as *"Questions on your acceptability"*, also features four identical questions that vary only regarding indoor climate parameters, covering temperature, humidity, air movement, and indoor odors. The fourth section, under the heading *"Questions on your preference"*, consists of two questions inquiring about the respondent's room temperature preferences and their actions related to environmental control. Table 2-8 presents the scale used in the analysis following the questions in the second, third, and fourth parts.

Scale	Question on your perception				Question on your acceptability				Question on your preference
	Temperature	Humidity	Air movement	Odor	Temperature	Humidity	Air movement	Odor	Temperature
3	very hot	very humid	very strong	strong smell	-				-
2	hot	humid	strong	weak smell	clearly accetpable				-
1	neutral	neutral	correct	no smell	just acceptable				warmer
0				-	-				no change
-1				-	just unacceptable				cooler
-2	cold	dry	weak	-	clearly unacceptable				-
-3	very cold	very dry	immobile	-	-				-

Table 2-8. *Scales of sensation acceptability and preference votes*

This study's thermal perception vote metric was derived from the ASHRAE seven-point scale, a standard used to evaluate thermal comfort ratings ranging from -3 (very cold) to +3 (very hot). To simplify the questionnaire, the comfort range was narrowed, considering that the

-1 and +1 scale points on the ASHRAE vote are within the comfort range, as suggested in a review paper [129]. This adjustment resulted in a five-point scale as follows: {-3, -2, 0, +2, +3}, as shown in Table 2-8.

Prior research [177] has emphasized the significance of humidity and air velocity in determining physiological thermal comfort. Studies have shown that elevated indoor humidity levels obstruct the body's ability to cool down through sweat-induced evaporation, which is a primary mechanism for dissipating heat, especially in warm environments. Air movement also plays an important role in influencing both evaporating and convective heat exchanges with the body, thereby impacting its overall temperature regulation. To comprehensively evaluate thermal comfort, the questionnaire integrated assessments of humidity comfort and air-movement comfort, utilizing the ASHRAE five-point scale.

The entire survey procedure yielded 1047 responses, with 339 from winter 2022, 437 from winter 2023, and 271 from winter 2022. Due to some data missing from the physical sensors, the final result was 981 valid responses from 3 buildings (GC, GEII, and GMP) in 36 rooms (27 classrooms and 9 workshops). Table 2-9 summarizes the questionnaire responses in terms of study phases and building states correspondingly.

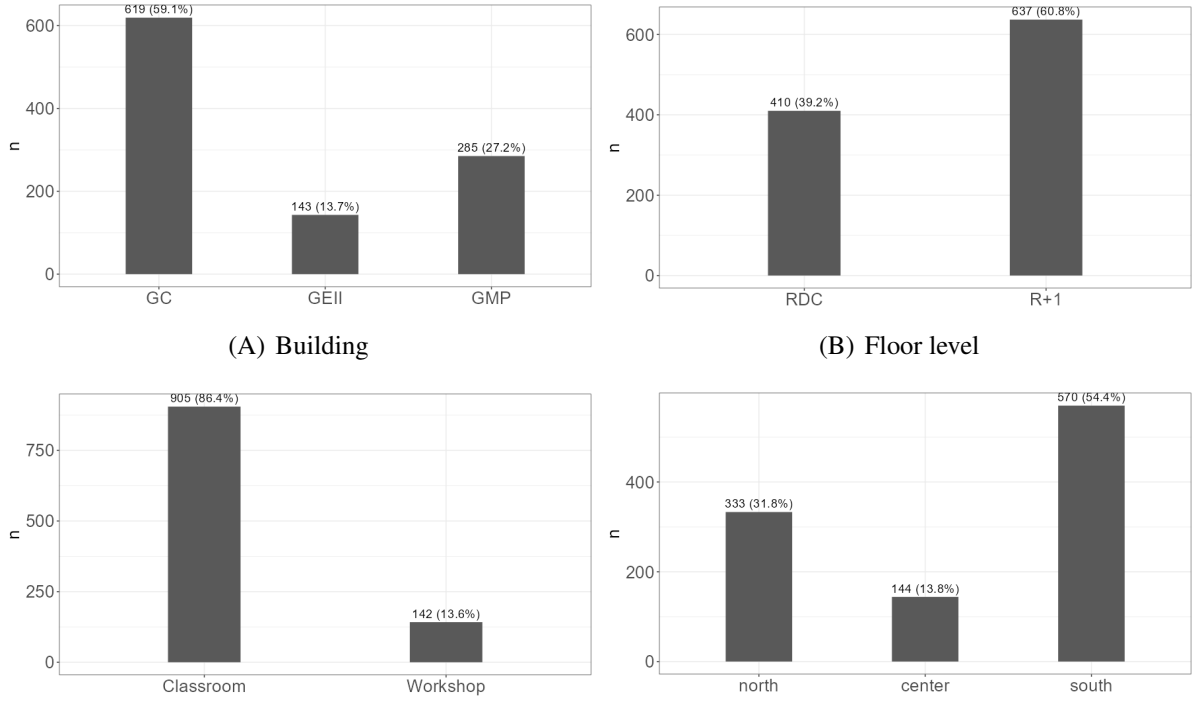
<table>
<tr><th colspan="4">Building state in terms of the survey period</th></tr>
<tr><th>survey period</th><th>Season</th><th>Surveyed building(s)</th><th>Building State</th></tr>
<tr><td>17/02/2022 - 23/02/2022 (phase 1)</td><td>Winter</td><td>GC</td><td>Before</td></tr>
<tr><td rowspan="2">6/3/2023 - 15/03/2023 (phase 2)</td><td rowspan="2">Winter</td><td>GEII, GC</td><td>After</td></tr>
<tr><td>GMP</td><td>Before</td></tr>
<tr><td rowspan="2">16/06/2023 - 21/06/2023 (phase 3)</td><td rowspan="2">Summer</td><td>GEII, GC</td><td>After</td></tr>
<tr><td>GMP</td><td>Before</td></tr>
<tr><th colspan="4">Vote counts</th></tr>
<tr><th>State</th><th>Season</th><th>Vote count</th><th>Total vote</th></tr>
<tr><td rowspan="2">Before</td><td>Winter</td><td>466</td><td rowspan="2">580</td></tr>
<tr><td>Summer</td><td>114</td></tr>
<tr><td rowspan="2">After</td><td>Winter</td><td>253</td><td rowspan="2">401</td></tr>
<tr><td>Summer</td><td>148</td></tr>
</table>

Table 2-9. *Summary of vote counts from both room types: classroom and workshop*

II.4.3 Student survey analysis

II.4.3.1 Vote count according to building characteristics

Figure 2-21 depicts the distribution of survey responses from the three phases categorized by building (panel A), floor level (panel B), room type (panel C), and room orientation (panel D). Figure 2-21A highlights that the GC building receives the highest number of respondents, making up approximately 59% of the total responses. Following GC, the GMP building accounts for 27% of the responses, while the GEII building receives 13%. Indeed, the timing of the GC building's renovation allows for a unique opportunity to conduct surveys both before and after the renovation, making it a focal point for research. Consequently, this building attracts a higher density of responses, encompassing distinct eras, further enriching the data analysis.



(A) Building (B) Floor level

(C) Room type (D) Room's orientation

Fig. 2-21. *Survey collection count based on different categories: (A) Building; (B) Floor level; (C) Room type; and (D) Orientation*

Typically, classrooms accommodate a larger number of students compared to workshops. As a result, the total vote count tends to be skewed toward classrooms (Figure 2-21C), which are primarily situated on the first floor (R+1) (Figure 2-21B). Concerning the orientation of the rooms, the survey responses (Figure 2-21D) indicate that rooms facing the south make up 54% of the total votes, followed by north-facing rooms at 31% and the rest are associated with rooms in the center.

It is worth noting that the survey specifically focuses on the study of solar gains indoors, which is why rooms with east and west orientations are not separately categorized. Instead, they are considered part of the center category unless they are located directly adjacent to the exposed wall on either the south or north side, in which case they are classified accordingly.

II.4.3.2 Vote count according to room usage

In addition to considering the fundamental building characteristics, the analysis of survey responses takes into account room usage, as indicated in the first section of the survey questionnaire, *"Inquiries about room overview"*. As shown in Figure 2-22A, respondents are evenly distributed based on their seating positions: around 35% in the center of the room, approximately 31% next to the exposed wall, and about 32% next to the internal wall. This question aims to investigate the influence of seat location on how individuals experience the indoor environment. For instance, those seated next to an exposed wall may be more exposed to solar gain, potentially leading to variations in their sensation and perception of the indoor climate.

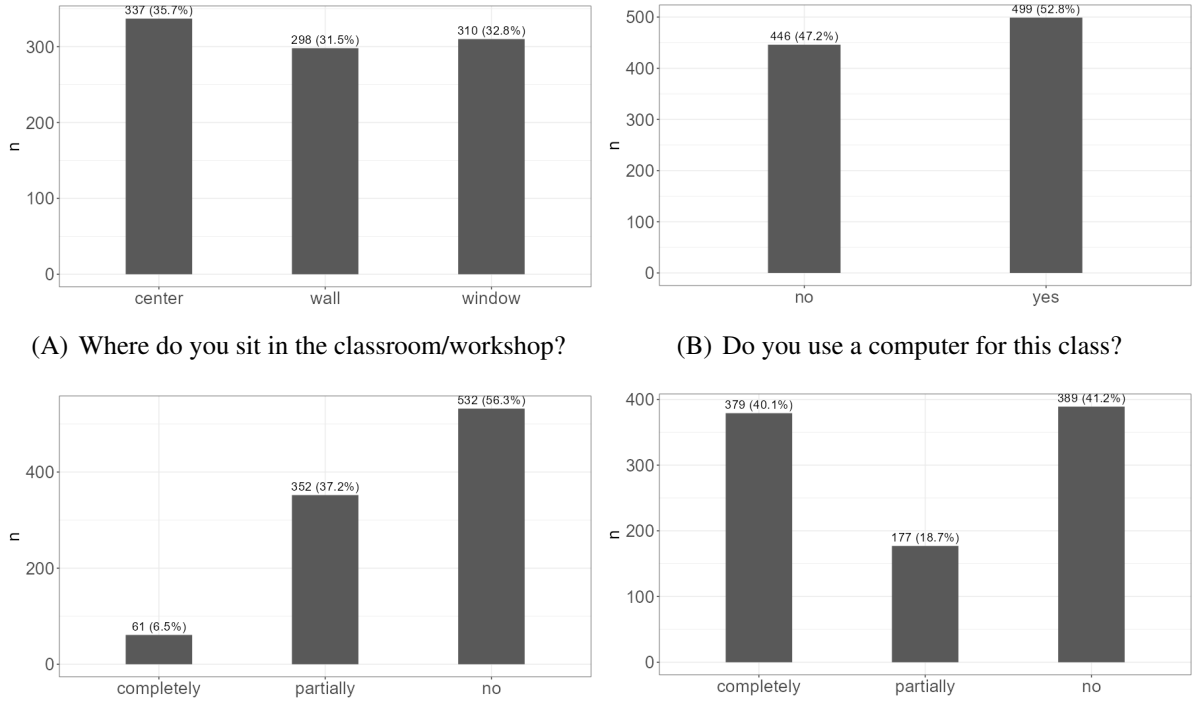
Another inquiry, shown in Figure 2-22B aims to determine if computers or mechanical machines were in the surveyed areas during the data collection period. This investigation is to understand potential sources of indoor heat gain, as these appliances can significantly affect indoor thermal conditions. The responses are fairly equal, with around 47% answering "no" and approximately 52% answering "yes".

Figure 2-22C provides an overview of the distribution of rooms with various window states. The majority of votes, approximately 56%, correspond to rooms with no windows reported as open during the survey period. This is followed by the category of rooms where windows are partially opened, constituting approximately 37% of the responses. A smaller fraction, around 6%, reports rooms with windows completely opened during the survey.

The term "partially opened" here means that the windows in a room are open to some extent, either halfway or some of them are open. This classification is determined by the room's volume and the arrangement of its windows. For example, a classroom with multiple windows is considered "partially opened" if only some windows are open, regardless of the total number of windows. On the other hand, if all windows are open, it is classified as "completely opened".

This question is useful in the survey, particularly during non-heating periods. The degree to which windows are open can significantly affect the air exchange within the room, thus influencing indoor air quality and thermal comfort. The data gathered in response to this question offers valuable insights into the occupants' preferences and practices regarding window openings and their potential impact on the indoor climate.

Figure 2-22D illustrates responses about the state of window shutters, aiming to under-



(A) Where do you sit in the classroom/workshop?

(B) Do you use a computer for this class?

(C) Are there any windows open?

(D) Are there any shutters open?

Fig. 2-22. *Survey collection count based on different categories of room usage: (A) Respondent's seat position; (B) Usage of computer/mechanical machines; (C) Presence of windows opened; and (D) Presence of shutters opened*

stand occupants' preferences for solar control. The data shows a nearly equal split, with 40% of rooms having completely opened shutters and 41% having completely closed shutters, implying diverse occupant behaviors and preferences in managing window shutter positions. While many rooms prefer fully open shutters for natural light and potential solar gain, some opt for fully closed shutters, possibly for privacy, temperature control, or blocking external light.

II.5 Conclusion

The IUT de Nîmes campus, built in the late 1960s, recently underwent an energy-efficient renovation to enhance its overall energy performance. The renovation strategies encompassed critical aspects such as building envelope improvements, including external wall insulation and replacing traditional windows with low-emissivity glazing. New building systems were also integrated, featuring single-flow mechanical ventilation and thermostatic control on newly installed radiators in each room across the campus buildings.

This chapter presents tools and methodology for a comprehensive investigation to assess the renovation's impact on various facets, including energy consumption, indoor climate quality,

and occupant comfort. To facilitate this analysis, climate sensors were strategically deployed within a selection of 94 rooms (classrooms, workshops, and offices) across four buildings within the campus.

The climate sensors employed in this study, namely Class'Air and Elsys, were explicitly designed to measure critical environmental parameters, including air temperature, relative humidity, and CO_2 levels. These sensors were meticulously positioned to capture the most accurate and representative data, considering variables such as floor level, room orientation, and room type. This comprehensive approach ensures that the data collected effectively reflects the diverse character of the buildings under investigation.

In conjunction with installing climate sensors, a questionnaire survey was conducted three times: winter 2022, winter 2023, and summer 2023. The total valid responses are 981 from 27 classrooms and 9 workshops. This rigorous approach allowed for direct feedback from the occupants about their comfort and preferences, both before and after the renovation.

Chapter III

Indoor climate

"I was taught that the way of progress
was neither swift nor easy"

— MARIE CURIE

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III.1 Introduction

This chapter delves into a comprehensive examination of the indoor climate within the investigated buildings, which is divided into three essential parts, each discussing a distinct facet of the indoor environment.

Part A investigates the pre-renovation conditions of IUT de Nîmes buildings. It aims to provide a complete overview of the indoor climate regarding their profiles and influential factors, building characteristics, and building usage.

Part B is dedicated to temperature prediction. The goal is not only to unveil a predictive model for indoor temperature but also to unravel the factors that significantly influence the variations in indoor temperature. Understanding these drivers is crucial in creating strategies for maintaining a comfortable and energy-efficient indoor environment.

Part C evaluates the performance of renovation in terms of the indoor climate, as two of the IUT de Nîmes buildings underwent refurbishments recently. This part focuses on how these renovation measures impact the air temperature, humidity levels, and CO_2 concentrations.

III.2 Part A: Investigating indoor climate in non-renovated buildings

Existing educational buildings from the last few decades typically follow a similar construction model that disregards energy performance and thermal comfort. For economical and quality of life reasons, these buildings are going through renovations, less expensive than construction from scratch. To assess the effectiveness of these renovation efforts, conducting a comprehensive analysis of the building's existing conditions and the indoor environment before any improvements are imperative.

This section delves into a thorough examination of indoor climate parameters, explicitly focusing on air temperature, humidity, and CO_2 levels within the pre-renovated buildings of the IUT de Nîmes campus. The primary objective is understanding how these indoor climate variables have evolved and identifying the factors influencing their fluctuations. This includes exploring building characteristics, such as building orientation and floor level, and investigating how building usage practices, including window and shutter operations, contribute to the variations in indoor climate conditions.

III.2.1 Data collection

The analysis in this part is divided into two seasons: the summer (June 21 to September 21, 2020) and the winter (December 21, 2020 to March 21, 2021). The buildings were predominantly unoccupied in summer due to the summer break, spanning from June 21 to August 01, 2020. Moreover, during the winter, the data was potentially affected by the COVID-19 safety measurements.

Based on the sensor's availability, 17 rooms that best represent the IUT de Nîmes buildings were chosen as follows:
- Building: BC, GC, GEII, and GMP
- Floor: ground floor (RDC), first floor (R+1), and second floor (R+2)
- Orientation: based on the exposed window's orientation, which is south (S), north (N), and middle (M) for rooms situated in the center of the building without any exposed walls
- Type: classroom (C), workshop (W), office (O), amphitheater (A)

Thus, the code of each room follows a pattern of *"Building_Floor_Orientation_Type"*.

Code	Building	Floor	Orientation	Room type	Surface area
BC_R+1_N_C	BC	R+1	North	classroom	46 m^2
BC_R+1_S_C	BC	R+1	South	classroom	64 m^2
BC_R+2_S_C	BC	R+2	South	classroom	51 m^2
BC_RDC_N_A	BC	RDC	South	office	180 m^2
BC_RDC_S_O	BC	RDC	South	office	18.5 m^2
GC_R+1_N_C	GC	R+1	North	classroom	90 m^2
GC_R+1_S_C	GC	R+1	South	classroom	102 m^2
GC_RDC_N_W	GC	RDC	North	workshop	49 m^2
GC_RDC_S_C	GC	RDC	South	classroom	51 m^2
GC_RDC_S_O	GC	RDC	South	office	34 m^2
GEII_RDC_M_W	GEII	RDC	Middle	workshop	242 m^2
GEII_RDC_N_C	GEII	RDC	north	classroom	88 m^2
GEII_RDC_S_C	GEII	RDC	Nouth	classroom	114 m^2
GMP_R+1_S_C	GMP	R+1	South	classroom	49.5 m^2
GMP_RDC_S_O	GMP	RDC	South	office	24.5 m^2
GMP_RDC_M_W	GMP	RDC	Middle	workshop	48.5 m^2
GMP_RDC_N_C	GMP	RDC	North	classroom	77 m^2
GMP_RDC_N_W	GMP	RDC	North	workshop	252.5 m^2
GMP_RDC_S_C	GMP	RDC	South	classroom	50 m^2

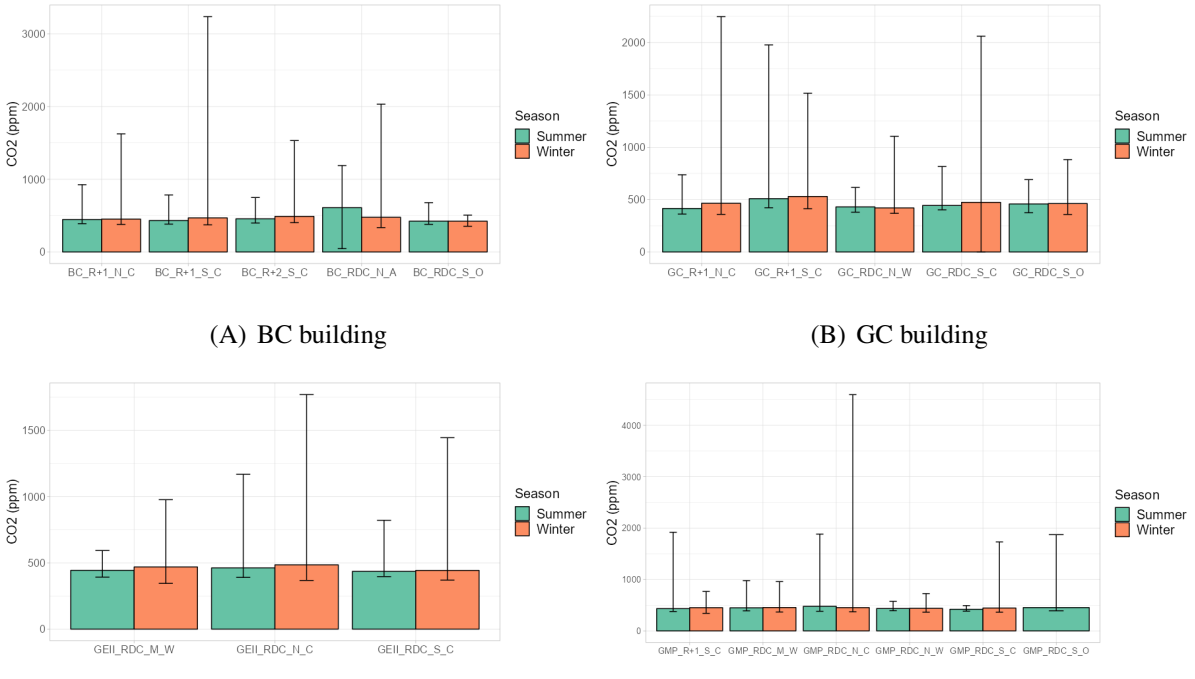
Table 3-1. *Selected room nominations and surface area*

III.2.2 Indoor climate in non-renovated buildings

III.2.2.1 CO_2 levels

The occupancy rate significantly influences the levels of CO_2 within the indoor environment. Within IUT de Nîmes buildings, classrooms have the highest occupancy rate, surpassing offices typically shared by two or three colleagues, and workshops are characterized by their larger volumes and fewer students present. This discrepancy in occupancy density directly impacts the rate at which CO_2 accumulates within these spaces.

The data collected from various room types, as depicted in Figure 3-1, corroborates the significant impact of room types and seasonal variations on indoor CO_2 levels. On average, the CO_2 concentration in each room across all four buildings remains consistently below 500 ppm, reflecting well-maintained indoor air quality.



(A) BC building

(B) GC building

(C) GEII building

(D) GMP building

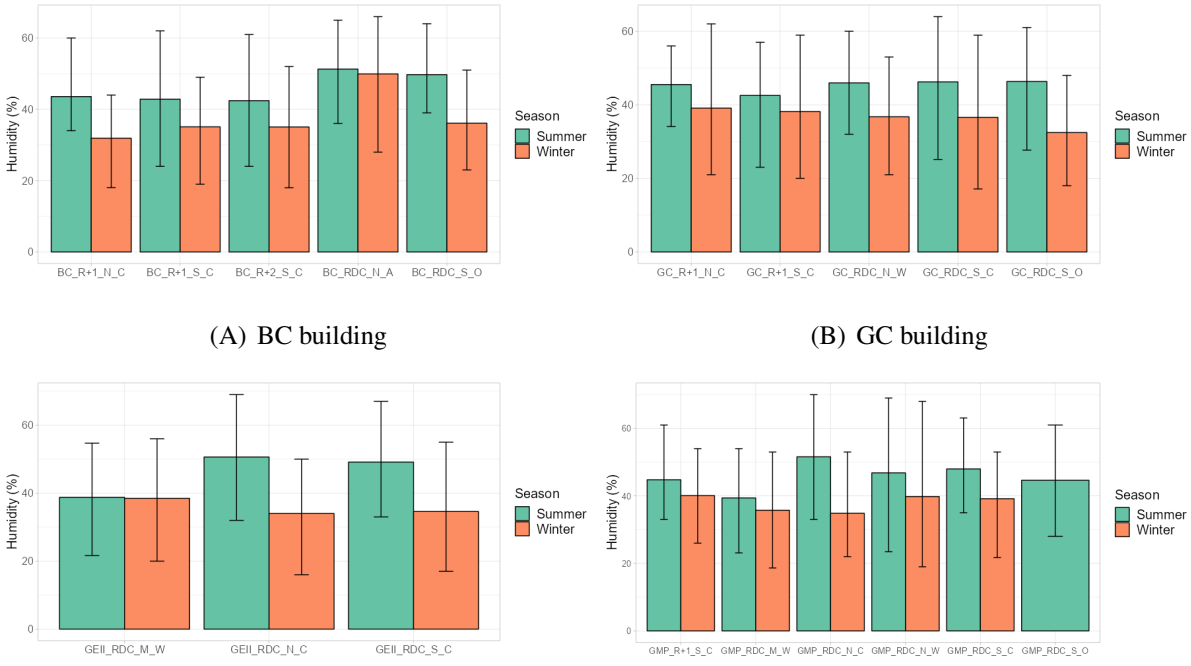
Fig. 3-1. *Grand average of each room's indoor CO_2 level in summer and winter during occupied periods. The whiskers represent the minimum and maximum average values of each room: (A) BC building; (B) GC building; (C) GEII building; and (D) GMP building*

However, it is worth noting that the maximum recorded CO_2 levels tend to peak during the winter months, with classrooms being the most affected. The classrooms frequently experience CO_2 levels surpassing 2000 ppm, with occasional spikes that soar beyond 4500 ppm, as evident in room GMP_RDC_N_C. These substantial fluctuations in CO_2 levels can be attributed

to increased occupancy and reduced ventilation rate. As classrooms tend to be densely populated and are less likely to have windows open for fresh air exchange during cold weather, CO_2 buildup is more pronounced in these spaces than in other room types. Consequently, it highlights the need for adequate ventilation and air quality management strategies to ensure occupants a healthier and more comfortable indoor environment, especially during winter when these conditions tend to be more pronounced.

III.2.2.2 Relative humidity

The data presented in Figure 3-2 provides valuable insights into the indoor humidity levels across various rooms and seasons within the IUT de Nîmes buildings. Notably, the humidity levels show consistent patterns, falling between 40% and 50% during the summer months and 30% to 40% in winter.



(A) BC building

(B) GC building

(C) GEII building

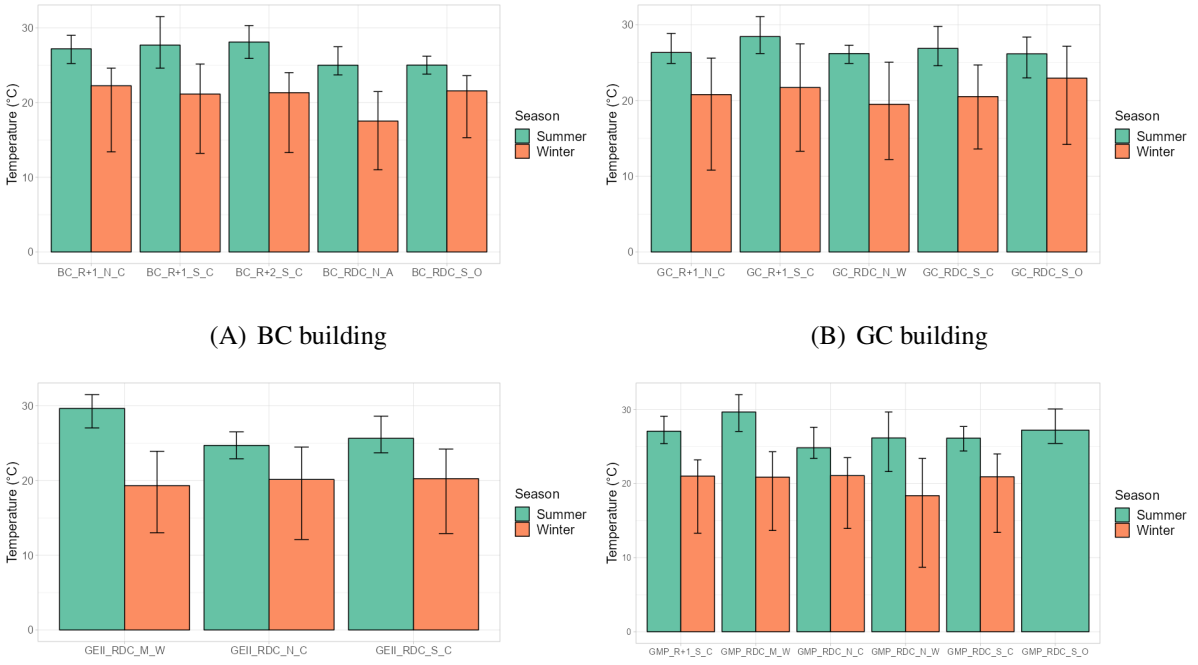
(D) GMP building

Fig. 3-2. *Grand average of each room's indoor relative humidity in summer and winter during occupied periods. The whiskers represent the minimum and maximum average values of each room: (A) BC building; (B) GC building; (C) GEII building; and (D) GMP building*

These results align with ASHRAE's recommended humidity levels, which suggests that indoor environments should ideally maintain humidity within the range of 30% to 60%, both summer and winter.

III.2.2.3 Temperature

The IUT de Nîmes buildings are naturally ventilated, allowing room climate regulation during the summer months by the manual operation of windows. The duration of sunlight exposure in the southern rooms is between 6h30 and 18h00. Conversely, the northern rooms are from 5h00 to 8h00 and 16h00 to 19h00. To mitigate the effects of glare and solar heat, the building's south side exterior is equipped with metallic shutters. Unfortunately, many of these shutters are damaged, leaving some either opened or closed wholly or partially.



(A) BC building

(B) GC building

(C) GEII building

(D) GMP building

Fig. 3-3. *Grand average of each room's indoor temperature in summer and winter during occupied periods. The whiskers represent the minimum and maximum average values of each room: (A) BC building; (B) GC building; (C) GEII building; and (D) GMP building*

During the investigated period, the average outdoor temperature was 22.9 ± 4.6°C in summer and 8.2 ± 4.3°C in winter. Figure 3-3 depicts the average indoor temperature of the selected rooms during the occupied period of summer (1st to 21st September 2020) and the whole winter (21st December 2020 to 21st March 2020). From the length of whiskers, which represents the minimum and maximum of each value, it is implied that the temperature variations in summer are notably more minor compared to those in winter.

In winter, indoor temperatures are primarily influenced by heat emitters' energy and are not significantly affected by outdoor temperatures. Consequently, the average indoor temperatures remain relatively uniform across all four buildings, approximately 21°C. Nonetheless,

there is a substantial temperature fluctuation during this time of the year. One of the contributing factors to more significant temperature fluctuations is using two different heating modes in a day. The "eco" mode is designed to reduce energy consumption by lowering the indoor temperature, particularly during nighttime and on weekends. Conversely, the "comfort" mode is activated during daytime hours. This mode aims to provide a more comfortable and warmer indoor environment when occupied. The transition between "eco" and "comfort" modes can result in noticeable temperature fluctuations as the heating system shifts to meet the desired temperature settings.

In summer, indoor temperatures in buildings are often closely linked to the prevailing outdoor weather conditions. It is common for buildings to exhibit a strong correlation between outdoor and indoor temperatures during this time. Although outdoor temperatures can vary significantly, the indoor climate experiences relatively minor fluctuations, which could be attributed to the implementation of passive cooling measures. These strategies include closing windows and shutters to preserve the coolness of the indoor air, preventing it from heating up too rapidly to deliver a comfortable and consistent indoor environment for occupants.

However, the summer average temperature of each room shows otherwise. They are approximately 27°C in all buildings. For instance, the temperature can also reach 30°C in GEII_RDC_M_W and GMP_RDC_M_W, which is remarkably high for summer comfort.

III.2.3 Building characteristic

A complex set of factors influences the thermal performance of buildings and determines the energy required for the mechanical control of indoor climate. This section attempts to visualize the effect of orientation and floor level on indoor climate, specifically on air temperature.

III.2.3.1 Orientation

Solar energy provides a thermal input to all buildings directly or indirectly. This input might be advantageous if it contributes usefully to the energy requirements for space and water heating, as in cold and temperate climates. On the other hand, this heat input can be disadvantageous, causing high internal temperature conditions that may necessitate energy use for air cooling. The amount of heat gained within a building from solar energy will depend on building design and construction aspects, such as location, orientation, and layout.

Figure 3-4 illustrates a statistic summary that includes a minimum, maximum, and mean of temperature, humidity, and CO_2 level in each room (classroom on the south, classroom on the north, and workshop in the middle). The data for this figure comes from a three-week occupied period of summer when the windows and shutters were open.

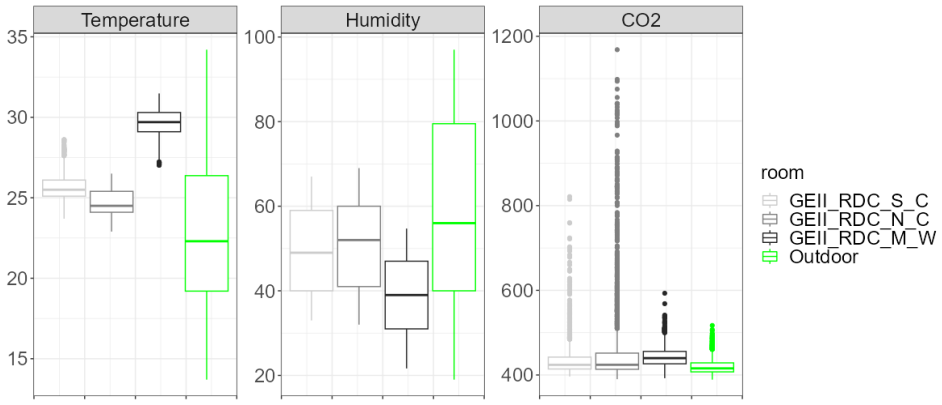


Fig. 3-4. *Comparison of the GEII building's indoor climate in summer during the occupied period from 1st to 21st September 2020 in three different orientations: south (S), north (N), and middle (M)*

In south-oriented rooms, solar radiation is received for approximately 12 hours daily. This solar gain contributes to heating the wall, resulting in heat storage within the wall and the indoor air when the shutters are open. Consequently, while rooms in the north start cooling down at the end of the day, those facing south continue to accumulate heat. However, for rooms facing north, the solar radiation is received in July between 5h00 and 7h30 and 16h30 to 19h00 but not at all in September. Consequently, the temperature between night and daytime is relatively consistent, resulting in a small boxplot size for showing the slightest temperature variation. As a result (Figure 3-4), the mean temperature in the south is 1°C higher than in the north, and the maximum temperature can be 3°C higher.

The workshop consistently maintains a high average temperature of 30°C, considerably warmer than other rooms. The technical section of the GEII building features skylight windows, and the steel sheeting roof accumulates and transmits additional heat, contrasting with a more insulated concrete terrace roof in classrooms. Despite lacking exposed walls, limited air circulation due to the absence of windows contributes to elevated temperatures. Though not externally exposed, the shared walls absorb warmth from neighboring rooms, gradually raising the overall air temperature.

III.2.3.2 Floor level

An analysis is carried out during the unoccupied summer period to evaluate the influence of floor levels on temperature. During this time, both windows and shutters are closed, effectively minimizing the potential impact of solar radiation. Figure 3-5 presents the boxplot of indoor climate in different floor levels: ground floor, first floor, and second floor. The average temperature of the respective floors is 27°C, 29°C, and 30°C.

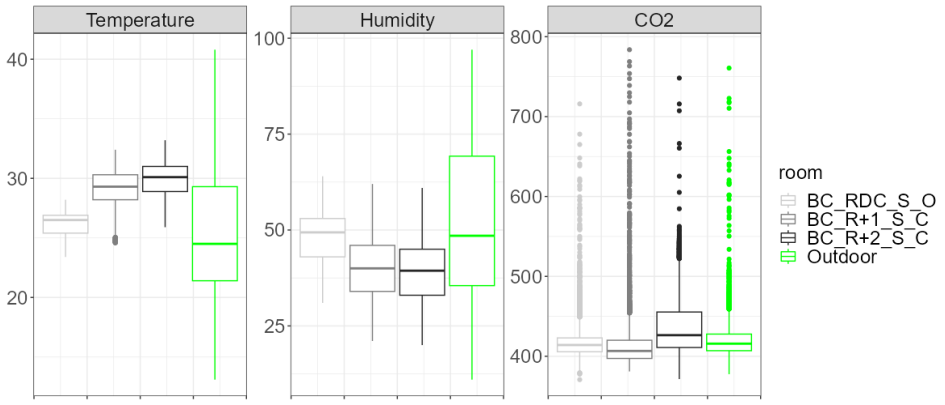


Fig. 3-5. *Comparison of the indoor climate in summer during the unoccupied period from* 1st *to* 30th *August 2020 in three different floor levels: ground floor (RDC), first floor (R+1), and second floor (R+2)*

Underneath the ground floor of each building, there is a darkened sanitary void that maintains a cool temperature throughout the day, contributing to the ground floor's overall coolness. Conversely, the first and second floors receive heat from the lower ceiling, influenced by the floated hot air and the reflected radiation. Moreover, the top floors also receive heat from the roof terrace, which stores and transmits part of the solar radiation received.

III.2.3.3 Building usage

Internal heat gains within a building encompass various sources of heat produced within the indoor environment, which significantly impact the temperature, comfort levels, and energy consumption. The free heat gain comes from solar radiation and indoor activities such as occupant's metabolism and equipment.

III.2.3.4 Presence of occupants

The occupants of a building contribute to generating heat due to their metabolic processes and physical activities. The level of heat production varies from person to person and can depend on factors such as body size, activity level, and clothing. In densely populated spaces like classrooms, the cumulative heat generated by occupants can be substantial. This human heat can affect indoor temperature and air quality, making adequate ventilation and temperature control crucial to maintaining comfort while optimizing energy use.

Figure 3-6 presents the evolution of temperature and CO_2 level of a GMP classroom in the north. In 2020, the heating system of the GMP building was defective and overheated the building to around 22°C, day and night, throughout the heating period. Thus, this figure allows

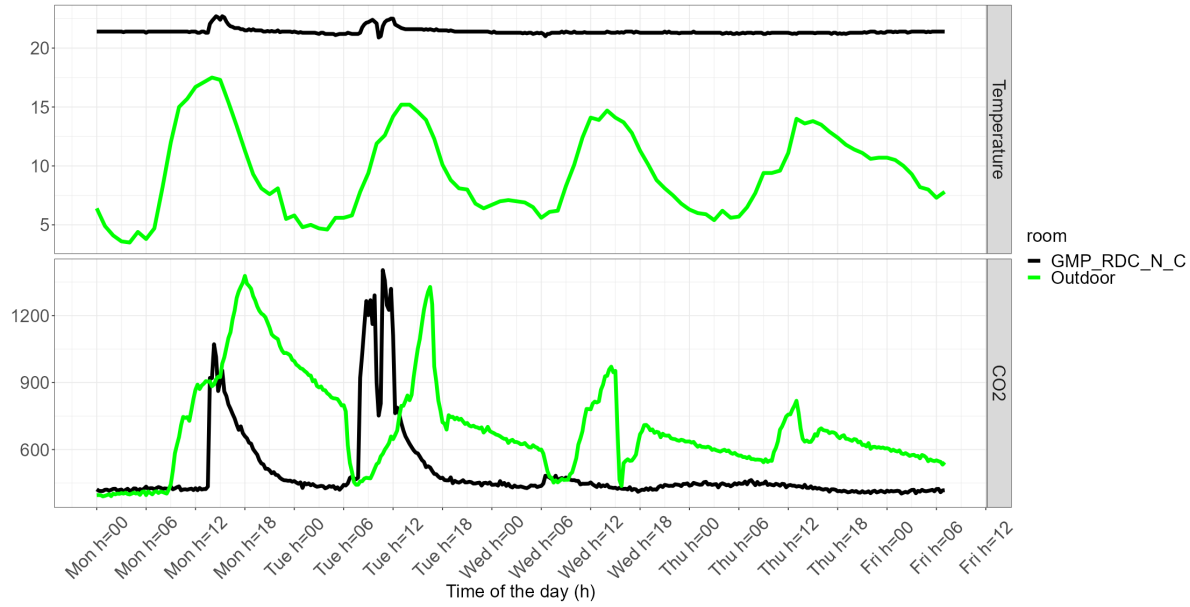


Fig. 3-6. *Evolution of CO_2 concentration and temperature in a GMP building's classroom during the heating period*

for evaluating a room's temperature gain due to the occupants' thermal contribution without the impact of external climatic conditions and heating.

The temperature evolution is closely correlated with that of CO_2. For instance, when the CO_2 concentration increased (Tuesday at 8h00) to approximately 1200 ppm, the temperature increased by 1°C. Similarly, the temperature reverts to its initial state when the CO_2 decreases to 750 ppm (Tuesday at 10h00), confirming occupants' impact on indoor heat gain.

III.2.3.5 Usage of machines/equipment

Another source of internal gains is the heat generated by mechanical machines (in workshops) and equipment such as desktops (in classrooms), office equipment, and other electrical devices. The heat produced by this equipment can accumulate and affect indoor temperature depending on its performance and ratio compared to the room volume.

Figure 3-7 depicts the evolution of temperature and CO_2 level of the workshop of GC, GEII, and GMP buildings. These workshops are high in space volume but low in occupancy rate, resulting in insignificant CO_2 levels. This figure shows that the GEII workshop has the highest temperature, averaging 29°C daily this week, due to its larger skylight window areas compared to the other buildings. Despite this, its temperature trend is similar to that of the GC building, with a minimum altitude between nighttime and daytime. The GMP workshop has the highest fluctuation temperature between 22.5°C and 26°C.

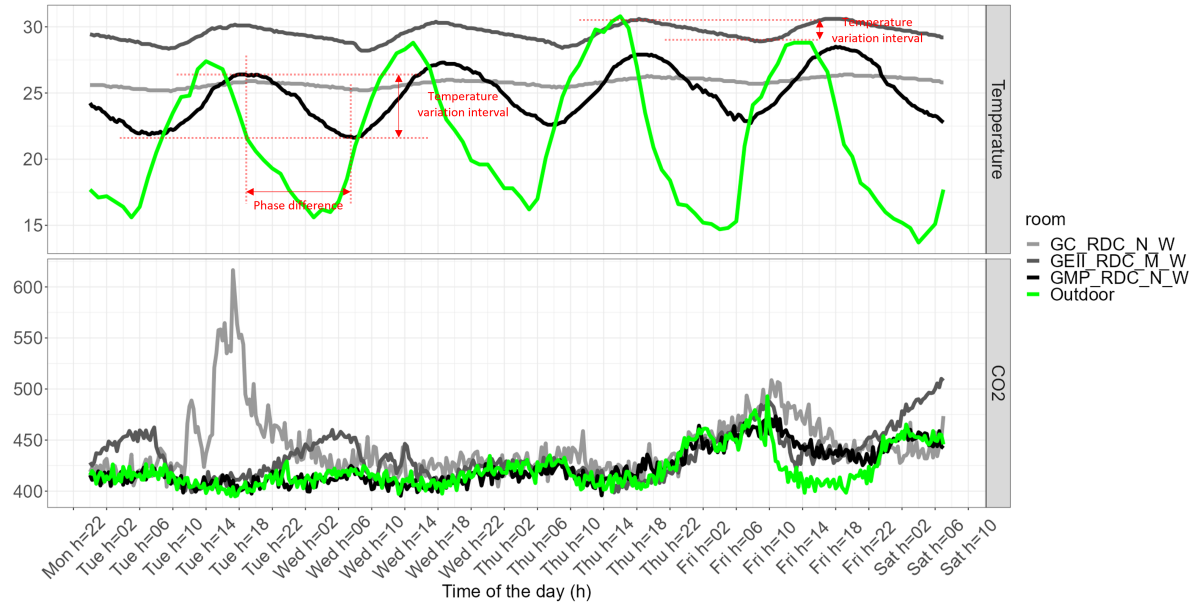


Fig. 3-7. *Evolution of CO_2 concentration and temperature in a workshop of GC, GEII, and GMP buildings during the non-heating period*

Each teaching building comprises a workshop section, but the machine types differ drastically from one department to another. To meet the department's objective of training operational technicians in the mechanics and production engineering field, the GMP workshops are fully equipped with heavy mechanical machines, as shown in Figure 3-8A. These machines are essential for various industrial processes such as manufacturing, fabrication, and assembly. They are known for their robustness and capability to perform heavy-duty tasks, but they also generate significant heat when in operation. The GC building, on the other hand, is a specialized facility within the field of civil engineering that serves a different purpose compared to the GMP building. In contrast to GMP workshops, which are more oriented towards high-volume manufacturing and the production of mechanical components, civil engineering workshops are centered around materials, processes, and equipment required for construction and infrastructure projects, as seen in Figure 3-8B.

Consequently, there is a notable temperature disparity within GMP's workshop, with daytime (during machine operation) and nighttime exhibiting distinct variations. It is even worse for students, as they must wear fully covered clothes with another layer of protective gown and closed shoes for safety precaution. The recommended indoor temperature for energy calculations in France for summer is between 22°C - 27°C [148]. If the standard temperature is used in the calculation instead of the real ones, these workshop halls will remain problematic even after the renovation.



(A) GMP building (B) GC building

Fig. 3-8. *Mechanical machines in the workshops of (A) the GMP building and (B) the GC building*

III.2.3.6 Usage of windows

Solar radiation is a prominent source of free heat gains, especially in regions with abundant sunlight. It occurs when the sun's rays enter the building through windows, skylights, or other transparent surfaces. This natural heat source can contribute to indoor warmth during colder months and help reduce the need for additional heating, thus enhancing energy efficiency. However, during the summer, excessive solar heat gain can lead to overheating, necessitating cooling strategies like shades or blinds to manage this source effectively.

The temperature change in south-facing classrooms from each building in three situations is depicted in Figure 3-9. When the windows and shutters are closed during the non-occupied period, it becomes apparent that the variations in temperature from one day to another are negligible. The amplitudes change significantly when the windows and shutters are open in BC_R+1_S_C and GC_R+1_S_C during occupied periods. Another scenario involves opening shutters while the windows remain closed, showing a minimal fluctuation in temperature.

Shutters are used to block direct sunlight, which keeps the indoor air temperature in a lower range than the outdoor temperature. However, before the renovation, these shutters were made of a metallic material, which allowed a strong restitution by radiation of the heat accumulated by prolonged exposure to intense solar radiation. Therefore, closing the shutters and windows is a common practice to minimize heat gain. On certain occasions, individuals may find themselves compelled to shut the windows due to the malfunctioning and immobility of the shutters.

Windows in school buildings are typically closed during the winter for several reasons,

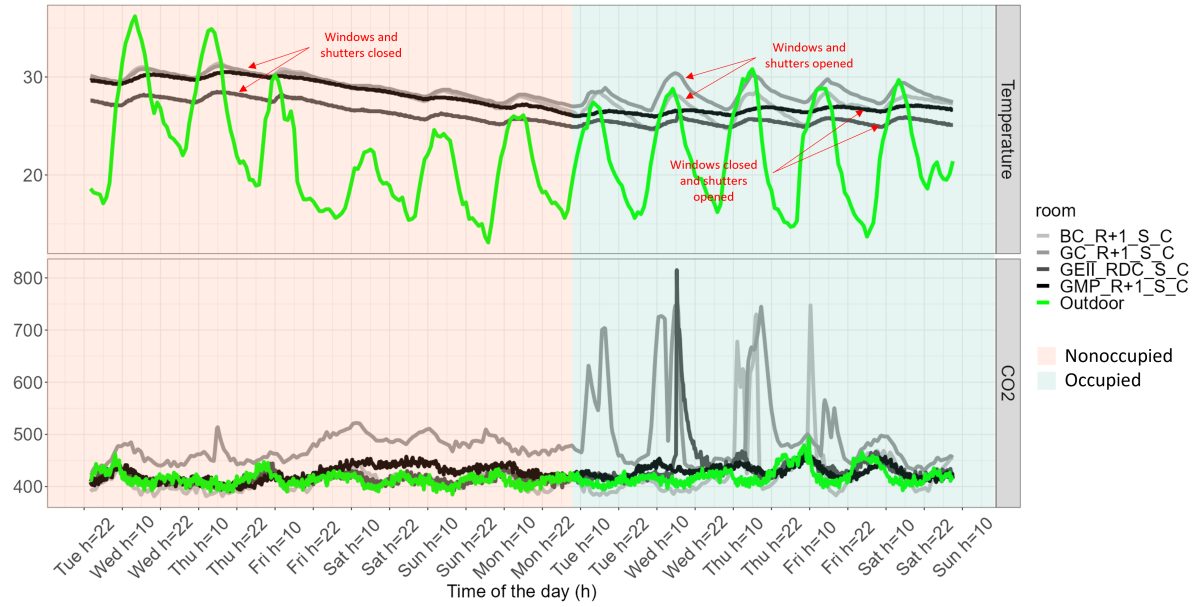


Fig. 3-9. *Evolution of CO_2 concentration and temperature of four classrooms on the south in summer during non-occupied and occupied periods*

one of which is temperature control. This practice regulates indoor temperatures by preventing cold air from entering the building, ensuring a comfortable and consistent indoor temperature for students and teachers. It also plays a critical role in energy conservation. Closed windows also help prevent drafts and air infiltration that could cause discomfort, distractions, and reduced productivity.

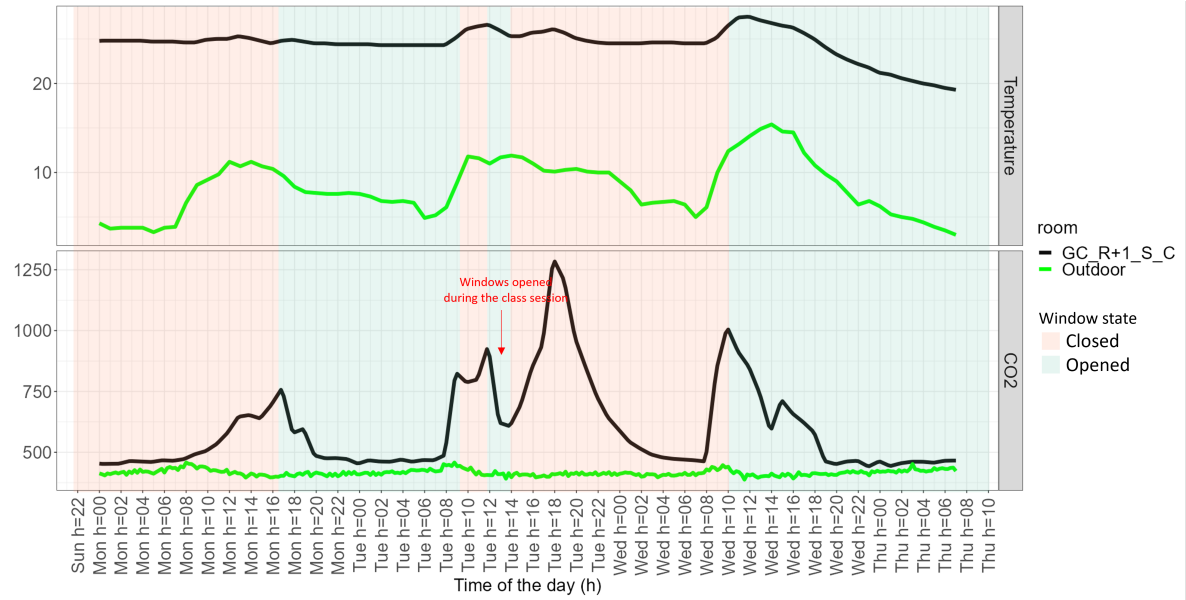


Fig. 3-10. *Evolution of CO_2 concentration and temperature in a classroom equipped with an opening/closing window sensor in winter during the COVID-19 era*

Figure 3-10 presents the indoor climate evolution during a typical winter week in 2020 in a first-floor classroom of the GC building. According to the building usage recommendation, all windows should be closed during winter. Consequently, maintaining an adequate indoor air temperature while managing CO_2 levels is the primary challenge. Although keeping windows closed effectively conserves heat, the CO_2 concentration exceeds the recommended range.

However, from March 2020 to late 2021, public buildings followed COVID-19 measures to limit the spread of the virus. One of the safety recommendations is to improve ventilation by opening windows regularly, especially during teaching sessions. Hence, the evolution of temperature, humidity, and CO_2 rate during winter 2020 may be affected by this recommendation.

As a result of the COVID-19 pandemic, empirical evidence suggests that opening windows during classes is a viable method to maintain CO_2 levels below 1000 ppm. An alternative approach involves a short break between sessions of 2 hours or more. It is advisable to open windows during the break period and subsequently close them at the resumption of the course. Nevertheless, integrating mechanical ventilation systems is crucial to providing a consistently comfortable and safe environment.

III.2.4 Conclusion

Achieving a comfortable and healthy indoor environment in school buildings is challenging due to their high occupancy rate and the study schedule. Moreover, school buildings under Mediterranean weather face a more severe problem in summer due to the excessively high outdoor temperature. Analyzing existing buildings helps better understand the challenges ahead in renovation projects or future new builds.

This section analyses the factors that affect the evolution of room temperature, both building characteristics and building usage factors. A summary of the research results in this study is as follows:

- In summer, the ground floor has the lowest temperature while the top floor (first floor for GC, GEII, and GMP buildings, second floor for BC building) has the highest temperature. However, ground floor rooms (workshops) in the middle of the building tend to have the highest temperature when equipped with heavy mechanical machines. At any floor level, rooms' temperatures on the south are higher as they are exposed to insulation for a long duration. However, the temperature is also more stable than in the north if the shutters are closed.

- In winter, the heat emitter energy is the main factor that defines the pattern of indoor temperature evolution. The secondary heat source comes from mechanical machines for workshops. Two similar rooms, with heating running and windows closed, may have different indoor temperatures due to the number of users and the room's orientation.

- Examining the window's state over both seasons reveals that the occupant behavior significantly impacts the indoor climate evolution by closing or opening the windows. Opening windows can result in a noticeable CO_2 level reduction, but it causes a rapid loss of the indoor cool air in summer and heat loss in winter.

Generally, the comfort level in non-renovated buildings is higher in winter than in summer. It is important to note that school buildings are typically vacant during the summer, from late June to early September. In most cases, classrooms and offices within each building can easily maintain a comfortable temperature and ensure healthy CO_2 levels by enhancing the building's envelope and implementing efficient ventilation systems. However, more attention should be paid to the workshops that have an unacceptable temperature range throughout the non-heating period.

III.3 Part B: Investigating influential factors on indoor temperature through a predictive model

This section led to the writing of a conference article titled "Multiple Linear Regression Model to Predict Indoor Temperature in School Buildings," published in the Academic Journal of Civil Engineering, 41(1), available at https://doi.org/10.26168/ajce.41.1.22. The findings were presented at the French Civil Engineering Congress: City of the Future and Climate Change CFGC 2023 in Paris-Saclay.

III.3.1 Introduction

The building sector accounts for approximately 40% of carbon dioxide (CO_2) emissions in developed countries, 37% of energy use, and 40% of trash production [178]. Hence, the building sector significantly affects climate change and the present trade deficit brought on by energy imports [179]. To save heating and cooling energy, implementing appropriate operational and control strategies that require forecasting for continuous monitoring is essential [180]. Forecasting demand and energy usage heavily depend on the air temperature, a critical characteristic linked closely to indoor thermal comfort, and strongly affects building energy consumption [180, 181]. The indoor temperature prediction model is utilized as the feedback input of the optimal energy-saving management of the heat exchanger station to achieve the balance between heat demand and production in the heating system, which allows for economic optimum while fully fulfilling residents' heat comfort [182, 183]. Smart sensors and predictive control systems can be combined with the prediction algorithm to prepare them for eventualities in the future [184].

Various techniques have been created over time to anticipate indoor temperature estimation. There are three basic categories that they fall under: physical (white-box models), data-driven (black-box models), and grey-box (hybrid models). The white-box models are based on integral-differential energy and mass balance equations, which necessitate extensive knowledge of a building's features, lighting gains, equipment loads, and actual occupant density [185]. This method has a high computational cost and requires a detailed understanding of the building's overall structure, components, and energy systems [186, 187]. Using data-driven methodologies, grey-box modeling seeks to close the gap between actual buildings and white-box simulations [188]. Black-box models can use different methods such as ANN (Artificial Neural Network), SVM (Support Vector Machine), and MLR (Multiple Linear Regression) to model massive data with high predictive accuracy and performance differing in computation time [189, 190].

This research is carried out on existing educational buildings with the availability of sufficient historical data, so the black-box model is adopted. Moretti et al.[191] used MLR to predict temperature trends in historic buildings and found that eight input variables yield R^2_{adj} coefficient of determination of 0.92. Input data included outdoor air temperature, solar radiation, heating system, and season type. Özbalta et al.[192] used day of the year, outdoor temperature, outdoor relative humidity, and wind speed in regression models and found that the best model achieved an R^2 of 0.87 and 0.81 in training and testing, respectively. Pérez-Lombard et al.[193] compared multiple linear regression and random tree models using outdoor temperature, relative humidity, wind speed, visibility, pressure, dew point temperature, and total electrical energy consumption. The results show that the R^2 of the regression model varies between 0.83 and 0.95 in training over different study areas.

Outdoor climate is commonly used as input data. However, only some studies consider building characteristics (surface area and orientation) in model development. This article aims to investigate the accuracy rate of the indoor temperature prediction model using the multiple linear regression technique incorporating outdoor climate, building characteristics, and time index.

III.3.2 Methodology

The prediction model is based on the Multiple Linear Regression (MLR), which is the analysis of conditional distribution $Y|x$ of the response variable Y given by the vector of predictors $x = (x_1, ..., x_p)^T$. The model of MLR can be described as [194]:

$$Y = x_1\beta_1 + x_2\beta_2 + ... + x_p\beta_p + e_i \tag{III.1}$$

for $i = 1, .., n$. Here n is the sample size and the random variable e_i is the ith error.

This section uses a set of data from the case study that includes qualitative and quantitative variables to build the model using a "Training set" of k random samples from the n cases for p predictors to build a model where $10p \leqslant n/2 \leqslant k \leqslant 0.9n$. Then uses the "Testing set" for the other $n-k$ cases to confirm that the model built with the *training set* is good. This technique may help to reduce biases but needs $n \geqslant 20p$ [195]. A final model is valid for inference if it has been demonstrated helpful on other data obtained after the model was developed. On the other hand, a trained model that displays reasonable predictions on both the training and testing set can be utilized for description and explanatory purposes [195]. There were 25290 cases collected in the case study. Consequently, 70% of the data collected will be used as a *training set* and 30% as a randomly selected testing set over three months (June 21st to September 21st 2020). A *validating set* is implemented from May 1st to May 31st, 2020, and collected over a different period to verify the model. Figure 3-11 summarizes the flow work of model development.

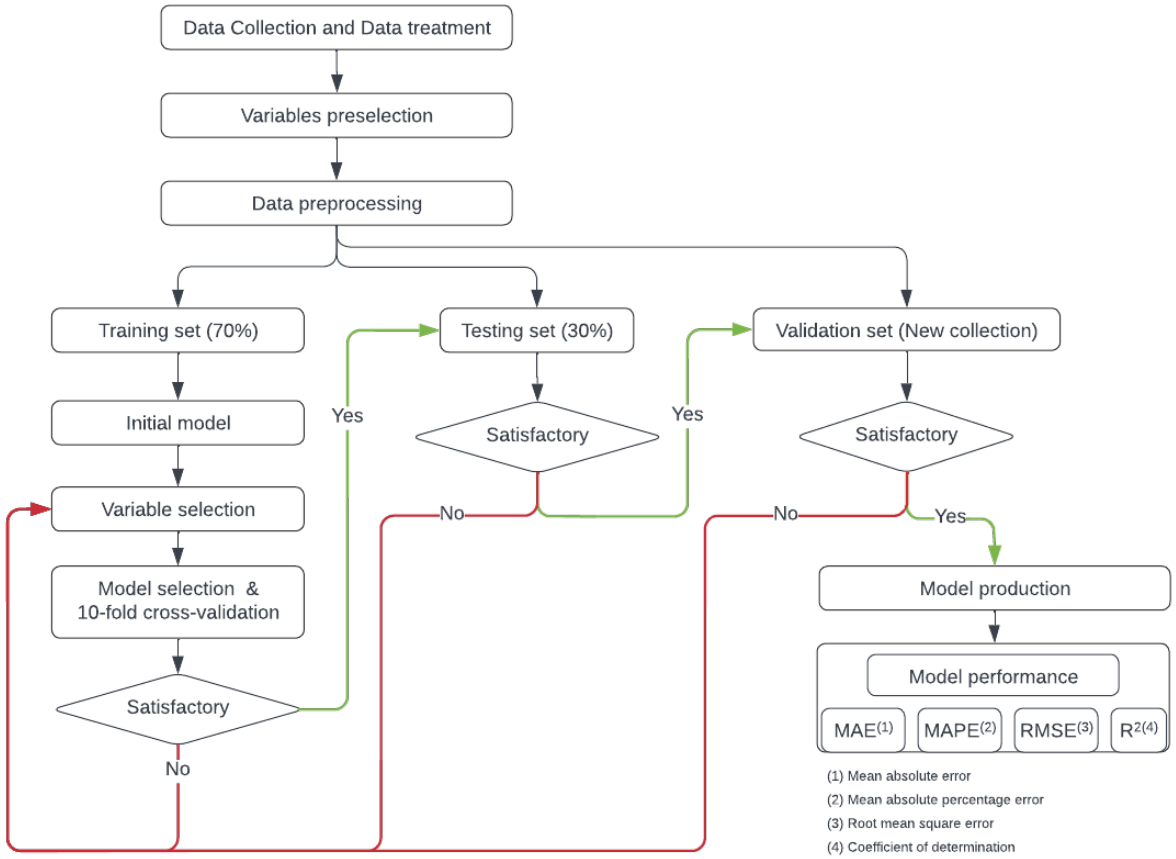


Fig. 3-11. *Flowchart of MLR Model Development*

III.3.2.1 Model evaluation

The conventional metrics are incorporated as primary indicators of model performance evaluation [196]:

- R^2 (coefficient of determination): the coefficient of how well the values fit compared to the original values. The value from 0 to 1 is interpreted as a percentage.

$$R^2 = \frac{\sum(\hat{y}_i - \bar{y}_i)^2}{\sum(y_i - \bar{y}_i)^2} \tag{III.2}$$

- *MAE* (mean absolute error): the average of the absolute difference between the actual and predicted values in the dataset. It measures the average of the residuals in the dataset.

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|y_i - \hat{y}_i| \tag{III.3}$$

- *MSE* (mean square error): the average squared difference between the original and predicted values in the data set. It measures the variance of the residuals.

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2 \tag{III.4}$$

- *RMSE* (root mean square error): the square root of Mean Squared error. It measures the standard deviation of residuals.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \tag{III.5}$$

- *MAPE* (mean absolute percentage error): Percentage errors are calculated in terms of absolute errors, without regard to sign.

$$MAPE = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \tag{III.6}$$

where $\hat{y}$ and $\bar{y}$ are respectively predicted and mean value of y measured value at the ith moment, and N represents the number of predictions.

III.3.2.2 Building environment analysis

This study examined three teaching buildings (GMP, GC, and GEII) and one administrative building (BC) on the campus from the summer of June 21 to September 21, 2020. Figure 3-12 shows comparisons of indoor temperature (T_{in}) of 31 rooms selected. Panel (A) indicates that the indoor temperature data is normally distributed. Panel (D) shows that although the average T_{in} is approximately around 28°C, the confidence interval of the big surface varied between 27°C and 32°C wider than the others. Panel (G) summarizes the combined effects of floor, orientation, and type parameters on the indoor temperature. In a nutshell, workshops have the highest temperature in most cases.

Therefore, one workshop in each teaching building is used to build the model to predict hourly indoor temperatures. Table 3-2 is a summary of statistics of environmental parameters for the three workshops. As a result, the average indoor temperature was 30°C while the outdoor temperature was 25°C.

III.3.3 Result and discussion

27 predictors X in total are pre-selected for data processing to calculate the response variable Y. They are as follows:

- x_1: *day* - Day index (weekday, weekend and vacation)
- x_2: *time* - Time index (daytime, nighttime)
- x_3: *ori* - Orientation (North and South)
- x_4: *area* - Surface area (Big, Small)
- x_5: Outdoor relative humidity - HR_{ext} (%)
- x_6: Indoor relative humidity - HR_{in} (%)

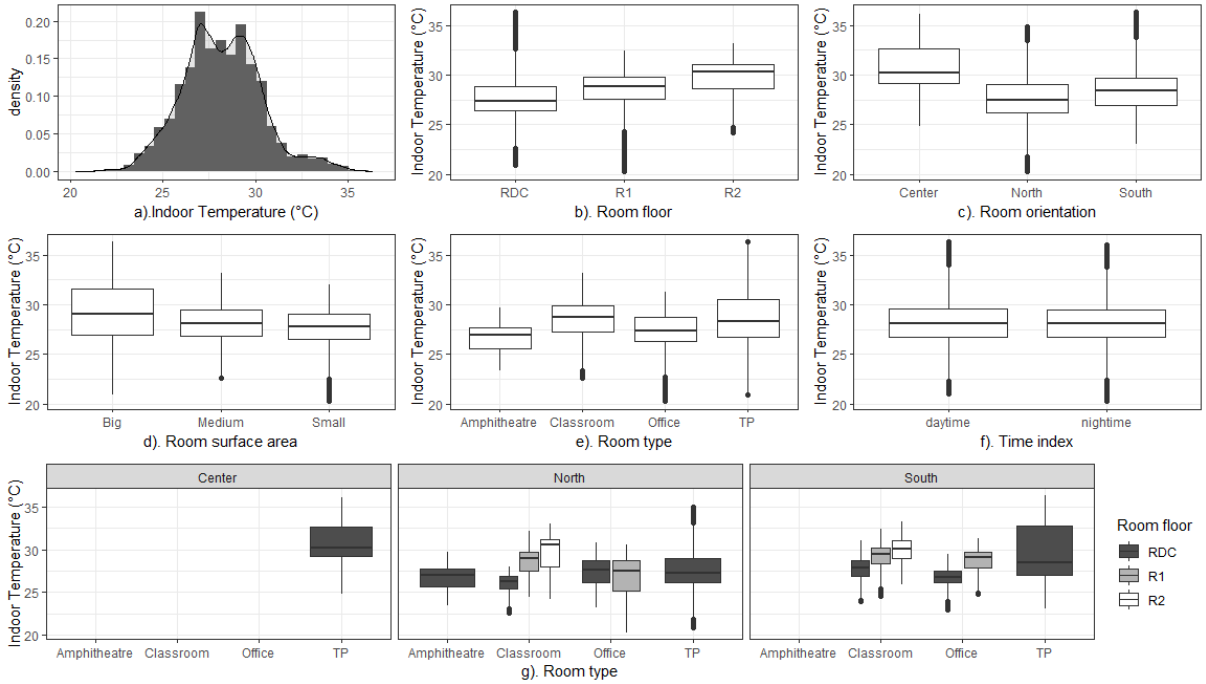


Fig. 3-12. *Analysis of indoor temperatures: (A) Distribution of data set; (B) Room floor; (C) Room orientation; (D) Room floor area; (E) Room type; (F) Time index; and (G) combined three factors of rooms on each floor by type and by orientation*

(B) Room floor: RDC - Ground floor; R1 - First floor; R2 - Second floor
(C) Room orientation: Center - Rooms without exposed wall to outdoor environment; North - Rooms face northeast; South - Rooms face southwest
(E) Room type: Amphitheater - lecture hall; TP - Workshops
(F) Time index: Daytime - 8h00 to 19h00; Nighttime - 19h00 to 8h00

Variables	min	median	mean	max	Q25[a]	Q75[b]	SD[c]	SE[d]
CO_2	376.6	420.2	423.7	593.1	409.0	434.9	20.9	0.26
HR_{ext}	11.0	49.0	52.8	97.0	35.0	69.0	30.0	0.26
HR_{in}	15.0	39.0	39.3	69.0	33	46	9.06	0.11
SR	0.0	0.3	0.60	2.0	0.0	1.1	0.7	0.00
T_{ext}	13.1	24.5	25.14	40.8	21.4	29.3	4.9	0.06
T_{in}	21.0	29.6	29.85	36.1	28.4	31.9	2.63	0.03

Table 3-2. *Statistical characteristics of environment data of three workshop halls from June 21 to September 21, 2020*

[a] confidence interval at 25%.
[b] confidence interval at 75%.
[c] Standard deviation.
[d] Standard errors.

- x_7: Outdoor air temperature - T_{ext} (°C)
- $x_8 \rightarrow x_{13}$: $T_{ext_2} \rightarrow T_{ext_7}$ - delayed of 2 to 7 hours of T_{ext} (°C)
- x_{14}: CO_2 (ppm)
- $x_{15} \rightarrow x_{20}$: $CO_{2_2} \rightarrow CO_{2_7}$ - delayed of 2 to 7 hours of CO_2 (ppm)

- x_{21}: Solar radiation - SR ($MJ.m^{-2}$)
- $x_{22} \rightarrow x_{27}$: $SR_2 \rightarrow SR_7$ - delayed of 2 to 7 hours of SR ($MJ.m^{-2}$)

The term "solar radiation" here refers to the calculated irradiation on a tilted surface derived from the global radiation on a horizontal surface as recorded by weather stations. The calculation is based on the Isotropic Sky Model and Perez Model [197] as detailed in Annex A.

Applying equation (III.1) to the current data set, the initial model can be written as:

$$Y = \beta_0 + \beta_1 x_1 + \cdots + \beta_{27} x_{27} \tag{III.7}$$

The analysis uses the "Caret" package in Rstudio version 4.0.3. (2020-10-10) to embed hyperparameter tuning and cross-validation. A 10-fold cross-validation is used on forward regression to specify the parameters used to control the model training process. A model with the lowest $RMSE$ of 0.079 and the highest R^2 of 0.79 is systematically suggested. This model includes 16 predictor variables and is called "$Model1$":

$$\begin{aligned} Y = {} & 0.29 + 0.63x_7 + 0.45x_{13} - 0.38x_6 + 0.33x_5 - 0.18x_3 - 0.09x_1 + 0.06x_{15} + 0.06x_2 \\ & - 0.06x_{27} - 0.06x_{20} + 0.05x_{14} - 0.05x_{12} - 0.05x_{17} + 0.04x_{22} - 0.02x_4 - 0.02x_{24} \end{aligned} \tag{III.8}$$

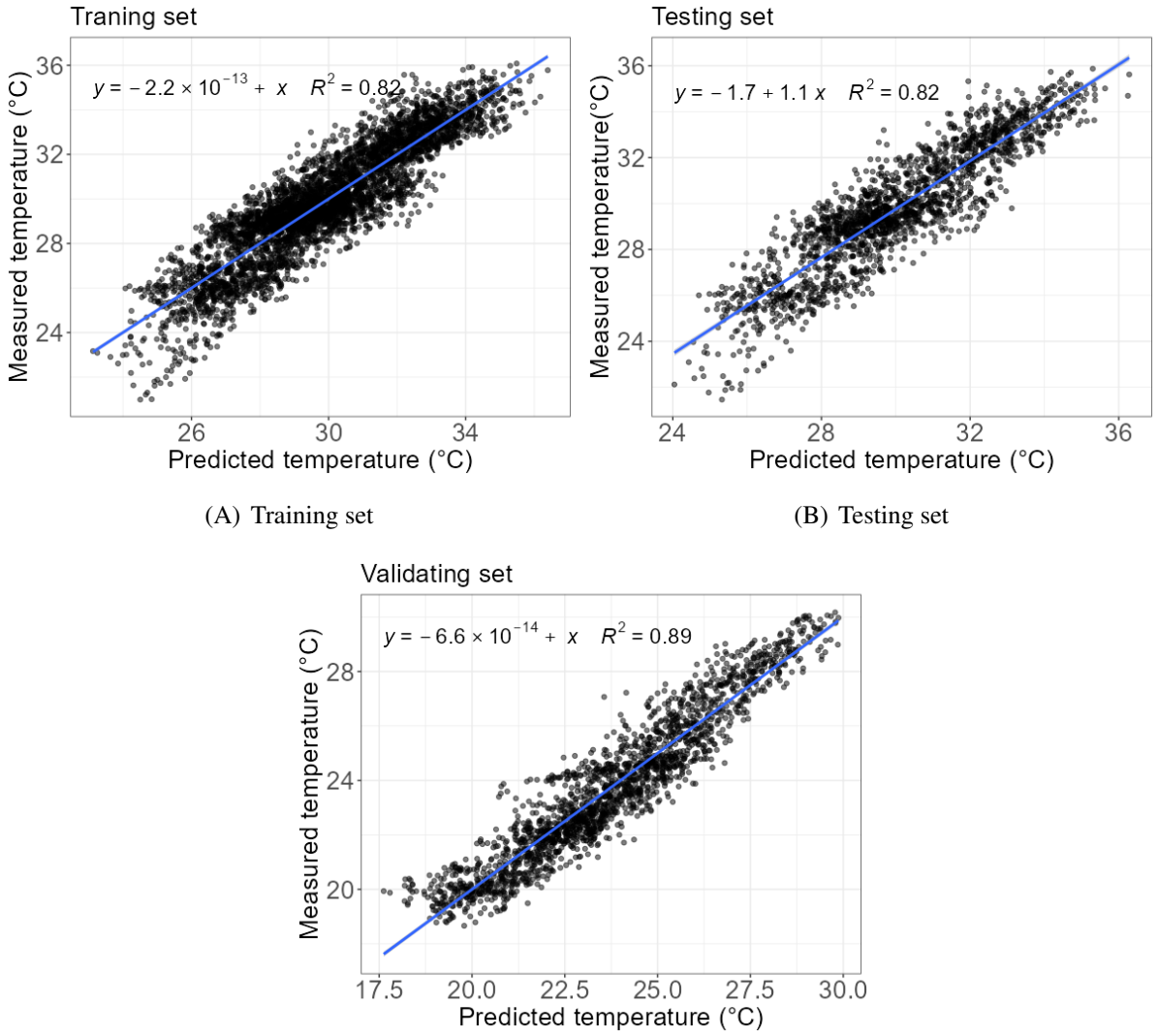
$Model1$ is applied to the *training set* and the linear regression presumptions are verified. The model is then applied to the *testing set* if the assumptions are not violated. If the R^2 value remains higher than 70%, the model will be implemented in the *validating set*. Figure 3-13 is a response plot of response Y (measured values) versus fitted values $\hat{Y}$ (predicted values). The closer the data points are to the blue line (regression line), the better the data fit. For plots a) and b), the distance between the points and the regression line grows as the temperature decreases. This demonstrates that when the temperature is lower than 24°C, $Model1$ does not reliably forecast T_{in}. The R^2 of $Model1$ is 82%, 82% and 89% for the *traning set*, *testing set*, and *validating set*, respectively.

A second model comprises nine predictors, referred to as "$Model2$". This model can be expressed by the equation below.

$$Y = 0.3 + 0.65x_7 + 0.47x_{13} - 0.4x_6 + 0.34x_5 - 0.19x_3 - 0.08x_1 - 0.08x_{12} - 0.07x_{27} + 0.05x_2 \tag{III.9}$$

The difference in performance between $Model1$ and $Model2$ is minimal, except for the validating set where the R^2 drops from 89% to 81%. Another model removes predictor variables whose coefficients in $Model1$ are less than 0.1, giving an estimate of indoor temperature from five variables, "$Model3$" is then expressed as:

$$Y = 0.29 + 0.61x_7 - 0.42x_6 + 0.4x_5 + 0.34x_{13} - 0.18x_3 \tag{III.10}$$



(A) Training set

(B) Testing set

(C) Validating set

Fig. 3-13. *The correlation between measured and predicted indoor temperature using Model*1 *on: (A) Training set; (B) Testing set; and (C) Validating set*

The ability to predict value has decreased for the *training set* and *testing set* since R^2 drops from 82% to 76%. On the contrary, the *validating set* has remained relatively stable at 80%. The model's accuracy rate remains acceptable, for it is higher than 70% while deducing predictor variables from 16 to 5. It is plausible that this model is relatively robust in prediction ability.

A comparison of coefficient variation between the three models is shown in Figure 3-14. The bigger the distance from the dashed line, the more influence the predictor has on the model. In this study, the CO_2 level is used to evaluate the indoor air quality as it could reflect the occupancy rate and/or the possibility of a defective ventilation system. When comparing the weights of each factor, it is evident that T_{ext} has the most influential factor in the models,

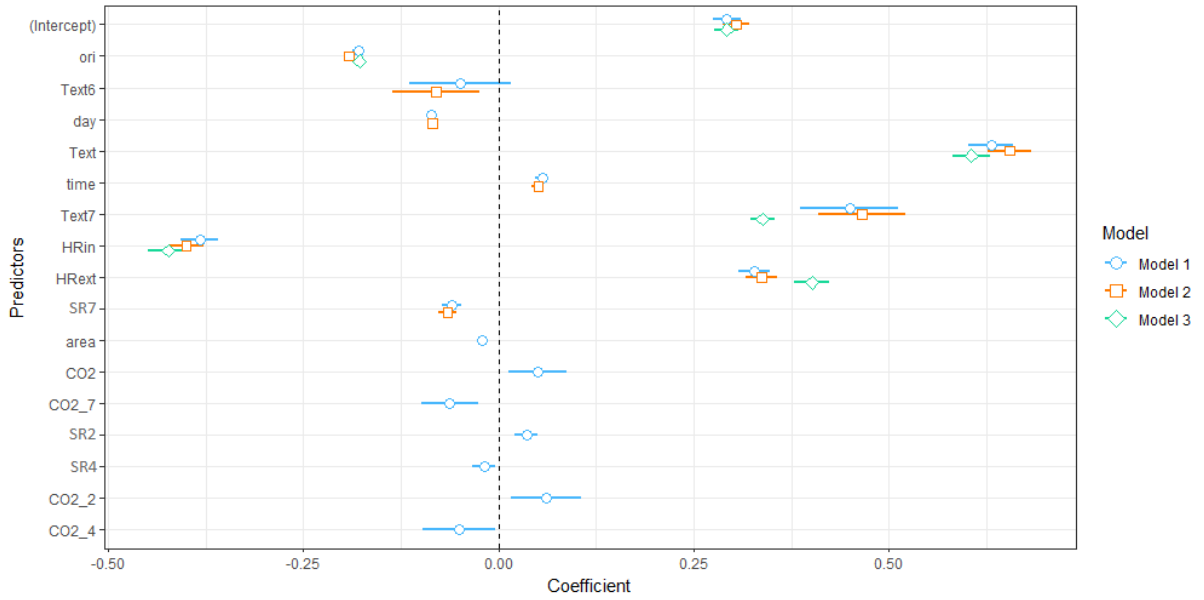


Fig. 3-14. *Comparison between coefficients of predictor variables between Model*1 *equation(III.8), Model*2 *equation(III.9) and Model*3 *equation (III.10). The dashed line defines the negative and positive correlation of the variables when they are on the left and right, respectively. The further the data point from the dashed line, the more influential the variable in the model*

whereas CO_2 and SR have the most negligible impact. This implies that the coefficient of the occupancy rate in the workshops is smaller compared to that of the size.

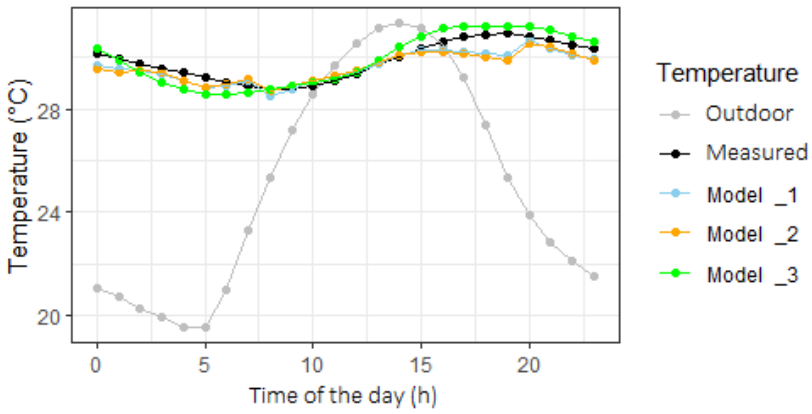
Additionally, the combination of all coefficients of time-delayed T_{ext} ($x_8 \rightarrow x_{13}$) with the coefficient of T_{ext} expresses the thermal inertia of the building, which is about three hours set back. This indicates that the effect on indoor temperature reaches its peak approximately three hours after an increase or a decrease in outdoor temperature. Figure 3-15A supports this explication in which the minimum of T_{ext} is at 5h00 and the minimum of T_{in} is around 8h00. Table 3-3 indicates four error matrices and coefficients of determination to evaluate the

Model	MAE (°C)	MSE (°C)	MAPE (%)	RMSE (°C)	R^2 (%)
*Model*1 (III.8)	0.89	1.26	0.03	1.12	0.81
*Model*2 (III.9)	0.90	1.30	0.03	1.14	0.81
*Model*3 (III.10)	1.04	1.65	0.03	1.28	0.76

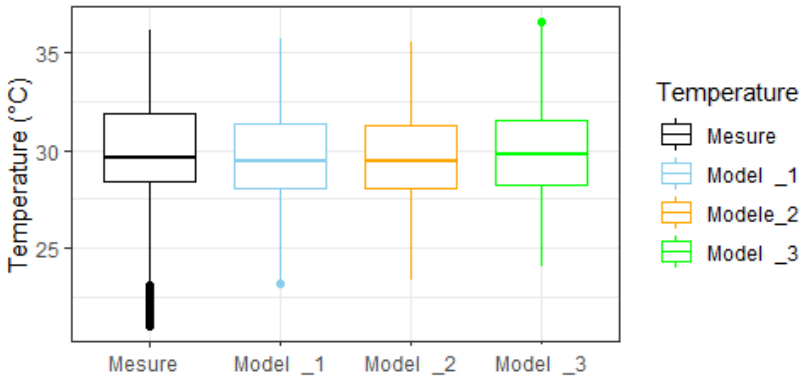
Table 3-3. *Statistical errors and coefficients of determination of the proposed models*

three models across the whole training and testing data collecting period. As expected, the results obtained from the 5-input model are slightly worse than the others, where coefficients of variables lower than 0.1 are also included. Still, the results acquired are satisfactory. Aside from the lowest R^2, the error percentage rate calculated by *MAPE* is essentially the same as the

others. The significant advantages of having a small number of parameters in the model are that the results can be interpreted more efficiently, and the correlation of parameters is less complex, making the inferences trustworthy.



(A) Evolution plot



(B) Boxplot

Fig. 3-15. *Comparison of measured values with the predicted values of the three models in: (A) Evolution of mean temperature grouped by time of day and (B) Box plot*

Figure 3-15 compares measured temperatures with the predicted values of the three models. Panel (A) shows a slight difference (less than 0.5°C) between the three models' mean measured and predicted temperature values. Nevertheless, the minimum values of the measured data are more than 2°C lower than those of the proposed models. Each data point in panel (B) represents the average hourly value for three months. It is clear that *Model*1 and *Model*2 show identical progression trends, primarily steep but close to the actual values. In contrast, the trend in *Model*3 is smooth compared with the measured data, although the minimum and maximum values are respectively underestimated and overestimated. This figure also shows the typical deviations between the measurements of each model at each hour of the day. The maximum average inaccuracy of *Model*3, which is less than 1°C, occurs at 05h00.

III.3.4 Conclusion

This paper aims to propose and explore the robustness of a multiple linear regression model that aims to forecast the hourly indoor temperature in educational facilities. Model training relies on 27 predictor variables such as day index, time index, room orientation, room surface area, outdoor humidity, indoor humidity, outdoor temperature, CO_2, solar radiation, and their time lag from 2 to 7 hours.

Three models were designed and compared using just rooms with the most similar conditions, three workshops. $Model1$ and $Model2$ perform better overall than $Model3$ with R^2 values of 82% compared to 76%. The final model, however, is suggested to be $Model3$ since its performance is satisfactory and the accuracy rate is acceptable. In addition, this model, which contains only five predictors, is desired for a simple structure, correct interpretation, and straightforward correlation of parameters.

Compared with previous studies such as Moretti et al. (R^2_{adj} = 0.92), Özbalta et al. (R^2 = 0.87) Pérez-Lombard et al. (R^2 = 0.83), the proposed model is the weakest. However, this study revealed that room orientation correlates strongly with temperature variation and that solar radiation is less important than other predictors. The most influential variables were outdoor temperature, indoor and outdoor humidity, outdoor temperature shifted by 7 hours, and room orientation.

Another area for improvement is the possibility of using this model in other rooms with varying conditions. The distinct nature of each room makes it difficult to develop a model for actual school buildings. In this case study, each building section differed in height, number of floors, size, equipment, and building use. Consequently, other rooms could have significantly lower prediction accuracy rates using the model proposed in this article. Other room types (classrooms and offices) have larger windows than workshop ones, which increases solar radiation. The classroom's occupancy rate is also higher than in workshops, so if windows remain closed, the CO_2 level can become a predictor of the indoor temperature model (due to the occupants' metabolic intake).

III.4 Part C: Impact of energy-efficient renovation on indoor climate during heating periods

This section has resulted in the writing of an article titled "Does Energy-Efficient Renovation Positively Impact Thermal Comfort and Air Quality in University Buildings?" published in the Building Engineering Journal, accessible via https://doi.org/10.1016/j.jobe.2023.107507.

III.4.1 Introduction

European policy currently aims to improve energy efficiency by 27% by 2030, which can be achieved by using energy-efficient materials when constructing new buildings and improving existing buildings [13, 198]. Renovation strategy could decrease EU energy use by 5-6%, but unfortunately, only 1% of the building stock is renovated annually [22, 199]. For educational facilities, such as the University Institute of Technology (IUT) buildings, ensuring energy efficiency is essential for cost savings and the well-being and performance of students and other occupants. Over the past two decades, extensive research has shown a correlation between Indoor Environmental Quality (IEQ) and occupants' performance, health, and attitudes [108, 200–205].

The IEQ factors are broad, but most literature focuses on four factors that can be measured and controlled actively: indoor air quality and ventilation, thermal comfort, visual comfort, and acoustic comfort [203]. Previous studies have individually examined the impact of these factors on human perception and performance, emphasizing the importance of maintaining optimal conditions in educational settings. For instance, a study by Clements-Croome [206] found that bad indoor air quality in school buildings, as assessed by short-term computer-based tests, is associated with poor student performance, mainly due to inadequate ventilation rates and high occupancy densities (1.8–2.4 $m^2/person$). Haverinen-Shaughnessy showed that the ventilation rate also plays an essential role in student academic performance [207] and reducing sick absences [9, 208]. Additional research [208–212] also supports the previous findings emphasizing the importance of indoor air quality and ventilation factors. Other aspects were also extensively investigated: thermal comfort [213–220], visual comfort [221–225], and acoustic comfort [226–228], which demonstrate that each of them could have a significant impact on the overall comfort conditions. According to ASHRAE [229] and a previous review paper [204], among other components, thermal comfort and indoor air quality are the most significant in defining comfort. Nonetheless, more effort was put into investigating the combined effects of IEQ indicators [230–234] and suggested that the interaction effect could evaluate overall human comfort better than the individual indicator.

The IUT of Nîmes has been significantly renovated to enhance energy efficiency, mainly targeting heating and ventilation energy. It is worth noting that visual and acoustic comfort has not been a subject of concern or complaints from the users at the institution. Consequently, the aspects of visual and acoustic comfort have been excluded from the scope of this investigation, while the primary focus remains on evaluating thermal comfort and indoor air quality. By outlining the key priorities, the study seeks to provide valuable insights into the influence of energy-efficient measures on the indoor environment's thermal conditions and air quality. These two factors primarily depend on the outdoor meteorological condition [235], air exchange rate [236], and occupancy patterns [237, 238] for the same building envelope.

When the energy efficiency of school buildings is discussed, it is often relatively complex to maintain excellent indoor climate conditions and cost-effectiveness, as indoor climate conditions and energy efficiency are conflicting objectives. Therefore, it causes difficulties when designing new and renovated buildings [239].

Recent cross-sectional investigations in classrooms at Danish and foreign schools have shown that CO_2 concentrations frequently exceed the maximum of 1000 ppm, which is the maximum limit of the thresholds authorized by existing guidelines and building regulations in terms of classroom air quality [148, 240]. It has been reported to occur particularly often in classrooms where ventilation relies on the manual opening of windows, specifically during the heating season in regions with a temperate climate [211, 241–244]. Zhang and Bluyssen [245] conducted an observational study of existing schools to determine potential correlations between energy consumption and building characteristics. During the investigation, they brought to light that when the buildings consumed 71.9 $MJ.m^{-2}$ of electricity and 358.8 $MJ.m^{-2}$ of gas, the average indoor climate of classrooms is as follows: 23°C of indoor temperature, 41% of humidity relative, and 1260 ppm of CO_2. Almedia and Freitas [246] compared two non-retrofitted and seven retrofitted schools. Throughout the winter, the average temperature was 14.9°C and CO_2 of 1905 ppm in non-retrofitted buildings, while those of certain retrofitted buildings were 20°C and 1052 ppm. They inferred that non-retrofitted schools need to improve their indoor environmental conditions, and in renovated buildings, mechanical ventilation systems are not efficiently utilized, with significant consequences on indoor air quality. Zinzi et al. [247] did a case study on a school building in Italy. The deep renovation includes an insulated building envelope, installed mechanical ventilation, energy-efficient windows, and new sun shades. The results show that the IEQ indicators of the classroom can increase to 20°C from 18.5°C at 8h00 in the early morning and remain below 1600 ppm with mechanical ventilation. However, it exceeds the recommended values far lower than those without mechanical ventilation.

A recent study by Mocová and Mohelníková [248] examined the renovated schools from the 1970s, including upgrading building fabrics, installing regulated heating systems, and renovating the water supply. The energy consumption reduced from 271 GJ/year to 105.8 GJ/year.

However, an unexpected increase in CO_2 levels within the renovated classroom was observed. Zaeh et al. [249] have investigated seven school buildings in pre- and post-renovation states. The retrofitting strategy includes replacing windows and renewing the HVAC system. The study has revealed that, prior to renovation, a noteworthy proportion of indoor CO_2 measurements (more than 30%) and indoor temperatures (over 50%) exceeded the recommended guidelines. After the refurbishment, it was observed that 10% of CO_2 levels and 28% of temperatures deviated from the recommended ranges.

Despite solid theological and calculation evidence supporting the need for renovation to meet the required IEQ values [148, 240, 246, 249], school renovation projects remain challenging due to multiple stakeholders and limited funding from local authorities. The existing literature on renovation's impact on IEQ needs to be improved, emphasizing the necessity for more case studies involving different school building types and climates. Moreover, previous research has predominantly focused on evaluating the renovation performance solely in classrooms, while higher education buildings accommodate various activities and functions, including offices, laboratories, workshops, and e-learning spaces [193]. Ensuring a healthy and comfortable environment in all the rooms within the building is of utmost importance.

To fill the gap in previous papers, the objectives of this section are to:
i) assess the renovation's impact on the thermal comfort and indoor air quality of the entire school building by incorporating classrooms, offices, and workshops in the analysis;
ii) investigate the relationship between energy-efficient refurbishment measures and the tackled IEQ components;
iii) analyze the level of user comfort during the heating period following the renovation.

III.4.2 Materials and methods

This section is based on physical measurements of 4 classrooms, 2 offices and 4 workshops from GC and GEII building during heating period from January to March 2021 (before renovation) and 2023 (after renovation). Student t-test statistics were adopted and performed through "anova_test" in RStudio to compare these measurements. The continuous measurements of indoor temperature (T_{in}), relative humidity (HR_{in}), and CO_2 concentrations are taken from Class'Air and Elsys sensors.

III.4.3 Results

III.4.3.1 Results of monitoring of indoor climate

Figure 3-16 presents the cumulative percentage distribution of the measured values of CO_2, HR_{in}, and T_{in} during the investigated period. In both buildings and states (before and after renovation), the CO_2 trends concave upwards nearly vertically at 500 ppm and then remain at the same level horizontally from 750 ppm to 1500 ppm or more. This signifies that approximately 75% of CO_2 data are lower than 500 ppm, another 20% is between 500 ppm and 750 ppm, and the rest of the data, less than 5%, are higher than 750 ppm. However, the level of HR_{in} differs remarkably in the GEII building after renovation. The data initially concave upwards simultaneously at 20% HR_{in} for all cases (both buildings and both states). However, while the others continue to increase to 50% gradually, the HR_{in} of the renovated GEII building increases more rapidly from 40% to 65%, surpassing that of the others. As the rise is rather loose (diagonally), the interpretation of that variation is that after renovation, the HR_{in} level of GEII appears to be higher than in another state casually from time to time. On the other hand, the temperature's

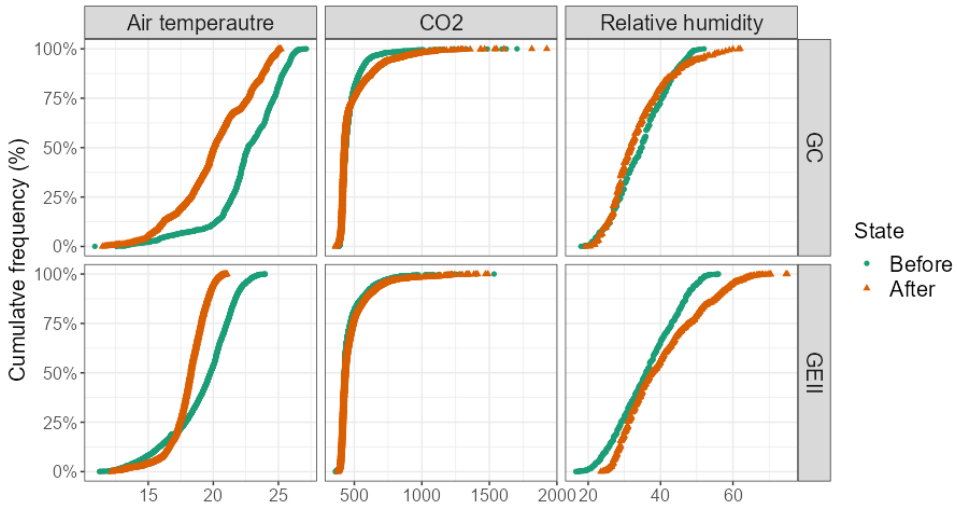


Fig. 3-16. *Overall cumulative frequency of the indoor climate in GC and GEII buildings from January to March 2021 (before renovation) and 2023 (after renovation)*

frequency evolves differently in all cases. In the post-renovated GEII building, the data quickly moves from 10°C horizontally to 16°C then proceeds to concave upward vertically between 16°C and 20°C. At the same time, the non-renovated GEII building concave up slower and further from 18°C to 24°C (for 75% of measures). Only 55% of temperatures in the renovated GEII building are above 18°C, compared to 75% before renovation. This demonstrates that the renovated building is colder than the non-renovated building, explaining the increase in the HR_{in} level as indicated previously. Indeed, indoor temperatures below 18°C correspond to un-

occupied periods such as nighttime, weekends, and holidays during which the heating system's temperature threshold has been reduced.

For the GC building, the temperature increase is more diagonal before and after renovation, especially in the renovated state, which shows that the temperature varies much more during the investigated periods. In addition, 25% of temperatures are below 18°C after renovation, compared with 8% before renovation. This shows that buildings were generally overheated in winter due to uncontrolled operation before renovation. Overall, the renovation led to a reduction in indoor temperature (without inducing thermal discomfort), which translates into heat demand savings.

A study in 2015 by Almeida [250] determined that the occupancy levels of educational institutions may significantly surpass those found in conventional office buildings, with up to four times more individuals occupying a given area per square meter. Therefore, a prominent focus of previous research has been the examination of classroom indoor climates as they are particularly susceptible to the impact of CO_2 levels. However, universities possess various functions and activities, including administrative units, lecture halls, classrooms, e-learning, laboratories, and workshops [193]. They are differentiated regarding spatial requirements, building equipment, and occupancy rate. The study of classrooms alone is insufficient to evaluate the overall efficacy of a building's renovation; all spaces must adhere to the appropriate health-related standards for each IEQ indicator.

Different room types (classroom, office, and workshop) are integrated into the analysis in order to undertake discrete evaluations and attain a greater comprehension of statistical accuracy. Figure 3-17 presents a boxplot of classrooms, offices, and workshops featured by indoor climate values during school hours from 8h00 to 18h00 over the weekdays. In France, according to regulations, EN 15251 [148], the acceptable indoor environment of school buildings for category II (Renovated buildings) and category III (Existing buildings) are the following, respectively, indoor temperature ranges for heating: 20°C – 24°C and 19°C to 25°C, CO_2 concentrations: 500 ppm and 800 ppm, relative humidity range: 25% to 60% and 20% to 70%. ASHRAE's journal just published a summary article by Stumm et al. [1], which takes a fresh look at the guideline of 1000 ppm of CO_2 as an upper limit in indoor environments. Based on that, the average values of CO_2 and HR_{in} in renovated and non-renovated buildings conformed to the recommended values.

Nevertheless, extreme values surpass 1000 ppm in most cases, together taking 1.3% of the studied data. Notably, GC and GEII's temperatures drop out of prescribed ranges by 25% and 25% in the pre-renovation state and 53% and 90% in the renovated state. While the temperatures were generally warmer than wanted in the old buildings, in the retrofitted buildings, particularly GEII, the temperature got cooler and rarely reached the comfort range (around 10% of the time). These are due to the lack of energy control before renovation and the rise

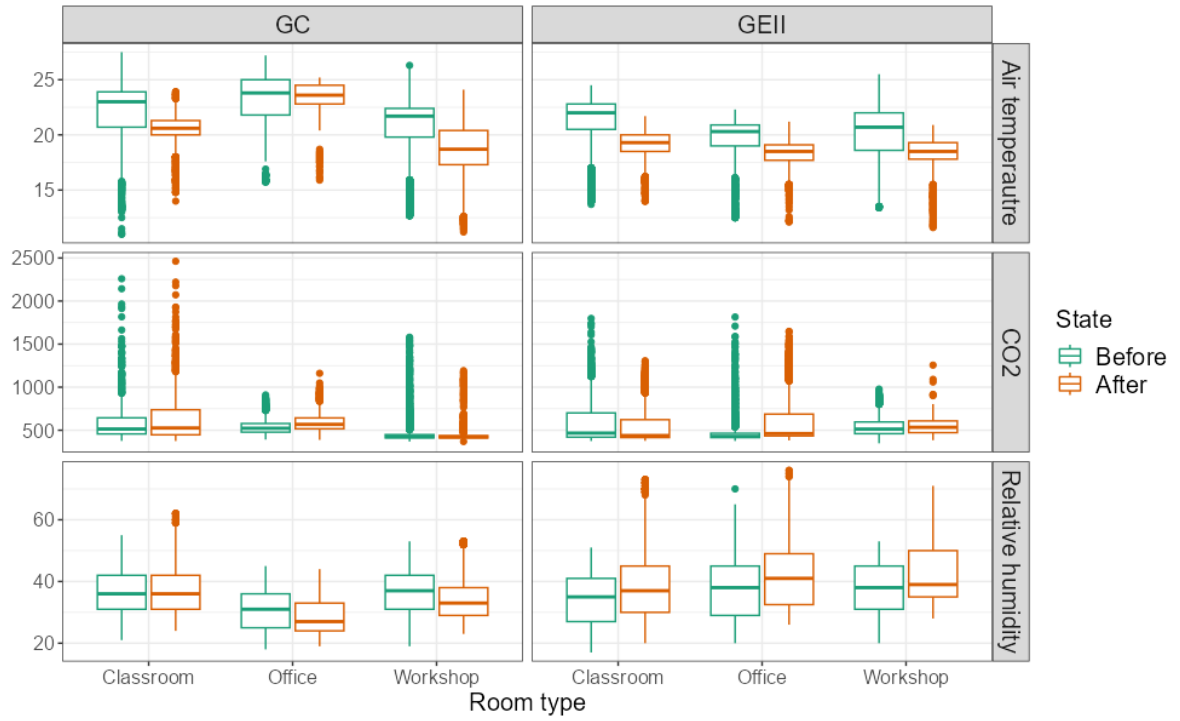


Fig. 3-17. *Boxplot of the indoor climate in different room types on weekdays during the occupied hours from 8h00 to 18h00 from January to March 2021 (before renovation) and 2023 (after renovation)*

of energy prices in 2021, after the renovation. In the pre-renovation state, indoor temperature accumulated per day considers the heat by heaters and available internal heat gain. Although some internal heat gains compensate for heat loss, solar radiation in the Mediterranean region is relatively robust even in winter, making rooms facing south sensitive to solar gains. Without indoor regulator valves, these internal heat gains are ignored, and heaters usually waste energy on unnecessary heating, making the indoor temperature warmer than the comfort threshold. In 2023, when both GC and GEII buildings were renovated, energy prices surged enormously. To reduce energy bills, the new temperature threshold during occupied hours is lowered to 18°C. When coupled with the available thermostats, the indoor temperature is maintained at around 19°C after including the internal heat gain.

III.4.3.2 T-test comparison of before and after renovation

The ANOVA test (one-way analysis of variance) is employed to compare data points before and after renovation. This statistical test extends the independent two-sample t-test and is specifically designed to compare the means of multiple groups. As such, ANOVA is the appropriate technique for this case study, where the means of each group of room types are compared. The ANOVA of the "rstatix" package of RStudio [251] takes into account two types of variations -

the SSn Sum of Squares in the numerator (i.e., SS effect), the SSd Sum of Squares in the denominator (i.e., SS error). The ANOVA test also calculates effect sizes *ges* by dividing SS_{effect} by SS_{total} as follows:

$$ges = \frac{SS_{effect}}{SS_{effect} + SS_{error}} \tag{III.11}$$

Table 3-4 summarizes the t-test results of the pre-buildings and post-buildings of each room type. The p-value is the significant value if it is less than 0.05 and is denoted with a star "*". The *ges* value (generalized eta squared) is the level of significance with three ranges, namely, "0.2" for small and not noticeable by experts, "0.13 +" for medium and noticeable to the expert eye, and "0.26 +" is large and noticeable even to the untrained eye. This t-test is vital to determine the degree of change in indoor climate, whether remarkable or subtle.

Indicator	Type	Effect	p-value	p < 0.05	ges
CO_2	Classroom	States (Before, After)	3.05e-05	*	0.021
	Office		1.75e-13	*	0.072
	Workshop		2.86e-01		0.002
Temperature	Classroom		1.00e-17	*	0.084
	Office		1.20e-02	*	0.009
	Workshop		2.06e-17	*	0.094
Humidity	Classroom		2.06e-16	*	0.078
	Office		1.91e-04	*	0.019
	Workshop		7.31e-06	*	0.027

Table 3-4. *Relationship between pre- and post-renovation states of indoor climate in different room types of GC and GEII buildings during heating period from January to March*

As a result of both buildings combined, a statistically relevant relationship between renovation and indoor environmental quality is found for a p-value lower than 0.05 except for CO_2 of the workshop with p-value = 2.86×10^{-01} in consequence of unchanged ventilation in the workshop section.

Drawing on *ges* values, this degree of significance is relatively minimal, for they are inferior to 0.2. Globally, this denotes that the pre-building and post-building progress in similar patterns for each indicator, if not the same. The most prominent changes, according to *ges* values, are the temperature of the workshop (0.094) and of the classroom (0.084), attributed to a change in temperature threshold.

III.4.3.3 Investigation of indoor air quality indicators

Ventilation inside schools is essential for at least two reasons. One is the question of air quality and its impact on well-being and performance. Moreover, second, it is a heat loss path. Many

studies have found the effect of low ventilation rates on performance and health [252, 253]. The role of ventilation as a heat loss path in school classrooms is sometimes misconstrued. The occupation rate in a classroom is commonly exceptionally high, and thus, the metabolic gains are also high. Modern designs incorporate typical gains, even in winter, to compensate for fabric losses. This means regulatory minimum ventilation rates are unlikely to place a high load on the heating system [254].

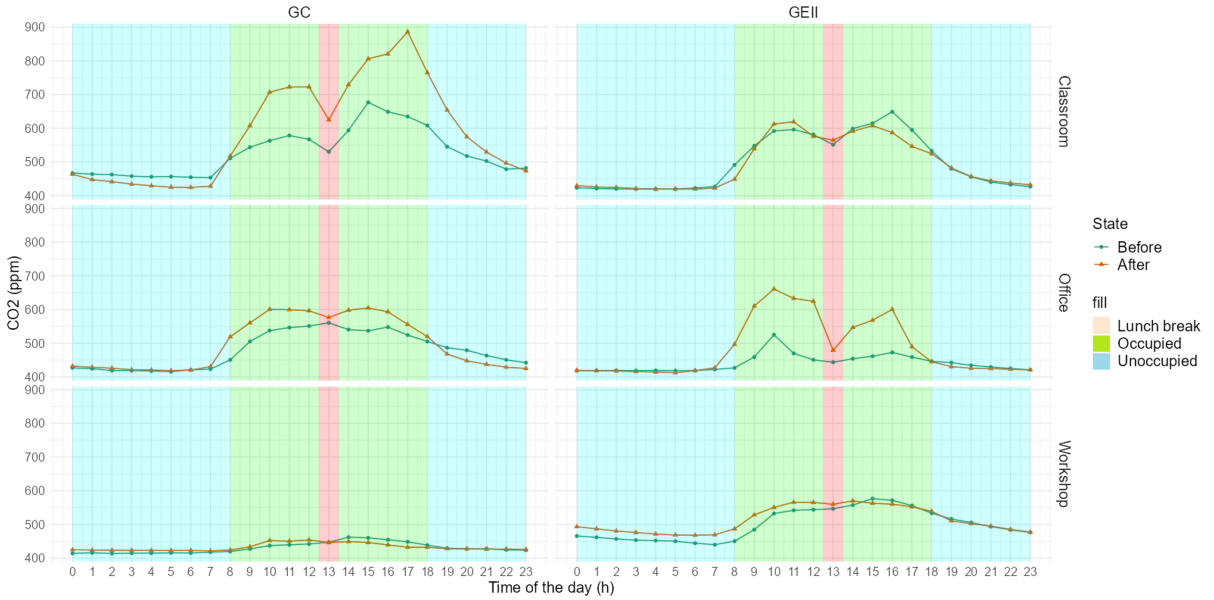


Fig. 3-18. *Mean CO_2 concentrations over the studied period on weekdays from January to March Before (2021) and After (2023) renovation. The filled color represents the global lunch break that usually takes place between 12h30 and 13h30, a typically occupied period of school hours and typical non-occupied periods*

Figure 3-18 illustrates the evolution of the average hourly CO_2 levels on weekdays during the pre-renovation period (January to March 2021) and post-renovation period (January to March 2023). It incorporates an unoccupied period at nighttime, an occupied period from 8h00 to 18h00, and a lunch break from 12h30 to 13h30. Surprisingly, the concentration of CO_2 in the GC building is higher after retrofitting than before, particularly in the classroom and office, by 11.7% and 3.8%, respectively. When non-ventilated, enclosed spaces are subjected to elevated concentrations of metabolically produced carbon dioxide emissions from the occupants' breathing [255]. A lower CO_2 level indicates the indoor air quality's freshness. This depends on the implementation of an appropriate ventilation strategy. Insufficient ventilation in buildings is a prevalent cause leading to a potential risk of sick building syndrome [256]. A ventilation test assessed the mechanical ventilation system's efficacy through airflow rate measurements. The results indicate that the extraction rate of each ventilation outlet is 50% lower than the proposed design value of $90m^3/h$. This design value conforms to the regulatory requirement for ventilation rates of $18m^3/h.per$. When it is not respected, excessive CO_2 levels happen, and more

seriously for renovated buildings when they are more air-tight following the renovation of the building envelope.

As for the GEII building, it was observed that the single-flow ventilation rate is correct, prompting similar patterns of CO_2 evolution trends, except for the investigated office. Nonetheless, this is not a problem caused by inefficient ventilation but rather by the change in room function. After renovation, this office was altered into a classroom, abruptly increasing the average CO_2. This effect emphasizes previous findings that, for the same air renewal, the CO_2 levels of the school are more important than the office's for it has higher occupant density.

Although the average CO_2 concentrations have worsened due to a defective ventilation system and a change in room utilization, they remain below 1000 ppm, with the highest peak at 900 ppm in the GC classroom at 17h00. The rest of the renovated buildings, which differ from the existing ones, reach a maximum of 700 ppm for the GC classroom at 10h00, 600 ppm for the GC office at 10h00 and 15h00, and 650 ppm for the GEII office at 9h00.

Another notable observation is the significant increase in CO_2 levels when classrooms reach full occupancy. Increasing ventilation rates is crucial to mitigate the CO_2 buildup. Another strategy involves encouraging teachers to periodically evacuate students and over-ventilate rooms by opening doors and windows for 10 minutes.

III.4.3.4 Investigation of thermal comfort indicator

In both states, the heating control system consists of two operational modes. The first mode, referred to as "$Comfort$", operates from 7h00 to 18h00. The second mode, known as "Eco", is intended for night-time use and on weekends. Following the renovation, it was decided to reduce the established temperature threshold in the *Comfort* mode from 20°C to 18°C for financial reasons. Nonetheless, it is essential to note that the actual temperature development may diverge from the pre-established setting due to the inefficient controlling system. An occurrence is observable occasionally wherein radiators maintain a consistent temperature at the designated comfort mode across the entire day, which may persist for several weeks.

Figure 3-19 presents the average hourly indoor temperature on weekdays of the two buildings in each state. The temperature in the pre-renovated GC building appears to be higher than in the pre-renovated GEII building. This is associated with the heat exchanger installed beneath the individual building after renovation. Before the refurbishment, the heat energy came from the GC sub-station, which benefits one of the two. This means that if the optimal temperature requested in GC is between 19°C and 25°C, depending on the set heating temperatures, the delivered temperature in GEII tends to be lower due to distribution energy loss. Since the installation of separate heat exchangers and the reduction in energy consumption due to the renovation of buildings, the transmitted energy is consistent with the energy needed in both

buildings.

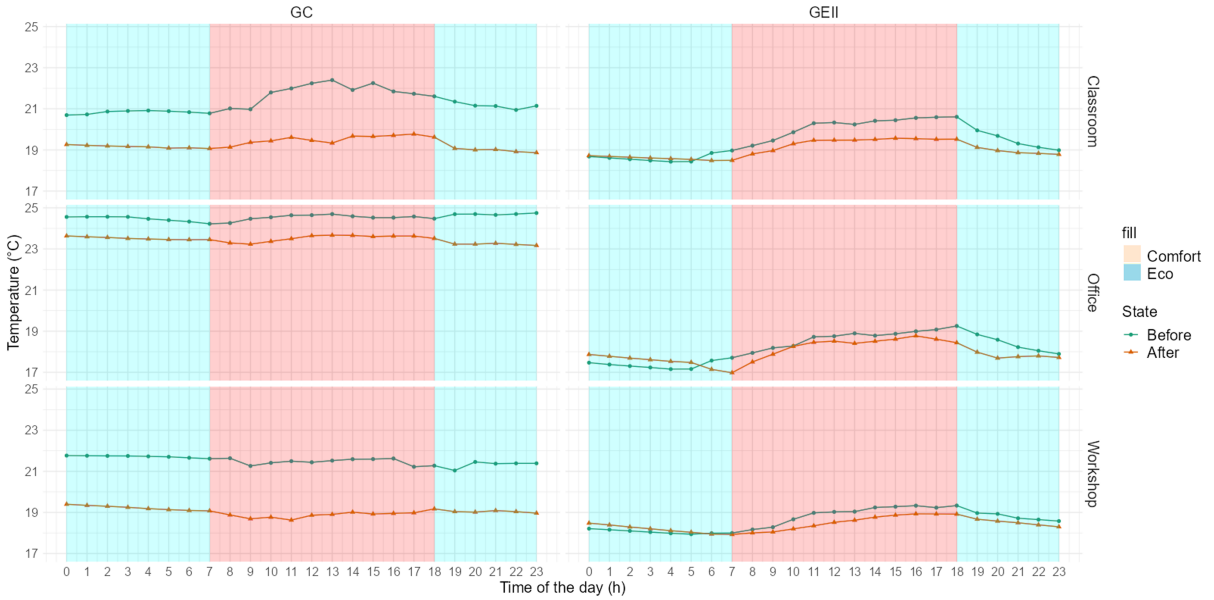


Fig. 3-19. *Mean indoor temperature over the studied period on weekdays from January to March Before (2021) and After (2023) renovation. The filled color represents two heating operation modes, namely "Comfort" that maintains a comfortable room temperature and "Eco" that economizes energy during nighttime and on weekends*

The historical heat distribution has been found to significantly influence the fluctuation of temperature experienced by the GEII and GC buildings. Given the new indoor temperature setpoint at 18°C, the temperature variation of the GEII building is less severe than that of GC because its final temperature was close to 19°C. Meanwhile, in the GC building, it is apparent that the temperature differences between before and after renovation are more prominent, with a maximum decrease of 3°C.

The temperature trends in GC are steady all day, unlike the progressions of GEII. Upon verification with GC's heating control, the supplied energy was consistently at the same level across all modes of operation. Another issue is related to continuous nighttime heating requested by an energy company in 2021 to avoid the energy spike that could cause temporary shutdowns. Since the GC's office floor area is relatively small, this results in consistently elevated temperatures at 24.5°C and 23.5°C in the pre-state and post-state.

As the occupancy rate of the classroom increases, there is a direct proportional rise in temperature. In contrast, the temperature decreases when students are absent, end-of-activity, or depending on the type of ventilation employed [257]. Based on the aforementioned studies, the discernible surge observed in GC's classroom before the renovation, between 10h00 and 13h00, may be attributed to indoor activities.

In the GEII, the typical temperature peaks can be observed at 11h00 in both states when provided with appropriate heat supply and scheduling as per demand. Besides occupancy density, numerous other factors significantly contribute to the fluctuations in average indoor temperature following retrofitting. These may encompass outdoor conditions, room characteristics such as size, orientation, and the surface of external walls, and the type of ventilation system employed, such as natural or mechanical ventilation with extraction.

The improved thermal insulation and new airtight windows help minimize the outside temperature's influence on the inside temperature, reducing the differences after the renovation. Indeed, the differences between the maximum and minimum temperatures in the renovated building were moderate, which underlines the effectiveness of the renovation in terms of heat conservation. The smaller the temperature fluctuations at night and during the day, the greater the energy saved the following day.

III.4.4 Discussion

After investigating two renovated buildings, several factors are needed for a better assessment. The heating system in a school building differs from that in residential and office buildings since individuals, such as students and teachers, lack the capacity to regulate it. Unless their impact pertains to the opening and closing of windows or doors, it has been studied and proved by Gao et al. [241] that it is rare for users to change them manually during the winter. Therefore, the change in the heating system relies heavily on the management strategy and its efficiency. In this case study, results have found that the supplied energy in one of the buildings, GC, does not conform to the energy demand by overheating predominantly. This affects not only energy consumption but also the occupant's comfort.

Furthermore, the new heating temperature threshold was reduced to 18°C to conserve energy. This effect leads to 90% of the temperature data falling into the uncomfortable zone concerning the recommended temperature range of the thermal guidelines for renovated buildings. Nonetheless, the designated temperature threshold may not be optimal for the workshops and the offices, where the number of occupants is minimal. After renovation, the average temperature of these two room types is as low as 18°C, equal to the threshold temperature since the internal heat gains are unavailable. Hence, it is crucial to maintain a delicate equilibrium between the user's comfort in different room types and overall energy saving. For instance, supplementary heating devices such as portable or convertible air-conditioners may be installed within office spaces. In the workshops, students are advised to wear additional clothing to decrease personal heat loss.

Regarding the modification in temperature consequent to the transition from the $Comfort$ to Eco heating mode, it has been observed that the temperature experiences a more rapid and

abrupt decline prior to the retrofitting measures. The findings suggest that the enhanced building envelope contributed to decreased heat loss through the building fabrics and parasitic infiltration, leading to extended heat retention and decreased temperature fluctuations between night and day. Consequently, the external renovation improved the building's time constant and thermal inertia.

The findings indicate that upgrading the envelope has decreased heat dissipation through both the fabrics and the ventilation system, resulting in prolonged heat conservation and reduced variation between nocturnal and diurnal temperatures.

Relevant to single-flow ventilation systems, the exchange air rate has become more vital in post-building than in pre-building. In incredibly air-tight rooms, indoor air quality is at risk if the air-flow rate does not meet the design value of 18 $m^3/h.per$, primarily for classrooms. The analyses in Section III.4.3.3 have proved that when the exchange air rate is incorrect, the CO_2 levels on average can increase up to 11.7% more than the typical CO_2 values of the pre-state. Consequently, regular checks and maintenance of the ventilation system are necessary.

Overall, the t-test statistics reveal a marginal significance between indoor climates before and after renovation for *ges* values less than 0.2. This suggests that this retrofitting strategy maintains the IEQ at roughly the same range without any noticeable improvement or deterioration. Although the CO_2 concentrations, HR_{in}, and T_{in} values on average are acceptable by remaining the same, they are sitting on the edge of the recommended zone according to the thermal benchmark of renovated buildings.

The results also show that during the occupied period of the heating season, the CO_2 levels exceeding 1000 ppm is only 1.3% of measured data in both states. However, occasional spikes can reach up to 3000 ppm within 15 minutes. The analysis was carried out during a period of use, but the rooms were not always occupied. Thus, the analysis presented in Figure 3-18 smoothes the average hourly rate of CO_2. Previous research has found similar patterns. For instance, Ramalho et al. (2013) [258] investigated 108 campus buildings in France and revealed that in the occupation period, 33% of the schools revealed CO_2 concentrations above 1700 ppm in more than 66% of the records. Santamouris et al. (2008) [259] monitored the indoor air quality in 27 naturally ventilated schools in Athens. The measurements were taken in the spring and fall seasons when window opening is the main ventilation procedure. The finding indicates that 52% of the classrooms presented CO_2 concentrations greater than 1000 ppm with a median of 1070 ppm. At the end of the class period, there was a maximum concentration of 3000 ppm with a median of 1650 ppm. Similarly, a study by Almeida found a marginal enhancement in indoor environmental conditions following the retrofitting process compared to the pre-existing state, albeit still falling short of the recommended criteria [246, 248, 249].

These similarities with previous research highlight the importance of ongoing efforts to

improve indoor air quality, especially during peak occupancy periods, to enhance the occupants' health and comfort within the building premises.

III.4.5 Conclusion

Students spend most of their time in school. Therefore, good indoor environmental quality must be provided. With the current trend of low-energy consumption buildings, university buildings, like many others, have undergone energy-efficient renovation. This renovation, however, does not guarantee better indoor environmental quality. This section is designed to comprehensively analyze the impact of refurbishment on thermal comfort and indoor air quality.

The t-test statistics showed subtle but significant changes in indoor climate parameters, including CO_2 levels, temperature, and humidity. However, these changes were not discernible to the occupants or experts.

Specifically, the detailed analyses yielded several noteworthy findings:
- Considering usable internal heat gain is crucial for retrofitting buildings in Mediterranean weather conditions. Accounting for heat release from occupancy and solar radiation in heating design and control strategies, such as thermostats, can prevent unnecessary energy wastage on heating;
- Adjusting heating set points to 18°C post-renovation did not impact the thermal comfort perception of classroom occupants. However, given their relatively low occupancy rates, this threshold was suboptimal for offices and workshops, limiting available internal heat gain. As a result, supplementary heating devices should be provided in these room types:
- Exchange air rate is more vital in the renovated building with extreme air-tight than in the existing building. This case study proves that defective ventilation systems led to a significant 11.7% increase in CO_2 concentrations, emphasizing regular verification and maintenance to meet regulatory standards and prevent building sick syndrome.

The research confirms that retrofitting buildings using energy-efficient methods offers substantial benefits, as it significantly reduces heating demand and overall energy consumption without compromising indoor climate conditions. While values of specific indoor environmental quality indicators may sit on the edge of the comfort zone defined by building thermal regulations for renovated buildings, they remain within acceptable limits. Future studies should confirm heat demand assessments through measurements of heating energy supplied by the building's substation, which will be accessible for the next heating campaign. Additionally, further investigations should explore combined effects, incorporating user comfort surveys in similar or mid-season periods and considering visual comfort and indoor air quality, including odor comfort. These endeavors will contribute to a more comprehensive understanding of the impact of energy-efficient renovations on indoor climate and occupant comfort.

Chapter IV

Thermal comfort

"An approximate answer to the right question is worth far more than a precise answer to the wrong one"

— JOHN TUKEY

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IV.1 Introduction

This chapter delves into a comprehensive examination of the perception and acceptability of votes within the investigated buildings, divided into three essential parts, each discussing a distinct facet of the respondents' votes.

Part A analyzes sensation and acceptability votes concerning thermal, air-draft, and humidity in existing buildings, focusing on room types (classrooms and workshops) and seasons (winter and summer).

Part B is devoted explicitly to assessing thermal comfort votes under transient conditions. This section adds credibility to the survey questionnaire selected from respondents during transient periods, affirming that the collected data can effectively analyze thermal comfort within both rational and adaptive models.

Part C assesses how energy-efficient renovation impacts respondents' perception and acceptability of thermal comfort and indoor air quality.

IV.2 Part A: Investigating thermal perception and acceptability votes in non-renovated buildings

IV.2.1 Introduction

This chapter delves into a comprehensive analysis of sensation and acceptability votes concerning thermal, air-draft, and humidity in existing buildings before renovation, focusing on room types (classrooms and workshops) and seasons (winter and summer). Beyond examining the sensation and acceptability votes, the study explores adaptive strategies adopted by respondents to achieve their desired comfort conditions, covering both environmental modifications and HVAC adjustments, aiming to understand how occupants naturally adapt to the conventional building environment. This chapter also investigates comfort/discomfort votes following different environmental conditions and setups within the classroom or workshop, such as seating positions, active mechanical machines, window states, classroom orientation, and shutter positions, to analyze their contribution to the occupants' subjective experiences.

IV.2.2 Methodology

The investigation within this section focuses on assessing the comfort and discomfort levels experienced by students within existing buildings, namely the GC and GMP buildings, before

the renovation. The analysis is based on data from survey periods conducted from February 18 to 25, 2022 (phase 1), March 07 to 15, 2022 (phase 2), and June 15 to 23, 2023 (phase 3). A total of 529 valid responses were obtained, representing participants in 13 classrooms and 5 workshops. The distribution of responses includes 288 from phase 1, 127 from phase 2, and 114 from phase 3, as detailed in Table 4-1.

Survey period	Season	Surveyed building	Room type	Number of rooms	Vote count	Total vote count
17/02/2022 - 23/02/2022 (phase 1)	Winter	GC	Classroom	5	288	288
			Workshop	0	0	
6/3/2023 - 15/03/2023 (phase 2)	Winter	GMP	Classroom	7	73	127
			Workshop	4	54	
16/06/2023 - 21/06/2023 (phase 3)	Summer	GMP	Classroom	6	87	114
			Workshop	2	27	

Table 4-1. *Summary of survey responses in each phase*

Table 4-2 provides a concise overview of this section's questions and corresponding responses. The questions are categorized into four groups: the sensation scale, acceptability scale, comfort parameter, and adaptive comfort strategies.

IV.2.3 Result and discussions

IV.2.3.1 Physical measurements

Figure 4-1 presents a time series of outdoor temperature (average values) and indoor temperature (minimum, average, and maximum values) over the survey periods. In phase 1, the minimum, mean, and maximum values are closely aligned, indicating minimal temperature variation across diverse rooms. In contrast, during phase 2, the indoor temperature minimums and maximums display a noticeable gap, suggesting a wider temperature fluctuation between different rooms compared to phase 1.

Note that the surveys in phases 1 and 2 were carried out during the heating season, where the primary factor influencing temperature was the heat emitters' energy. Ideally, in a well-regulated environment, each room should maintain a consistent temperature conducive to winter comfort, typically ranging between 20°C and 22°C, as recommended by ASHRAE standard [260] and ISO standard [124].

In phase 3, the temperature trend lines exhibit stable minimum values and fluctuating maximum values over time, attributed to (i) rooms with minimal exposure to internal and external heat gains maintaining a relatively constant temperature and (ii) rooms with higher exposure

Question		Scale point	TSV	ASV	HSV	Interpretation of or assessment
Sensation Scale	How do you find the climate of your room at this time?	3	very hot	very strong	very humid	Discomfort
		2	hot	strong	humid	
		1	neutral	correct	neutral	Comfort
		0				
		-1				
		-2	cold	weak	dry	Discomfort
		-3	very cold	immobile	very dry	
		-	**TAV**	**AAV**	**HAV**	**-**
Acceptability Scale	What is your level of acceptability of the climate at this time?	2	clearly acceptable			Acceptable
		1	just acceptable			
		-1	just unacceptable			Unacceptable
		-2	clearly unacceptable			
Comfort parameter	Where do you sit in the room?	- Next to the window			- Next to the internal wall	
		- In the center of the room				
	Do you use desktop/ machine in this room?	- Yes			- No	
	Are there any windows opened?	- No			- Yes, completely	
		- Yes, partially				
	Are there any shutters opened?	- No			- Yes, completely	
		- Yes, partially				
Comfort strategies	What would you do to satisfy your comfort at this time?	- Open the window			- Close the window	
		- Open the door			- Close the door	
		- Open the shutter			- Close the shutter	
		- Increase ventilation			- Decrease ventilation	
		- Increase heater			- Decrease heater	

Table 4-2. *Summary of survey questions and responses*

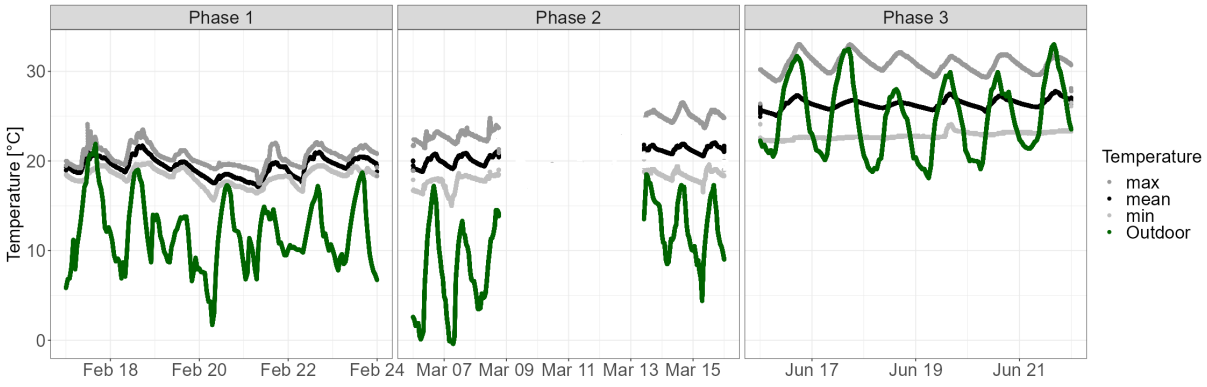


Fig. 4-1. *Evolution of outdoor temperature and indoor temperature (minimum, average, and maximum values from surveyed classrooms and workshops) during each survey phase. The empty lines in the 2nd survey phase are due to the missing values, as explained in Chapter 2*

experiencing significant temperature variations. The pronounced disparity observed between the trend lines of maximum and minimum values in both phase 2 and phase 3 can be ascribed to different room types' temperatures (classroom and workshop).

Figure 4-2 illustrates a boxplot detailing indoor climate values categorized by room types and seasons at survey moments of the three phases. During winter, classrooms and workshops show similar thermal patterns, with air temperatures around 22.5°C, humidity levels approximately at 42.5%, and CO_2 levels around 750 ppm. However, classrooms could reach up to 2000 ppm, signifying occasional periods of suboptimal indoor air quality, potentially linked to insufficient ventilation despite the presence of operable windows.

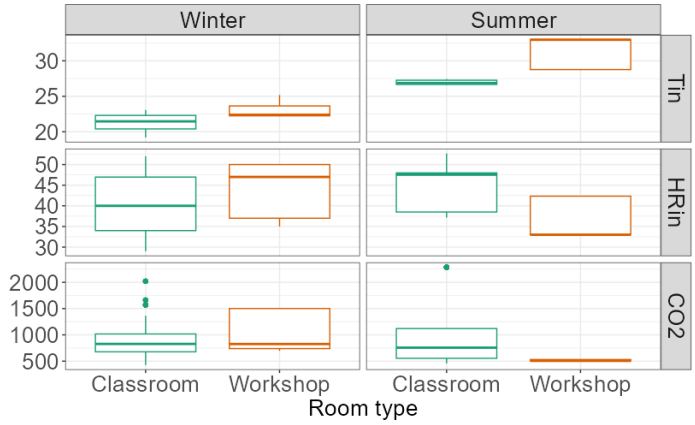


Fig. 4-2. *Boxplot of indoor air temperature (T_{in}), relative humidity (HR_{in}), and CO_2 concentrations across three survey phases at the survey moments, categorized by room types and seasons*

During the summer, a clear distinction in mean temperature values emerges between classrooms (26.5°C) and workshops (32°C). Although the difference in mean relative humidity is more pronounced in the summer compared to the winter, both still fall within the acceptable relative humidity range (30% - 60%) recommended by the ASHRAE standard.

IV.2.3.2 Perception of indoor comfort

Sensation votes

A t-test statistic is employed to assess the independence of thermal sensation votes of different room types, as detailed in Table 4-3. The analysis reveals a significant statistical difference between the two room types in both seasons (p-value < 0.05). Remarkably, the significance level is more distinct in summer (p. significance of ****) compared to winter (p. significance of ***), implying a more substantial difference in how respondents perceive or respond to the environmental conditions during summer compared to winter.

Season	Room types	mean TSV	n [a]	statistic [b]	df [c]	p-value [d]	p.signif [e]
Winter	classrooms	-0.05	360	-3.92	74.78	$1.89e^{-04}$	***
	workshops	0.57	54				
Sumer	classrooms	1.05	86	-6.72	54.23	$1.13e^{-08}$	****
	workshops	2.46	26				

[a] number of response.
[b] the t-test statistic (t-value) used to compute the p-value.
[c] the degrees of freedom.
[d] the significance level of the t-test.
[e] significance codes: 0 '****' 0.001 '***' 0.01 '**' 0.05 '*' 0.1 '.' 1.

Table 4-3. *Pairwise tests of mean TSV results in terms of room types in each season*

The significance is also evident in the mean TSV values. For instance, during winter, the mean TSVs are -0.05 and 0.57 for classrooms and workshops, respectively, falling within the neutral sensation categories. In contrast, during summer, the mean TSVs are 1.05 and 2.46 for classrooms and workshops, respectively, indicating hot and very hot sensations, thus establishing a clear distinction in votes during these seasons.

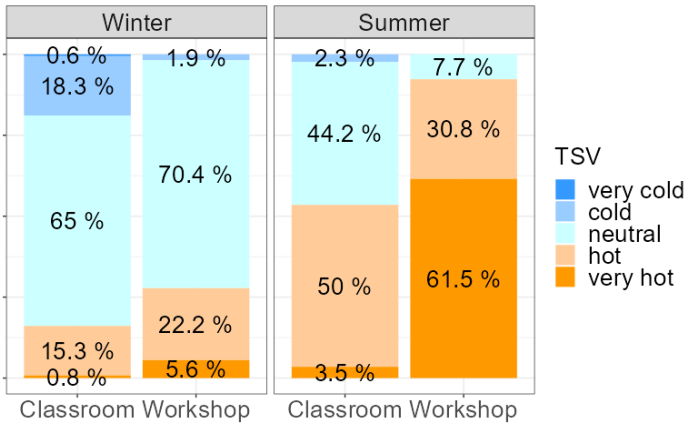


Fig. 4-3. *Thermal sensation vote distributions categorized by room types and seasons*

Figure 4-3 depicts the percentage distribution of thermal sensation votes across seasons and room types. In winter, indoor temperature is predominantly perceived as neutral, accounting for 65% of classrooms and 70.4% in workshops. Conversely, during summer, thermal conditions are mostly perceived as hot for classrooms (50%) and very hot for workshops (61.5%). This observed pattern aligns with the physical measurements illustrated in Figure 4-2, indicating a correlation between respondents' thermal perception and indoor temperature. Subsequently, most students report a neutral sensation in the cold season and a hot discomfort in the warm season.

Figure 4-4 displays the distribution of air draft sensation among respondents in class-

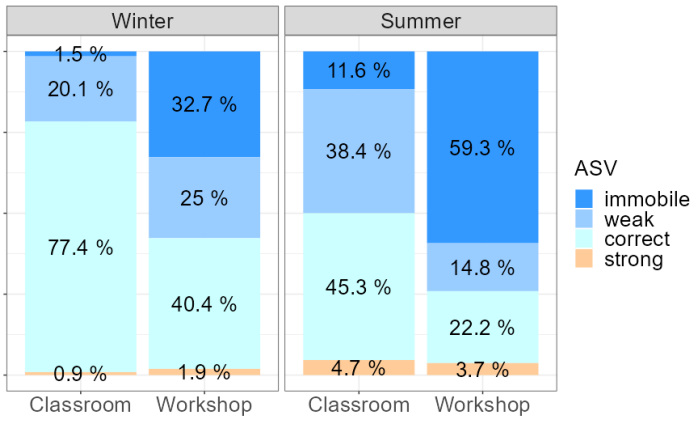


Fig. 4-4. *Air-movement sensation vote distributions categorized by room types and seasons*

rooms and workshops during winter and summer. In winter, respondents predominantly note correct air movement (77.4%), whereas those in workshops experience a higher prevalence of immobility (32.7%). Similarly, during the summer, respondents report correct air movement in classrooms (45.3%) and immobility in workshops (59.3%). This suggests that the nature of workshop activities, characterized by the presence of machinery, high levels of physical activity, and increased clothing insulation, may impact air circulation and draft perceptions differently compared to the relatively static environment of classrooms. Moreover, occupants prefer higher air speeds for improved heat dissipation in environments with elevated temperatures.

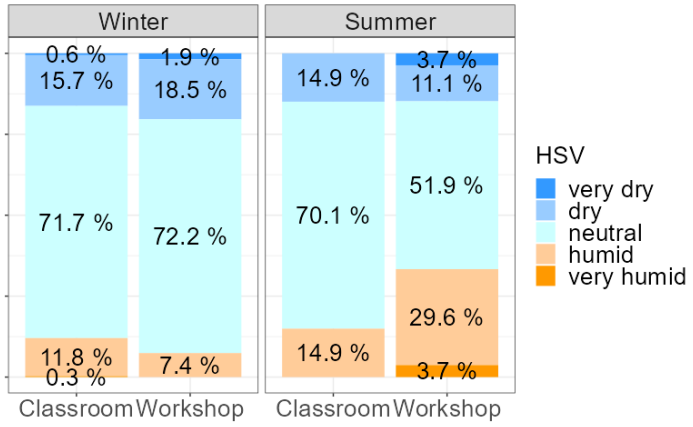


Fig. 4-5. *Humidity sensation vote distributions categorized by room types and seasons*

Figure 4-5 illustrates a percentage distribution graph depicting respondents' perceptions of humidity in classrooms and workshops during winter and summer. The results reveal a nuanced difference in humidity perceptions between the two room types. Both room types predominantly receive a neutral humidity rating (more than 70%) in winter. During summer, in general, the perception of humidity is correct, with over 70% of responses being "neutral", justified by the fact that the measurements are always within the acceptable range (Figure 4-2)

of the ASHRAE standard (30-60%). On the other hand, the students perceive humidity in the summer workshops as dry, very dry, humid, and very humid by 48.2% of the responses. Assessing humidity appears delicate, considering the hot discomfort of these rooms during this season.

Acceptability votes

This section utilizes a 4-level acceptability scale, encompassing categories such as clearly unacceptable, just unacceptable, just acceptable, and clearly acceptable. This scale assesses the acceptance levels of sensation, air-draft, and humidity.

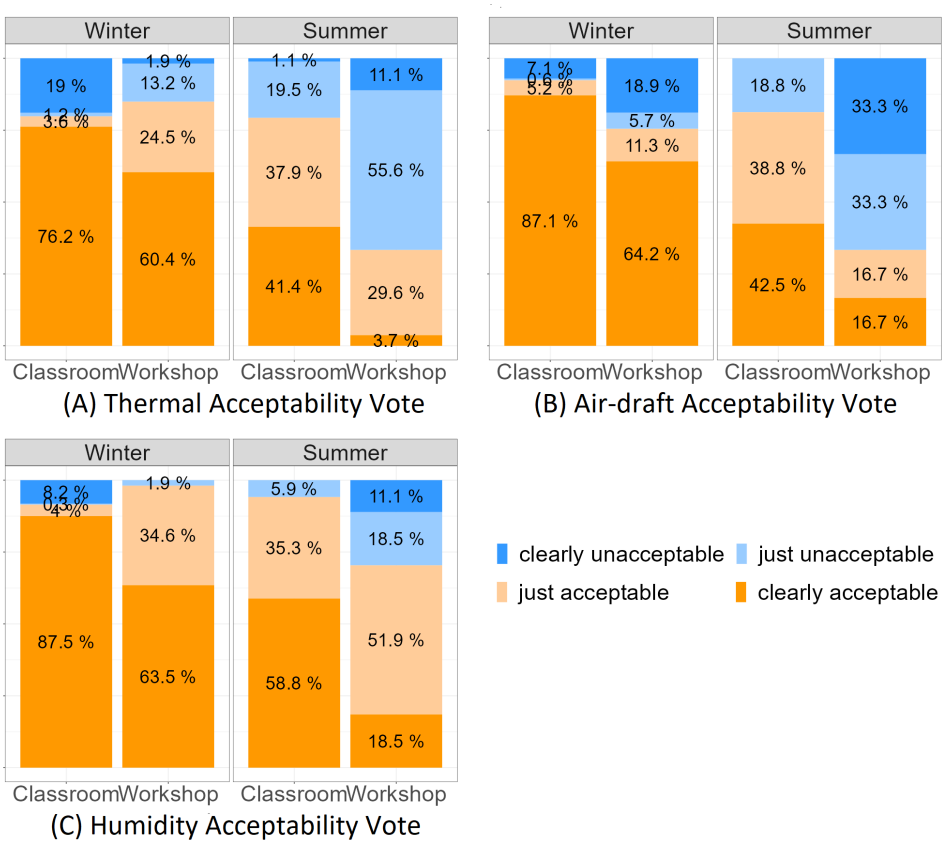


Fig. 4-6. *Acceptability vote distributions of (A) thermal, (B) air draft, and (C) humidity, categorized by room types and seasons*

Figure 4-6 illustrates the distribution of thermal acceptability vote (panel A), air draft acceptability vote (panel B), and humidity acceptability vote (panel C). Notably, the distribution patterns exhibit coherent trends across the three metrics. For instance, in winter, both room types are strongly inclined towards a "clearly acceptable" rating, with approximately 80% of respondents in classrooms and approximately 60% in workshops for all metrics. This unanimous preference for the "clearly acceptable" response suggests high satisfaction and comfort in both room types during the winter. However, in the summer, the vote distribution diverges.

In classrooms, "clearly acceptable" remains the most voted category, with approximately 40% for thermal and air draft and 58.8% for humidity. Conversely, in workshops, the most voted category is "just unacceptable" for thermal (55.6%) and air draft (33.3%), while for humidity, it is "just acceptable" at 51.9%.

Another noteworthy observation is the relationship between humidity voting patterns and temperature fluctuations. Specifically, data from both Figure 4-5 and Figure 4-6C consistently show that humidity sensation and acceptability votes maintain consistently high percentages in most cases (more than 70% in sensation and more than 90% in acceptability). This observation implies that (i) occupants tend to be less sensitive to humidity metrics compared to others, and (ii) there is a distinct shift in both humidity sensation votes and humidity acceptability votes, particularly in workshops during the summer when temperatures are highly elevated.

This finding aligns with the conclusions drawn by Toftum, supporting the idea that within a specific range, variations in humidity levels might exert minimal influence on thermal comfort. Nevertheless, these effects tend to become more pronounced at higher temperatures [261].

Comparing different comfort scales

Figure 4-7 summarizes the sensation and acceptability votes of thermal, air draft, and humidity categorized by winter and summer. Note that in this figure, the scale points {-3, -2} and $\{2, 3\}$ are aggregated into single categories. The outcome reveals a consistent pattern where the percentage of the "acceptable" category of acceptability scales is higher than the "neutral" of the sensation scales. Simultaneously, the "unacceptable" category remains relatively lower than the "non-neutral" category.

Specifically in summer, concerning the thermal metric, although most occupants (61.4%) perceive the classroom or workshop as hot, only 31.6% of them deem this temperature unacceptable. Similarly, in the case of air draft sensation, while a significant portion of votes (56.1%) express a perception of weak air movement in summer, only 29.8% consider it unacceptable. This indicates that occupants exhibit a higher tolerance on the acceptability scale but tend to be more critical regarding the sensation scale. Previous studies [262] have also reached similar conclusions, suggesting that the comfort votes derived from the thermal acceptability scale usually have higher percentages than the thermal sensation scale.

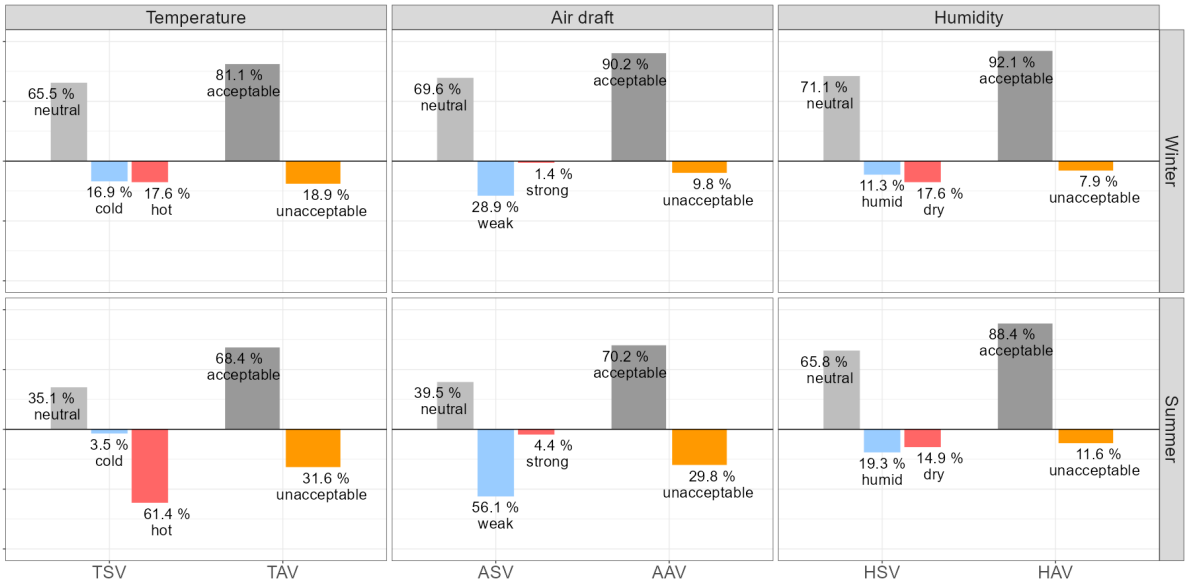


Fig. 4-7. *Comparison of the sensation scale and acceptability scale of thermal comfort, air draft comfort, and humidity comfort by seasons for both room types combined*

IV.2.3.3 Comfort adaptive strategies

When confronted with discomfort, individuals employ various strategies to enhance or maintain their comfort levels, categorically falling into three main groups: behavioral adjustment, physiological adjustment, and psychological adjustment [263]. Behavioral adjustment encompasses personal adaptations, environmental modifications, and HVAC modifications.

The non-renovated buildings of IUT de Nîmes rely on natural ventilation without a cooling system, except for certain offices. The heating system is centrally controlled by technical personnel, leaving students without direct access to or control over the HVAC system. Nonetheless, students can implement personal adaptive measures and make environmental modifications, although the latter option has limitations. Students remain engaged in class activities and might not frequently interrupt to regulate windows or doors. Those seated near windows or doors often have more influence over these adjustments.

This study narrows the focus to the environmental modifications and their potential interest in controlling HVAC settings if such options were available, as shown in Figure 4-8. The aim is to understand how individuals respond and adapt to their built environment, which could explain their preferences on both aspects (environmental adjustments and hypothetical HVAC adjustments). As outlined in Table 4-2, the multiple-choice format employed for answering the comfort strategies question gives respondents the flexibility to select more than two options based on their preferences or needs.

Subsequently, during winter, the most frequently employed strategy, constituting 34% of

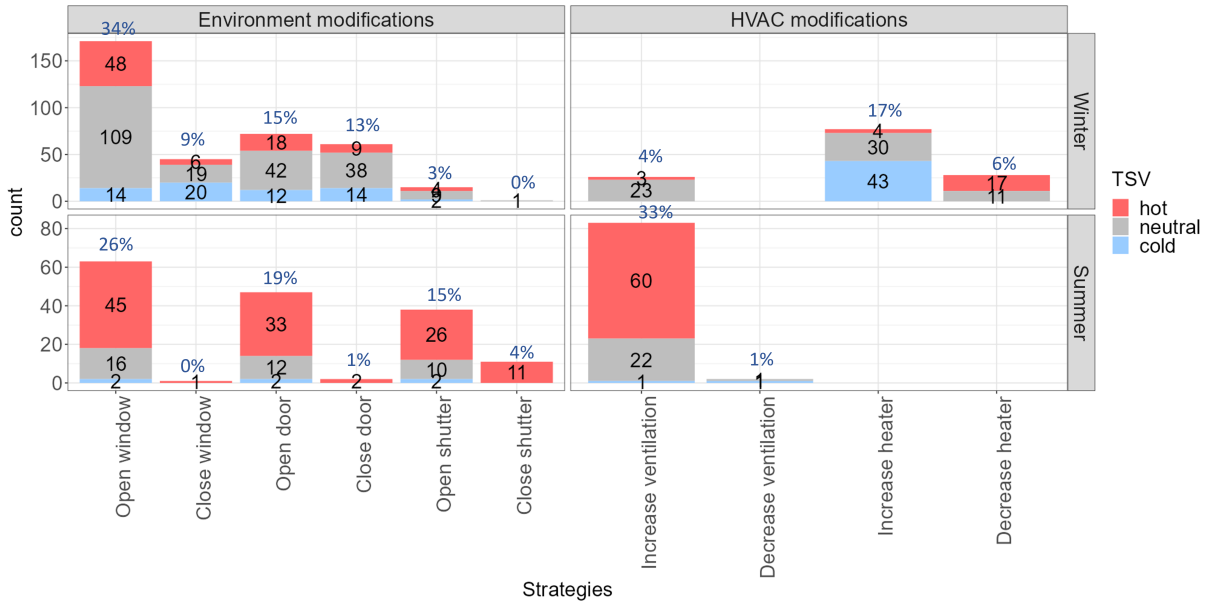


Fig. 4-8. *Respondents' adaptive strategies, encompassing environmental modifications and desired HVAC adjustments for optimal comfort conditions*

responses to combat hot and neutral sensations, is to open windows. Following closely, at 17%, is the strategy of increasing heaters, which students wish to implement in response to sensations of cold within the environment.

In summer, the most prevalent vote, accounting for 33%, is attributed to increasing ventilation, followed by the open window strategy at 26% and the open door strategy at 19%. These voting patterns strongly indicate robust tendencies among respondents to seek increased airflow in response to hot sensations by adjusting indoor ventilation methods.

At IUT de Nîmes, achieving comfort regarding temperature and air quality appears attainable in winter but presents challenges during the summer. Figure 4-8 also indicates that when faced with hot conditions, the individual response involves opening windows, doors, and closing shutters. However, respondents would prefer adjusting the HVAC system if the option is given. The range of passive reactions suggests that solely relying on these available strategies was inadequate to attain their desired comfort levels, as evidenced by the persistent hot sensation, which accounted for as much as 61.4% of the TSV scale (Figure 4-7).

Alternative methods, such as utilizing fans or controlled ventilation, become essential to achieve comfort without resorting to mechanical cooling. When combined with mechanical ventilation, it is imperative to consider integrating night ventilation strategies to tackle the challenge of achieving comfort in the specified environment effectively.

IV.2.3.4 Identification of discomfort factors

Identifying discomfort factors involves examining the percentage of non-neutral categories derived from thermal sensation votes, air draft sensation votes, and humidity sensation votes. This analysis involves a detailed investigation into various influential factors, such as the seating positions of respondents in classrooms, the presence of active mechanical machines in workshops, the status of window states and shutter states (whether opened or closed) in classrooms, and the orientation of the classrooms.

Impact on thermal comfort perception: Seating positions

This assessment seeks to understand how respondents' different seating positions affect their perceived comfort levels. Figure 4-9 represents the distribution of thermal response votes concerning the two seasons and the three seating positions, namely, next to the internal wall, in the center, and next to the exposed window.

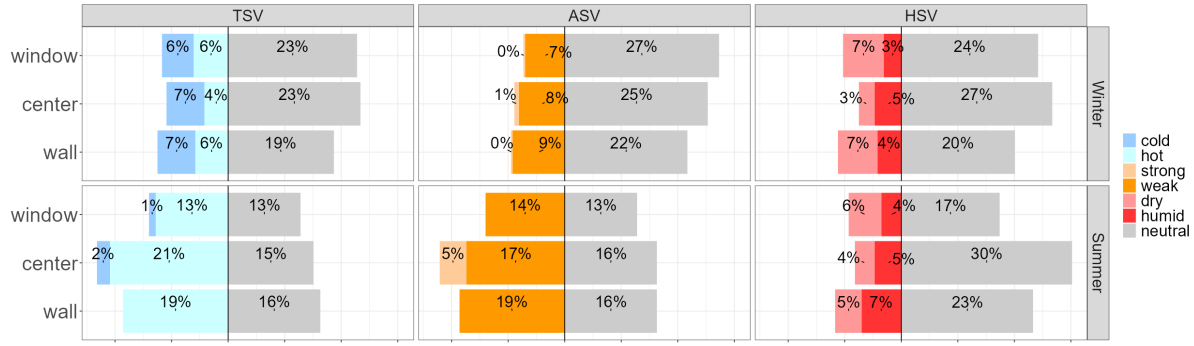


Fig. 4-9. *The distribution of TSV, ASV, and HSV votes is based on respondents' classroom seating positions for each season. "Window," "Center," and "Wall" represent positions next to the exposed window/wall, in the center, and next to the internal wall, respectively*

In winter, the sensation votes across the three metrics appear generally satisfactory, with the majority falling into the neutral category, regardless of the seating position. However, in summer, noticeable discomfort levels are observed in the hot thermal and weak air draft sensations. The "center" seating position accumulates the highest percentage of thermal discomfort votes (vote categories other than neutral) at a total of 23.1%, followed by the "wall" position at 19%, and the "window" at 14%. The lowest percentage in the "window" position can be explained by the proximity of respondents to the window, which exposes them to stronger air movement (as windows are usually open in summer), contributing to alleviating their sensation of heat, leading to higher satisfaction compared to other seating positions.

Impact on thermal comfort perception: Presence of active mechanical machines

As demonstrated in Section III.2.3.5, mechanical machines within workshops contribute to increased temperature. Consequently, this assessment only incorporates mechanical machines from workshop halls into analyzing sensation votes.

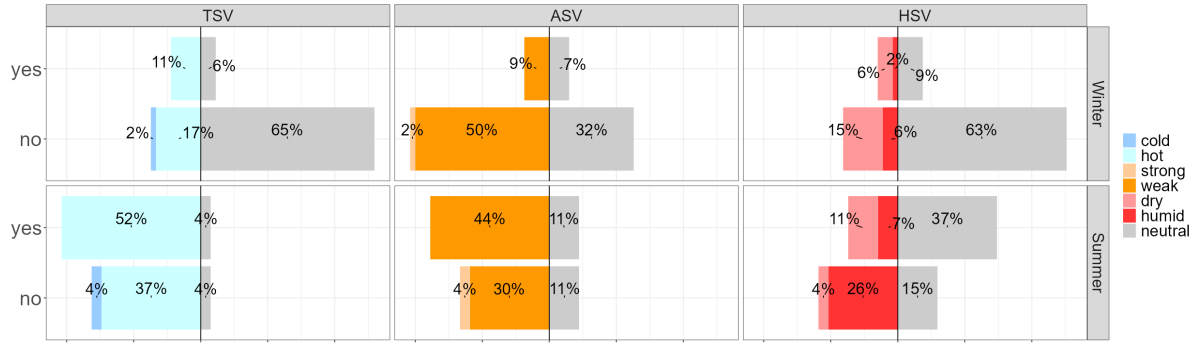


Fig. 4-10. *Distribution of TSV, ASV, and HSV votes based on the presence of active mechanical machines in workshops during winter and summer. Respondents indicated "yes" or "no" to the question "Do you use machines in this class?"*

Following Figure 4-10, the most remarkable response among the three metrics is ASV, which has a non-neutral vote percentage higher than neutral votes in both seasons, suggesting that students prefer increased air draft in workshops. Moreover, the non-neutral votes of TSV during summer are relatively high, specifically in hot sensation, both active mechanical machines (52%) and inactive mechanical machines (37%), showing that (i) the hot discomfort in the workshop is prominent and (ii) the presence of active machines slightly contributes to the higher hot discomfort in this room type.

Impact on thermal comfort perception: Window states

Before the renovation, IUT de Nîmes buildings were naturally ventilated; thus, occupants depended on opening or closing windows to enhance the air quality. The study investigates the impact of different window states (fully closed, partially opened, and completely opened) on respondents' sensation votes. Note that "Partially opened" refers to scenarios where one or more windows are open.

Based on Figure 4-11, it can be seen that the windows are rarely entirely open in winter, and most respondents are comfortable in all three metrics regardless of the window states. However, in summer, when the windows are in a "completely closed" state, the votes from respondents are evenly divided between sensations of comfort and discomfort in TSV and ASV. This observed pattern can be attributed to two phenomena related to different respondent groups, one sensitive and the other insensitive to outdoor temperature. Firstly, during this time of the year, maintaining closed windows preserves the coolness of indoor air, as outdoor temperatures are typically warmer than indoor temperatures, creating a thermally pleasing environment.

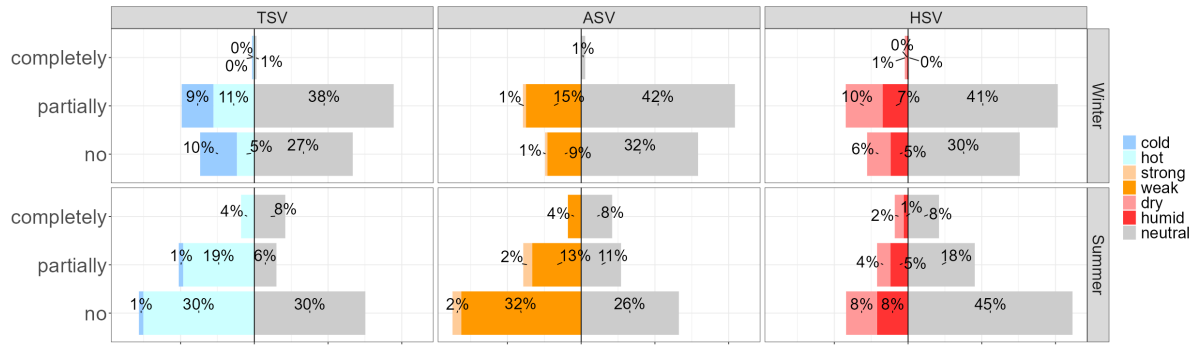


Fig. 4-11. *Distribution of TSV, ASV, and HSV votes based on the state of windows. Respondents answered the question, "Is the window opened?" with "completely" indicates fully open windows, "partial" denotes partially open or closed windows, and "no" signifies completely closed windows*

However, the second phenomenon arises from closed windows accumulating indoor heat from activities and solar gain, resulting in thermal discomfort.

When occupants perceive the environment as thermally hot, a higher airspeed is desired to compensate for the hot environment. As the air velocity is relatively low when the windows are closed, respondents perceive it as insufficient for their comfort, leading to a "weak" airspeed sensation vote. Conversely, in a thermally comfortable environment, they are not sensitive to the airspeed, resulting in a "neutral" vote for the same airspeed. These results suggest that window states have a different impact on thermal perception, which is in line with previous studies [177, 264–266] where they proved that the status of window states, whether they are open or closed, can significantly influence the perceived discomfort level of occupants.

Impact on thermal comfort perception: Orientations and shutter states

The orientation of classrooms significantly influences thermal comfort votes, especially the south-facing rooms, which typically receive more direct sunlight than the north, resulting in elevated indoor temperatures. However, potential discomfort from excessive sunlight can be reduced by installing solar protection, which limits solar heat gains and minimizes glare or screen reflections. Figure 4-12 depicts the sensation votes in relation to the classroom's orientation (panel A) and the shutter state in classrooms in the south (panel B). "Partially" refers to scenarios where one or more shutters are open.

In Figure 4-12, the winter response shows a higher proportion of respondents feeling cold in the north-facing classrooms compared to the south, possibly due to limited solar gain on the north side. Summer, however, reveals consistent and notably high discomfort from hot sensations (26%) in both orientations, suggesting thermal discomfort in this season.

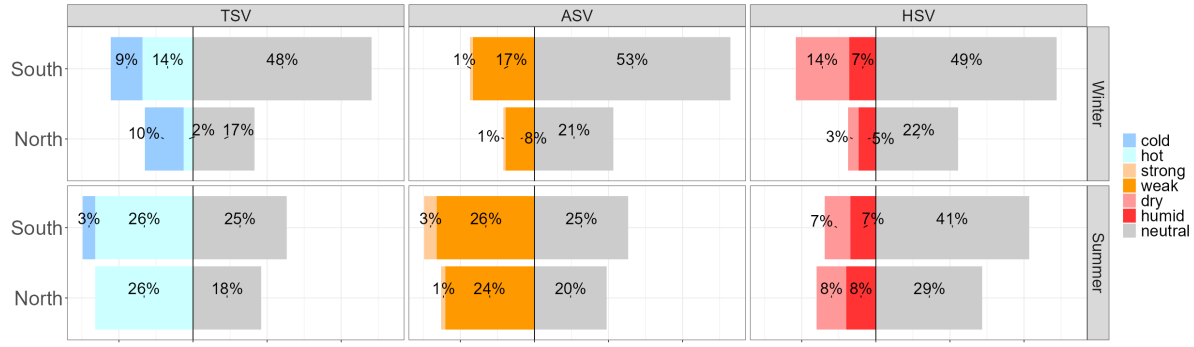


Fig. 4-12. *Distribution of TSV, ASV, and HSV votes based on classroom orientations*

IV.2.4 Conclusion

This section investigates thermal, air draft, and humidity comfort using sensation and acceptability scales within the existing school buildings. The results show a striking resemblance between the sensation and acceptability votes. This observation suggests a strong correlation among the perceptions of thermal comfort, air draft, and humidity, indicating a mutual influence among these metrics.

The overall result from the three metrics indicates that IUT de Nîmes buildings are comfortable during the winter but markedly uncomfortable during the summer. Comparatively, when assessing classrooms versus workshops, the workshop spaces exhibit a higher degree of discomfort, primarily due to their architectural design and slightly due to additional heat sources, which are the heat released by mechanical machines.

To satisfy their comfort, a majority of students resort to environmental modifications, particularly the strategy of "opening windows" in both seasons. Despite lacking direct access to the HVAC system and thus being unable to control the ventilation, students consistently express a strong inclination toward "increasing ventilation" as an adaptive strategy for dealing with the hot environment during summer, as the available environment modifications are not sufficient.

Another remark is that the temperature is not stabilized in winter for the students' votes according to the moments some wish to "open the windows" and others wish to "increase the heating". This highlights momentary overheating or lack of heating in different classrooms.

This study reveals intolerable indoor conditions during the summer, highlighting the urgent need for immediate solutions like implementing mechanical ventilation systems. In addition, the lack of control over indoor temperature regulation during the winter is another problem in non-renovated buildings.

IV.3 Part B: Influence of transient conditions on thermal comfort evaluations

IV.3.1 Introduction

IV.3.1.1 Overview

Educational facilities constitute a significant proportion of building stock and are accountable for a substantial amount of energy consumption in the country's non-industrial energy usage [267–269]. A significant portion of energy usage is allocated to the operation of HVAC systems and artificial lighting to uphold a satisfactory indoor environmental quality (IEQ) [230]. This aspect is widely recognized for its influence on occupants' physical well-being and cognitive abilities [200, 203, 205]. Research has indicated that students' sensitivity to the IEQ within school buildings can have an impact on their sickness absence rates and overall school performance [9, 207, 208]. The concept of IEQ encompasses several key aspects, which can be categorized into eight basic categories. Of these factors, four are amenable to active monitoring and management: thermal comfort, indoor air quality and ventilation, visual comfort, and auditory comfort [203]. According to a literature review on indoor environmental conditions, it has been observed that building occupants prioritize thermal comfort over visual and auditory comfort, as well as indoor air quality [204].

IV.3.1.2 Brief literature review

The literature extensively discusses and examines the difficulties of thermal comfort standards in classrooms [270–272]. The implementation of established standards [124, 148, 229] in educational facilities continues to pose difficulties as a result of several variables such as different age ranges [273–277], limited comfort adaptation opportunities [278, 279] and different occupant schedule profiles. For instance, university students usually move from one class to another and have different thermal behavior after each study session. Consequently, their thermal perceptions are heavily influenced by the prior ambient [280]. Most sessions last two hours, during which students typically require 10 to 20 minutes to adjust to a new thermal condition [281, 282]. This adaptation period is later referred to as the "transitional period".

The term "transient" has been discussed amongst researchers for years, and it can be summarized as follows:

i) Step change conditions: a transient term that investigates the human response to step changes from non-neutral (outdoor) to neutral (indoor) environmental and vice versa. They

have been observed experimentally in the climate chamber [282–284] using a small number of subjects (usually 10 - 30 healthy students).

ii) Temporarily occupied space (TOS): a transient term that focuses on the neutral zones that are occupied less than 40 minutes [285] such as shopping centers, post offices, bank branches, and fast-food restaurants. This field is evaluated in both climate chamber [285] and field survey [286], [287]. The field studies use a large random number of subjects on the spot upon entering the TOS.

iii) Transitional space: a transient term that focuses on spaces between interior and exterior environments that are not necessarily heated or air-conditioned, such as entrance canopies, foyers, lift lobbies, corridors, stairwells, etc. This group is also evaluated in both chamber experiments [288] and field surveys [289, 290].

Most climate chambers reported in the literature aimed at understanding the human response to the immediate change between two thermally conditioned spaces. Upon adopting this approach, previous papers employed the same experimental principles in study procedures and thermal environment conditions. They usually design two or three adjacent rooms, with the first room mimicking the outdoor temperature and the second room having a comfortable indoor temperature. All rooms are thermally controlled to 50% relative humidity and 0.05 $m.s^{-1}$ airspeed. Subjects usually have uniform clothing of 0.57 clo and they are prevented from having intense physical exercise before the experiment for at least two hours to have the same metabolic rate of 1.1 met. Subjects are asked to stay in the first room between 15 and 30 minutes to acclimate to the constant set-point temperature. At the end of this session, they would fill out the survey form for their thermal evaluation before moving to the second room. Seated in the second room, subjects are asked to refill the survey multiple times from the immediate moment upon entering until a fully adapted period that could last between 60 and 90 minutes. These conditions and procedures would allow an accurate comparison of thermal evaluation between the before and after-changing environments without the influence of other variables.

However, this approach is limited due to the absence of realistic settings in terms of context, human activities, and psychological expectations. Papers adopting a field study approach can overcome this issue by performing the questionnaire survey in actual buildings. However, a large sample size is required to obtain reliable findings due to the highly variable and complex conditions. Random subjects are asked to complete the survey upon entering the investigated space. Without a constraint procedure, usually, the subjects would only participate once in the survey, thus unable to have a direct comparison between the subjects. Instead of analyzing the human response to environmental changes, previous papers with this approach usually aim to evaluate the performance of the PMV model in the dynamic condition in question.

IV.3.1.3 Research goals

Studies in climate chambers indicated a shift of approximately 0.5 scale points in the Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) between the immediate votes upon entering the neutral zone and the adapted votes after staying for more than 20 minutes. Field studies revealed that the PMV model is adaptable to assessing transitional spaces [287]. However, there is currently no field study evaluating thermal perception changes or PMV model performance during the transitional period in a neutral environment.

Therefore, the objective of this part is to close these gaps with the specific aims of:
i) Evaluating the impact of the transitional period on occupants' thermal perceptions;
ii) Evaluating the PMV model in a transient condition;
iii) Investigating the thermal comfort of university buildings under transient and steady conditions.

IV.3.2 Methodology

Table 4-4 shows the variation of outdoor air temperature and relative humidity in the investigated site obtained from meteorological stations from January to August 2023. January had the lowest average temperature at 7°C with 69% humidity. The temperature increased in June, leading to the highest average temperature of 27°C in July. The subjective assessments were conducted in March for winter and June for summer, with the highest and lowest temperatures, respectively.

Statistics	Variable	January	February	March	April	May	June	July	August
min	T_{out} (°C)	-2	-2	0	5	9	14	20	19
	HR_{out} (%)	33	28	22	19	24	22	19	14
mean	T_{out} (°C)	7	8	12	15	19	24	27	26
	HR_{out} (%)	69	67	66	54	59	61	51	47
stdv [a]	T_{out} (°C)	4	5	5	5	4	4	4	6
	HR_{out} (%)	16	19	19	18	19	20	17	18
max	T_{out} (°C)	19	22	23	26	30	35	33	33
	HR_{out} (%)	97	99	99	98	95	95	93	94

Table 4-4. *Statistical summary of meteorological temperature (T_{out}) and relative humidity (HR_{out}) from January to August 2023*

[a] standardeviation.

IV.3.2.1 Survey procedure and assessment

This study conducted subjective assessments in three phases that covered winter and summer. Each phase lasted five consecutive working days, specifically during school hours from 8h00 to 17h00. To avoid teaching disruptions, each group of students was usually surveyed only once (with the teacher's permission) per phase. As a result, some groups were surveyed during the adapting period (between 0 and 15 minutes after entering classrooms), while others were done during the adapted period (between 20 and 35 minutes after entering classrooms).

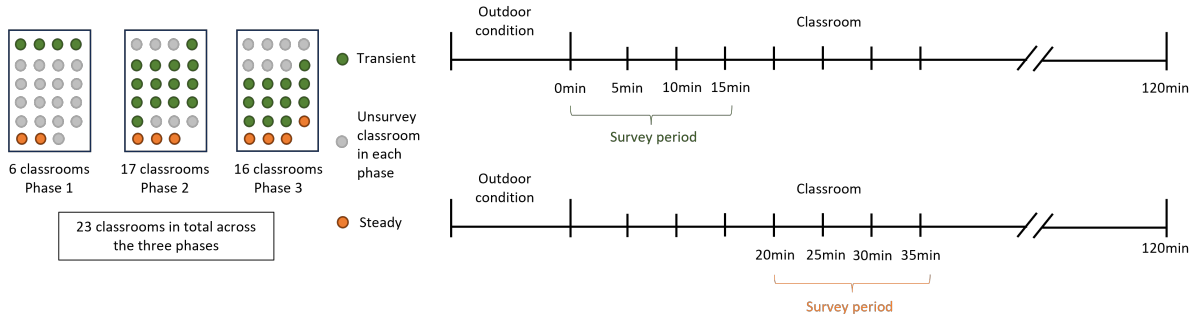


Fig. 4-13. *Survey procedure and information*

To increase the sample size, 23 classrooms in total were selected to allow for the inclusion of rooms of different orientations, sizes, and levels to better represent the overall indoor thermal conditions of the buildings. The survey procedure is summarized in Figure 4-13.

IV.3.2.2 Physical measurements and assumptions

The thermal comfort parameters of the rational model are air temperature (T_a), mean radiant temperature (T_{mr}), relative humidity (HR), air velocity (V_a), metabolic rates (met), and clothing insulation (clo) [128]. This study estimates the metabolic rate, clothing insulation, and air velocity data following the ISO 7730 standard [124]. Thus, the student's clothing is presumed to be 1 clo in winter and 0.5 clo in summer. The metabolic rate is assumed to be 1.2 for sedentary activity. Meanwhile, the air velocities are estimated according to season (0.2 $m.s^{-1}$ in summer and 0.0015 $m.s^{-1}$ in winter) from naturally ventilated air renewal rates in winter and window openings in summer.

The T_{mr} is calculated by a commonly used equation in previous papers [286, 291], which was proposed by Nagano K. and Mochida T. [292] as follows:

$$T_{mr} = 0.99 \cdot T_a - 0.01 \quad (R^2 = 0.99) \tag{IV.1}$$

However, it should be noted that equation IV.1 does not account for the varying radiation fluxes experienced by different seating positions within the room on the south or southeast

(whether exposed or not exposed to solar radiation), particularly during the summer. This limitation has been demonstrated by the research of J. Conejo-Fernández et al. [293] and N. Walikewitz et al. [294]. For a comprehensive understanding, readers should refer to their respective studies.

The ASHRAE 55-2010 standard states that in the majority of real-world scenarios with low relative airspeed or slight variation between mean radiant and air temperature, the operative temperature can also be determined using Equation IV.2.

$$T_{op} = A \cdot T_a + (1 - A) \cdot T_{mr} \tag{IV.2}$$

where T_{op} is the operative temperature and A is weighing factor that depends on air velocity V_a, and is determined as 0.5 for V_a smaller than 0.2 $m.s^{-1}$.

IV.3.3 Results and discussions

IV.3.3.1 Analysis of data collection

Indoor climate

Figure 4-14 presents the boxplot of the indoor environmental variables at the survey moments of the investigated classrooms, including minimum, 25% quantile, mean, 75% quantile, and maximum values. In winter, the average air temperature is 20.5°C, with a minimum of 18.8°C and a maximum of 23.1°C. In summer, the average temperature is 26.3°C, with a variation of 23.0°C at the minimum and 27.6°C at the maximum. The recommended level of

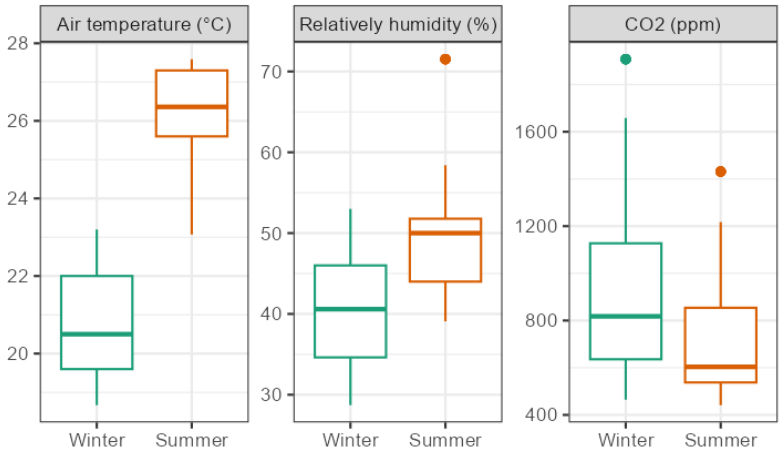


Fig. 4-14. *Boxplot of indoor environmental parameters at the survey moments*

CO_2 for a healthy range is below 1000 ppm in classrooms [229]. During winter, the average

CO_2 level is 800 ppm but often exceeds 1600 ppm, surpassing the recommended value due to the lack of air renewal (windows are closed to conserve heat). When the adaptive strategy of opening windows is practiced in summer, the average CO_2 level is lower compared to winter, with 600 ppm on average. The relative humidity varies from 30% to 53% in winter and from 39% to 58% in summer.

Thermal sensation vote and thermal preference vote

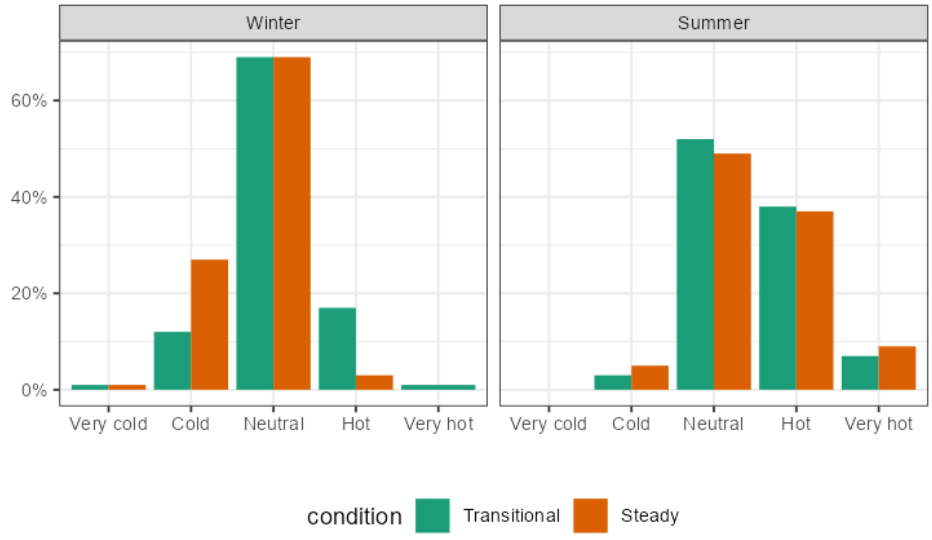
The survey questionnaire adopts two thermal comfort metrics: thermal sensation vote (TSV) and thermal preference vote (TPV).
The scale for TSV is: -3 = very cold, -2 = cold, 0 = neutral, 2 = hot, 3 = very hot
The scale for TPV is: -1 = wanting cooler, 0 = no change, 1 = wanting warmer

A total of 721 valid responses were collected from the three survey phases combined, with 549 responses in the transient condition and 172 responses in the steady condition. Figure 4-15 presents the distribution of thermal sensation votes (panel A) and thermal preference votes (panel B) concerning the season and condition.

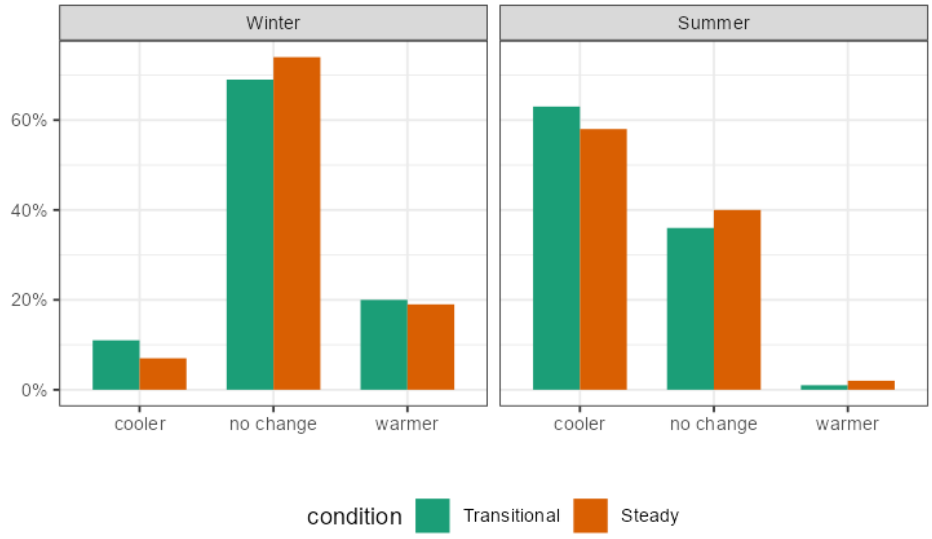
The data from the TSV panel indicates that the majority of votes fall into the "neutral" category, constituting 70% in winter and approximately 50% in summer. This suggests that respondents anticipate a higher level of comfort during the cold season than in the warm season. Notably, there is a disparity in the second-highest vote scale between transient and steady conditions in winter. At the same time, transient conditions evoke a hot sensation, and steady conditions lean towards a cold sensation. This implies variations in temperature across specific classrooms, with some experiencing lower temperatures than expected and others having higher temperatures. Furthermore, the findings suggest a bias among students towards perceiving a hot sensation during transitional periods and a tendency towards a cold sensation after fully adapting to the environment.

During summer, the votes are consistently distributed between the two conditions, with a hot sensation being the second most selected, followed by a very hot vote. This suggests that respondents uniformly lean towards perceiving a hot sensation from the initial moments upon entering the room until the end of class.

Although the distributions of thermal sensation votes usually reflect those of thermal preference votes, a more significant disparity is observed in summer, where the neutral scale is 10% higher than the no change scale. It implies that students are more tolerant of warm environments than cooler ones.



(A) Thermal Sensation Vote



(B) Thermal Preference Vote

Fig. 4-15. *Distribution of survey response in A) thermal sensation vote and B) thermal preference vote*

IV.3.3.2 Observations on temporal changes

This section aims to examine how occupants' responses change over time in neutral rooms during transitional state (the immediate upon arrival) and steady-state (30 minutes after staying). Due to the lack of continuous subjective assessment in the same room, five pairs of classrooms with similar outdoor and indoor conditions were chosen to compare the average TSV and TPV, as outlined in Table 4-5.

Season	pair	n*	condition	Thermal comfort metrics				Condition environmental							
				TSV	ΔTSV	TPV	ΔTPV	T_{in}	ΔT_{in}	HR_{in}	ΔHR_{in}	T_{out}	ΔT_{out}	HR_{out}	ΔHR_{out}
Winter	pair 1	7	Steady	-0.29	0	-0.14	-0.14	23.2	0.2	47	15.26	17	-1	38	-2
		7	Transitional	-0.29		0		23		31.74		18		40	
	pair 2	13	Steady	0	-0.33	0	-0.08	22.4	0.78	45.1	9.88	15	3	81	39
		12	Transitional	0.33		0.08		21.62		35.22		12		42	
	pair 3	37	Steady	0	-0.11	-0.16	-0.16	19.65	0.31	40.59	11.88	10	4	98	35
		18	Transitional	0.11		0		19.34		28.71		6		63	
Summer	pair 4	6	Steady	0.42	-0.33	0.5	-0.12	25.6	0.01	58.4	12.1	23	0	68	17
		23	Transitional	0.75		0.62		25.59		46.3		23		51	
	pair 5	15	Steady	1.13	-0.16	0.67	-0.21	27.4	2.07	50	-0.31	26	3	41	-11
		17	Transitional	1.29		0.88		25.33		50.31		23		52	

* total number of respondents.

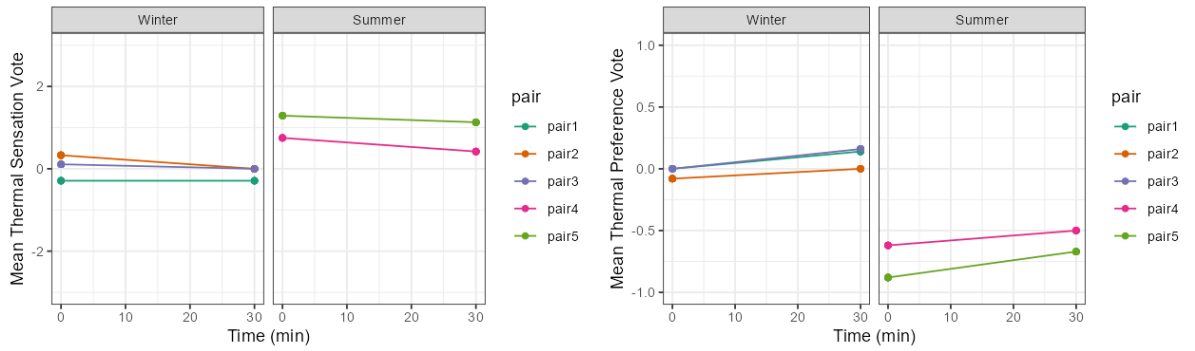
Table 4-5. *The overall thermal votes and thermal condition of the investigated pairs of classrooms*

Based on studies carried out in climate chambers, where the indoor environment is fully controllable while maintaining a consistent neutral temperature of 26°C and relative humidity of 50%, the neutral temperature in actual classroom settings experiences notable variations influenced by outdoor temperatures. Furthermore, indoor air temperatures within classrooms exhibit non-uniformity over time, signifying that fluctuations in temperature may occur between the adaptation period and the steady period, attributed to internal and external factors.

When directly comparing the mean votes between the two conditions, their differences (ΔTSV, ΔTPV) consistently remain below 0.5 scale points across the two metrics. Figure 4-16 illustrates the changes in votes for TSV (panel A) and TPV (panel B) between the 0-minute and 30-minute. In winter, the votes closely align with the neutral scales (0) in TSV and the no-change scales (0) in TPV. On the other hand, in summer, the votes lean towards the warmer scales (1) in TSV and the cooler scales (between -1 and 0) in TPV.

During winter, the indoor temperature consistently exceeds the outdoor temperature, with the maximum difference reaching 13.34°C and the minimum being 5°C, maintaining the indoor temperature within the comfort range. Consequently, the votes predominantly align with the neutral range, indicative of winter comfort. In contrast, during the summer, the classroom temperatures are around 25.5°C, approximately 2.5°C higher than the outdoor temperature. This leads to votes expressing discomfort in warm conditions.

Previous climate chambers research [284, 285, 288, 295, 296] mostly looked at how people reacted to the sudden change when they moved from the non-neutral zone to the neutral zone. While these studies did consider the temporal changes in TSV from the immediate step-change to the steady state, this aspect is not extensively discussed. Therefore, this section undertakes a comparison between the TSV of the field study and the observed TSV in climate chambers as reported in the mentioned papers, spanning from the 0-minute upon entering the neutral zone to the fully adapted period, shown in Figure 4-17.



(A) Mean Thermal Sensation Vote (B) Mean Thermal Preference Vote

Fig. 4-16. *Temporal change in A) Mean Thermal Sensation Vote and B) Mean Thermal Preference Vote*

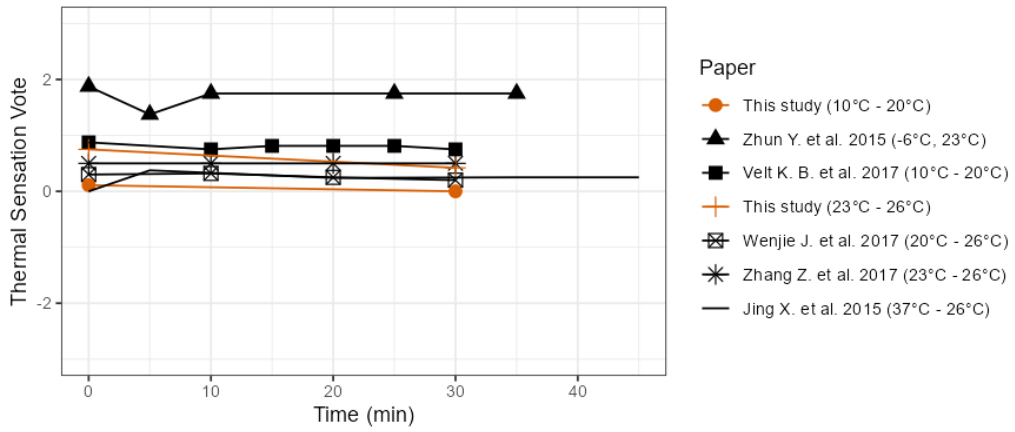


Fig. 4-17. *Comparison of temporal changes in a neutral environment between this study and prior climate chamber research from the immediate period after entering the zone until the fully adapted period*

As depicted in this figure, the findings from the field survey align with those derived from climate chamber studies such as Zhun Y et al. in 2015 [285], Velt K. B. et al. in 2017 [284], Wenjie J. et al. in 2017 [295], Zhang Z. et al. in 2017 [288], and Jing X. et al. in 2015 [296]. This alignment underscores two key observations: firstly, the time required to attain a thermal sensation steady state is less than 10 minutes, and secondly, the ΔTSV between the transitional state and the steady state remains below 0.5 scale points. Notably, the study by Zhun Y. et al. [285] stands out in this figure, exhibiting the most significant change between 0 and 5 minutes. This divergence is attributed to their study having the most substantial temperature differences, influencing the time needed to achieve a steady thermal sensation.

IV.3.3.3 Comfortable temperatures in school building during the investigated period

Neutral temperature

The neutral temperature can be derived from a linear regression that correlates ASHRAE scale votes with operative temperature [297], as shown in Figure 4-18.

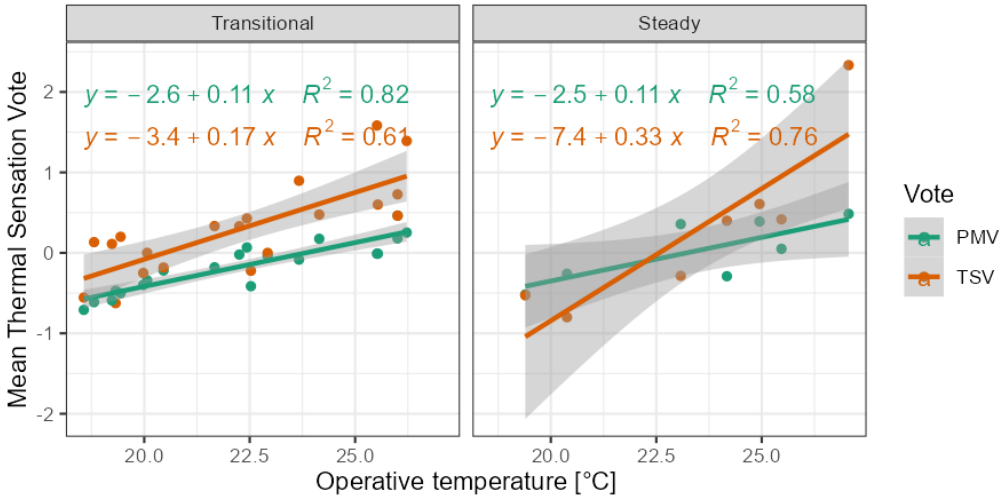


Fig. 4-18. *Proposed regression lines as a function of mean thermal sensation vote and operative temperature for transitional and steady states*

The relationships between TSV and T_{op} of both seasons combined under transitional and steady states were:

$$Transitional: \ TSV = -3.4 + 0.17 \cdot T_{op} \quad (R^2 = 0.61) \tag{IV.3}$$

$$Steady: TSV = -7.4 + 0.33 \cdot T_{op} \quad (R^2 = 0.76) \tag{IV.4}$$

According to Equations IV.3 and IV.4, the neutral temperatures for transitional and steady states were 20°C and 22.4°C, respectively, when the TSV equaled 0. For buildings under similar conditions, F. R. d'Ambrosio Alfano et al. [298] reported values of comfort temperature at 20°C. The linear regression line slope of the transitional TSV was lower than the steady TSV, suggesting that the TSV index exhibited reduced sensitivity to indoor air temperature changes. This phenomenon may be attributed to the influence of external temperature on respondents who promptly complete their survey upon arrival, as the outdoor temperature tends to be either lower or higher than the indoor temperature, depending on the season. According to Ji et al., [299], when people encounter an environment moderately warmer than the previous one they came from, even though it is still cold, their immediate thermal perception may improve because their previous thermal experience was more unpleasant and colder. However, as they continue to acclimate to the environment, their perception tends to align with the actual conditions in a

steady state. This misjudgment could cause a difference in comfort temperature between transient and steady conditions.

Preferred temperature

The preferred temperature refers to the point at which occupants neither seek a cooler nor a warmer environment. It is an essential metric for thermal comfort, impacting energy usage by directly influencing the energy power of heaters or air conditioners to achieve their desired temperature. This temperature was determined using a probit regression model on the TSV, as illustrated in Figure 4-19.

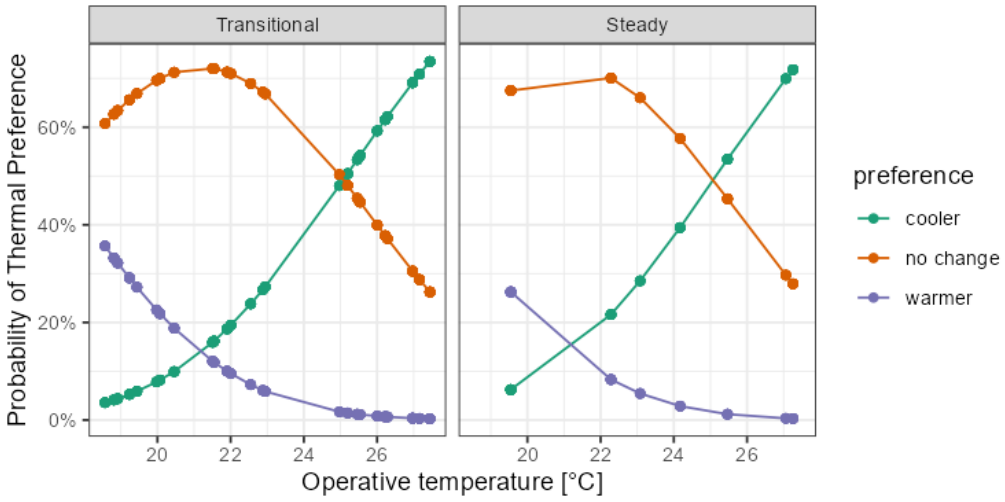


Fig. 4-19. *Probability of thermal preference in relation to operative temperature obtained by the probit regression model for transitional and steady states)*

The optimal temperature is determined by the intersection of preference curves for wanting warmer (formed by subjects voting very cold, cold, and cool) and wanting cooler (formed by subjects voting very hot, hot, and warm), resulting in a value of 21.2°C for both states. It indicates that the preferred temperature does not change over time, reflecting that occupants can fully acclimate to the environment at any instant upon entering the neutral zone.

The neutral temperature is 1.2°C lower than the preferred temperature during transient conditions, yet 1.2°C higher than the preferred temperature in steady conditions, highlighting how respondents perceive and respond to the neutral temperature under different conditions. For instance, in the transient state, students may adapt more readily to lower temperatures, perhaps from a perception that cooler temperatures are more tolerable during the transitioning period, but they expect a higher temperature. Conversely, in the steady state where data collection may have been biased towards warmer temperatures, respondents' perception of neutral temperature seems to correlate with that environment despite their preference for cooler temperatures. This

suggests that students can tolerate a broader range of temperatures, although those were not their preferred temperatures in both conditions.

IV.3.3.4 Evaluation of PMV model

To conduct a comparative analysis of thermal sensation, the data acquired from surveys (TSV) and the calculated predicted mean vote (PMV) are examined against the operative temperature as presented in Figure 4-20.

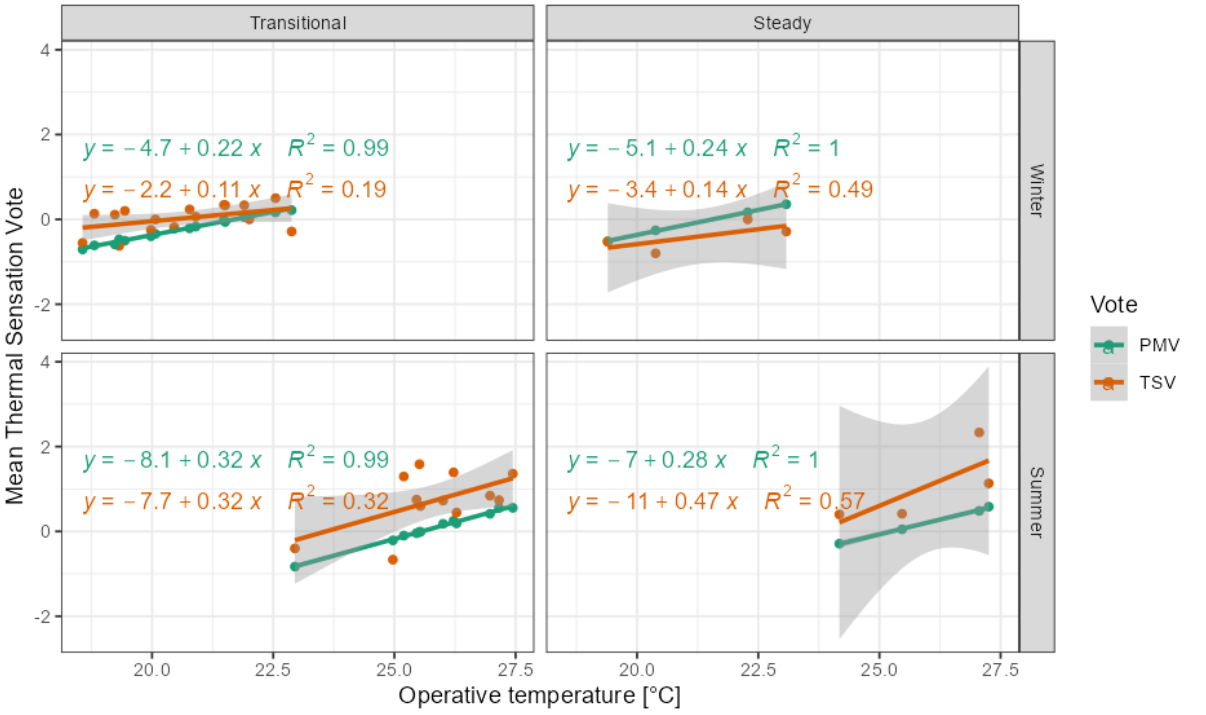


Fig. 4-20. *Mean TSV and PMV in relation to operative temperature (regression model was weighted by the number of votes falling into each of the temperature bins on the x-axis). The shaded area represents the standard deviation of TSV data points*

In both seasons, the PMV index consistently underestimates the TSV, aligning with findings from previous studies by P. Aparicio-Ruiz et al. [273] and S. T. Mors et al. [274], which reinforce the that PMV model tends to predict cooler sensations than the actual votes. Additionally, it is observed that the regression lines of the PMV and TSV models exhibit a closer alignment during the transitional phase than the steady state. As students transition from the non-neutral zone to the neutral zone, they become more satisfied with the current indoor condition, likely due to the contrast with the previously unsatisfactory environment. However, after the adaptation period, students appeared to judge their indoor thermal environment with more attention.

However, this result differs from what Yu-Chi W. and Ardeshir M. found in a climate chamber study [281]. In that study, the PMV values were more closely related to the TSV expressed by thermally adapted participants than non-adapted participants. In their research, participants underwent a series of spatial transitions, spending a minimum of 15 minutes in a sedentary state in one room before moving to another. The seven-scale survey questionnaire was administered twice: immediately after the transition and once again after a 15-minute adaptation period.

The calculation of PMV in this study is composed of many assumptions, such as clothing insulation, metabolism, and indoor environmental data measured (T_{in}, HR_{in}) or evaluated (T_{mr}), or estimated (airspeed). Figure 4-21 illustrates various scenarios of PMV's parameters compared to the default PMV model, which utilizes the basic assumptions. Each scenario exhibits a shift in regression lines, showing changes in the PMV model as a function of the operative temperature.

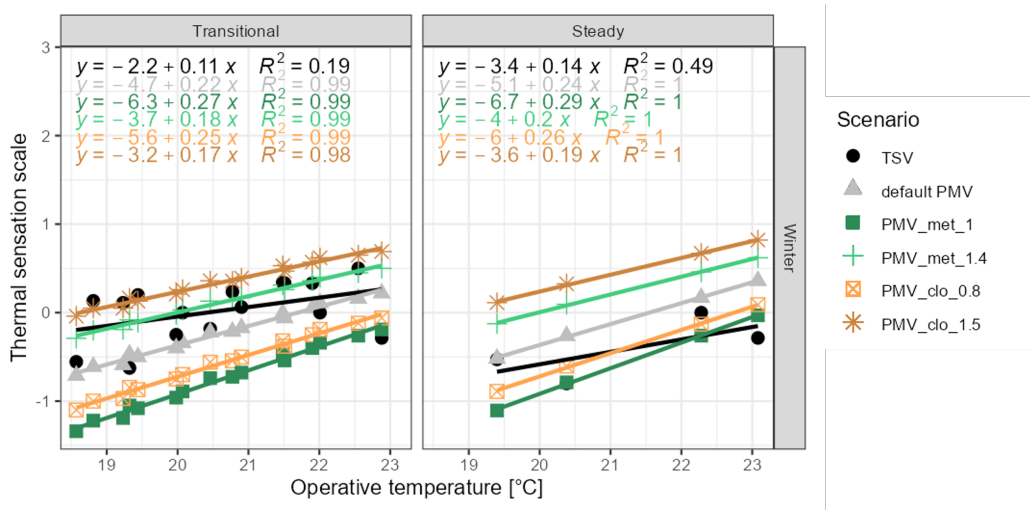
During winter, there is a notable difference in students' clothing, ranging from those wearing heavy layers to those in lighter clothing. The study incorporates two scenarios: clothing insulation equals 0.8 clo and 1.5 clo (refer to Figure 4-21A). The variation in clothing insulation from 1 clo (default model) to 1.5 clo leads to an increase of 0.8 thermal sensation scale points. Conversely, a shift from 1 clo to 0.8 clo results in a decrease of approximately 0.4 thermal sensation scale points.

All students wear light clothing during the summer, but the airspeed parameter can influence the PMV assessment. Figure 4-21B introduces air speeds of 0.1 $m.s^{-1}$ and 0.0015 $m.s^{-1}$, displaying a shift from the default model of approximately 0.3 scale points. However, there is a minimal difference between 0.1 $m.s^{-1}$ and 0.0015 $m.s^{-1}$, indicating a weaker influence on the PMV model compared to clothing insulation.

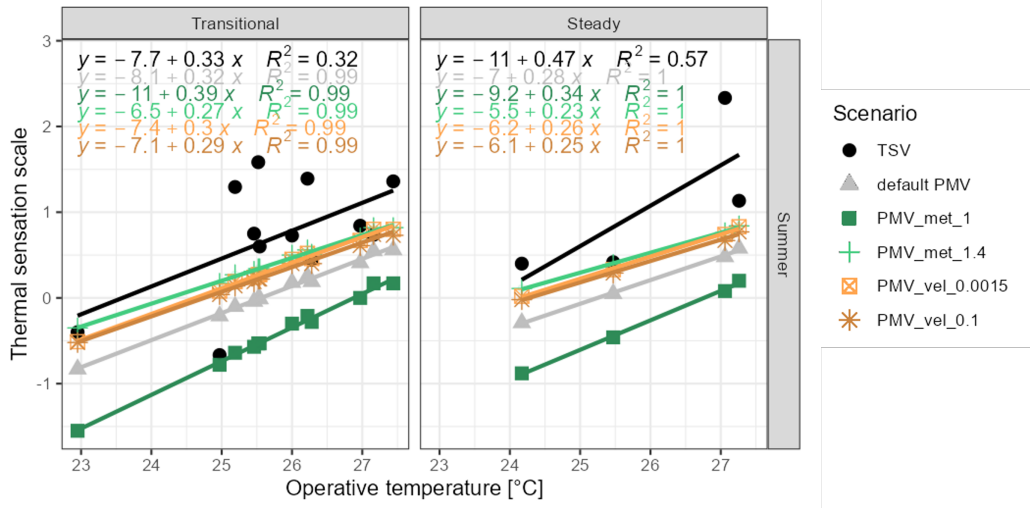
In Figure 4-20, a noticeable discrepancy between TSV and PMV models exists in both the transitional and steady states. Nevertheless, looking at different scenarios involving PMV parameters (Figure 4-21) reveals that accuracy can be improved by incorporating clothing and metabolism details and additional air velocity sensors close to occupants. This prompts the question regarding the significance of the steady or transient state in the PMV model.

IV.3.4 Conclusion

The research described in this section aims to evaluate the efficiency of field surveys conducted during transient conditions in assessing indoor thermal comfort. The study was conducted on university buildings in a Mediterranean climate during the winter and summer. The primary conclusions can be summarized as follows:



(A) Winter



(B) Summer

Fig. 4-21. *Scenarios parameters variation in PMV calculation of A) winter and B) summer*

- This field study aligns with the results of the climate chamber, showing that the thermal sensation takes less than 10 minutes to reach a steady state. The variation between the immediate step-change TSV and the steady-state TSV in a neutral environment is less than 0.5 scale points.

- Following the analysis of the investigated periods, the neutral temperature of the university buildings is 20°C in transient conditions and 21.5°C in steady conditions. Nevertheless, the preferred temperatures for both conditions are 21.2°C, suggesting that students tend to change their neutral temperature over time, yet their preferred temperature remains constant.

- Discrepancies exist between the TSV and the PMV index, where the PMV model generally underestimates TSV in both the transitional and steady states. However, the variation

between the two models is potentially caused by the assumed PMV's parameter values.

Undoubtedly, this study possesses certain limitations. Owing to the absence of actual measured data for rational and adaptive models, the analysis heavily relies on assumptions related to variables like airspeed, metabolic rate, clothing insulation, and radiant temperature. Reducing these assumptions would enhance the robustness of the results. Additionally, this study seeks to extrapolate findings from laboratory-based research to real-world buildings. Nonetheless, real-scale buildings consist of many uncontrollable factors, such as activities and outdoor and indoor environments, that impact respondents' thermal comfort. Furthermore, the study was conducted in 23 different classrooms under different thermal conditions, making the TSV change transitional and fully adapted periods not readily applicable to different case studies.

In future research, particular attention should be directed towards critical variables like clothing insulation and metabolism and other environmental parameters such as mean radiant temperature and operative temperature. Additionally, questionnaire surveys should be conducted using controlled participant groups in uniform room settings and conditions while maintaining a substantial number of surveyed rooms to represent the building accurately.

IV.4 Part C: Occupant satisfaction with thermal comfort and air quality in renovated buildings

IV.4.1 Introduction

Previous literature in the context of building renovation has shown statistical results that refurbished buildings are prone to have more positive perceptions of user satisfaction on IEQ compared to conventional buildings. For example, Abdul-Manan S. and Mohamed H. I. [300] conducted a survey targeting teachers to investigate the relationship between building renovations and occupants' well-being across psychological, social, and physical aspects. This study involved a numerical statistical comparison of satisfaction levels across various IEQ factors, including lighting, ventilation, thermal comfort, acoustics, and privacy. The author's analysis revealed statistically significant differences in teachers' satisfaction with IEQ factors between newly renovated and non-renovated schools. Additionally, the factors of ventilation and thermal comfort exhibited the most substantial statistical differences compared to other factors. Similarly, a study focusing on teachers' perceptions [301] also employed posthoc test statistics to compare user satisfaction across the four IEQ factors in existing, renovated, and green buildings. The statistical analysis indicated that teachers in green schools generally expressed the highest satisfaction with their classrooms, followed by those in renovated schools.

More comprehensive studies to achieve this objective often involve comparing quantitative and qualitative aspects. For instance, Almeida and De Freitas (2014) [246] observed that non-retrofitted buildings fail to provide adequate comfort and IAQ conditions, primarily due to cold indoor air temperatures averaging 14.6°C and low ventilation rates. In 2017, Antonio M.-M. et al. [302] conducted a post-occupancy evaluation survey involving teachers and pupils in a historic primary school in Spain. The findings highlighted differences in subjective opinions between students and teachers. Specifically, 32% of students, as opposed to 77% of teachers, reported a sensation of thermal neutrality, while 61% of students, compared to 92% of teachers, found the indoor thermal conditions acceptable. This suggests that children have a higher and more challenging threshold for achieving indoor thermal comfort.

Another field study conducted in a partially renovated building under year-round weather conditions [11] revealed a seasonal fluctuation in PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfaction), with data occasionally falling outside the recommended comfort range. This indicates a higher level of dissatisfaction in certain areas with regard to indoor thermal conditions. For example, during the winter, respondents reported slightly warm conditions in some zones, which may be attributed to occasional overheating of spaces. Conversely, during the summer, respondents expressed satisfaction with cooler temperatures.

A study carried out in Southeast Portugal [201] concentrated on thermal comfort in renovated buildings, examining aspects such as thermal acceptability, thermal sensation, and thermal preference. The findings indicated that, during mid-season, an average of 95% of students considered the temperature range acceptable within their comfort zone. The study also concluded that students prefer a slightly warm, neutral temperature. Students in five conventional buildings were surveyed in a separate survey conducted by Running Y. et al. [303]. The results showed that during winter, most responses leaned towards a slightly cool and humid sensation, while in summer, the most common response indicated a feeling of warmth and dryness.

In the context of investigations on seasonal variations, Michele Z. et al. [247] conducted a comprehensive study spanning five years to examine the impact of retrofitting on a school building. The findings indicate a varied perception of thermal comfort with respect to the time of year. During the winter season, individuals experience a shift in their perception of temperature from warm to cool. Additionally, following a refurbishment, there is a fall in the level of thermal acceptability expressed by users, declining from 77% to 69%. During the summer, the perceived warmth experienced by participants decreased from 86% prior to the renovation to 61% following the renovation. This reduction aligns with the corresponding improvement in thermal acceptability, which rose from 71% to 87%. The perception of air quality has significantly improved in both seasons, confirming the good effects of ventilation systems paired with natural ventilation.

Pre-renovation versus post-renovation refers to studies that surveyed the IEQ satisfaction of the same occupants before and after a renovation intervention. The advantage of these studies is their ability to determine the specific effect of IEQ-related renovations due to their use of the same group of respondents in their pre- and post-research design [304].

Despite the importance of each IEQ factor contributing to the individual and overall comfort of occupants, the main discussions in this part concern thermal environment and air quality aspects, which are directly associated with the renovation strategy applied to the investigated buildings. This study aims to document the correlation between students' perception of temperature, relative humidity, and CO_2 levels after a refurbishment compared to the previous condition—consequently, the analysis and discussion mostly center on students' subjective evaluation and related physical metrics. The primary aims of this part are:
i) Assess the influence of retrofitting on users' comfort on sensation and acceptability scales;
ii) Identify the root causes of under-performance in IEQ following the renovation;
iii) Determine the optimal conditions while considering seasonal variations.

IV.4.2 Refurbishment measures

Out of five buildings within the campus, two buildings, GEII and GC, were renovated in 2021 and 2022, respectively. Thermal inertia is a fundamental parameter whose increase improves comfort conditions and promotes energy efficiency in buildings [305]. Therefore, the focal point of this case study's refurbishment measures is upgrading the building envelope to increase thermal resistance and integrating mechanical single-flux ventilation to reduce heat loss through openings. The main thermal characteristics of the building envelope for the existing and renovated building and their associations with IEQ impacts are listed in Table 4-6. Mechanical ventilation rates remain low (as natural ventilation) but are better controlled to ensure the minimum healthy airflow rate. It operates continuously during the occupied period.

Element		**Materials**		**U-value** ($W.m^2.K^1$)		**Expected impact on IEQ**
		Before	**After**	**Before**	**After**	
Floor		Concrete	Unchanged	3.08	3.08	-
Roof	Teaching	Concrete + polyurethane foam 40 mm	Unchanged	0.51	0.51	-
	Workshop	Concrete + mineral wool 120 mm	Unchanged	0.25	0.25	-
Wall		Hallow brick	Hallow brick + rock wool insulation 120mm	3.52	0.27	- Minimize thermal loss of building envelope to avoid rapid fluctuations in indoor air temperature level - Increase building airtightness
Window		Single-glazed / Double-glazed	Double-glazed argon 16mm + Overhang on the south	3.6	1.5	
Building information				**Program**		-
Ventilation	Teaching	Natural (0.5 vol/h)	Mechanical extract ventilation (0.23 vol/h)	Permanent	6h00-20h00	- Enhance air quality and comfort
	Workshop		Air blower			
Central heating system	Teaching	District heating + Convection heater	District heating + Radiator + Thermostat control	7h00 - 18h00	7h00 - 18h00	- Improve heating control so the comfort temperature is better maintained
	Workshop	District heating + Air heater	Unchanged			

Table 4-6. *Thermal properties of the building envelope and short description of ventilation and heating systems before and after renovation*

Following the renovation, the heating systems are also improved by installing and regulating heat exchangers in the sub-station beneath each building. Therefore, the comfort temperature after renovation is expected to increase with the reduction in energy consumption. The district heating network supplies the IUT via four substations located in the basement of the four buildings. Before the renovation, the network supplied GMP, then GC, then two other buildings, and finally GEII. Historically, the GMP building has repeatedly overheated, and the GEII building has a heating fault with insufficient temperatures. Renovation of the buildings and heating networks should improve the regulation of energy distribution between buildings and significantly reduce their consumption.

IV.4.3 Methodology

In this section, the analysis focuses solely on the classrooms in the teaching section, as detailed in Table 4-6, as this section underwent complete renovation measures, including upgraded windows, external wall insulation, and mechanical ventilation. As a result, 758 valid responses were collected from 27 classrooms. Table 4-7 summarizes the questionnaire responses in terms of study phases and building states correspondingly. Due to the odd number of survey phases, the data collected in winter is more significant than in summer, both pre- and post-renovation states. Therefore, the visual comparison is done based on percentages of difference, while the analyses are done through Mann-Whitney U test statistics. Moreover, room availability differs from one studied phase to another, contributing to the measured data range discrepancy.

Building state during the survey periods			
Survey periods	**Season**	**Surveyed building**	**Building State**
17/02/2022 - 23/02/2022 (phase 1)	Winter	GC	Before
06/03/2023 - 15/03/2023 (phase 2)	Winter	GEII, GC	After
		GMP	Before
16/06/2023 - 21/06/2023 (phase 3)	Summer	GEII, GC	After
		GMP	Before
Vote counts			
State	**Season**	**Vote count**	**Total vote**
Before	Winter	361	448
	Summer	87	
After	Winter	175	310
	Summer	135	

Table 4-7. *Summary of vote counts from classrooms*

The questionnaire assesses the occupants' sensation, acceptability, and preference regarding the indoor environment, encompassing factors like temperature, humidity, air movement, and environmental odor, as outlined in Table 4-8. In the sensation category, a "0" signifies the preferred state, which could be neutral, correct, or no smell, depending on the question type. This study's Thermal Sensation Vote (TSV) scale comprises five points, adapted from the seven-point scale defined in the ASHRAE standard [123]. On the other hand, the acceptability vote scale is consistent across each criterion, with two-point scales, acceptable and unacceptable, the most commonly used scale in previous papers [201].

Scale	Sensation vote				Acceptability vote				Preference vote
	Temperature	Humidity	Air movement	Indoor odor	Temperature	Humidity	Air movement	Indoor odor	Temperature
3	very hot	very humid	very strong	strong smell	-				-
2	hot	humid	strong	weak smell					
1	neutral	neutral	correct	no smell	acceptable				warmer
0				-	-				no change
-1					unacceptable				cooler
-2	cold	dry	weak		-				-
-3	very cold	very dry	immobile						

Table 4-8. *Scales of sensation and acceptability votes*

IV.4.4 Results and discussions

IV.4.4.1 Indoor and outdoor environment measurements

The thermal environment is assessed using the indoor air temperature (T_{in}) and relative humidity (HR_{in}) parameters, as indicated by previous studies [123, 306], while the CO_2 level is employed for evaluating indoor air quality [307].

Table 4-9 provides a summary of external temperature and indoor climate parameters (temperature, relative humidity, and CO_2) during the survey periods. The outdoor temperatures are 12±4°C, 10±5°C, and 25±4°C for Phase 1, phase 2, and Phase 3, respectively. The table reveals that, on average, the temperature in the renovated building is 1°C lower than that in the non-renovated building, observed in both winter (phase 2) and summer (phase 3).

Statistics	State	Phase 1				Phase 2				Phase 3			
		T_{out}	T_{in}	HR_{in}	CO_2	T_{out}	T_{in}	HR_{in}	CO_2	T_{out}	T_{in}	HR_{in}	CO_2
minimum	Before	2	16	23	270	0	18	23	375	18	25	35	361
	After		-				15	24	210		22	31	375
mean	Before	12	19	40	514	10	21	40	773	25	26	52	469
	After		-				20	41	594		25	55	460
maximum	Before	22	24	54	1322	23	25	62	4012	33	29	68	2697
	After		-				25	63	2446		31	73	2214
standard deviation	Before	4	1	7	169	5	1	8	473	4	1	7	179
	After		-				1	9	279		2	9	133

Table 4-9. *Summary statistics of outdoor and indoor environmental conditions*

In summer (phase 3), the CO_2 concentration of the two building states is roughly the same, at 460 ppm on average and more or less 2400 ppm maximum. Although the average values of CO_2 levels in winter (phase 2) of the two states are comparable (773 ppm and 594 ppm for non-renovated and renovated buildings, respectively), the difference in their maximum values is evident. The CO_2 is approximately at 4000 ppm before renovation, twice higher than after renovation, showing a concern CO_2 range, as the recommended healthy CO_2 is to be less

than 1000 ppm [123]. However, when comparing the CO_2 level of the before state in phase 1 with phase 2, it is of phase 1 was significantly lower than phase 2. Phase 1's CO_2 level before renovation was also lower than phase 2's CO_2 after renovation. Notably, the data before the renovation of Phase 1 and Phase 2 comes from GC and GMP buildings, respectively. This explains that the GMP building, in particular, has a problem with air renewal and that the GC building, after renovation, has poorer air renewal than the previous state.

IV.4.4.2 Thermal comfort

Thermal sensation votes

Figure 4-22 illustrates the distribution of thermal sensation votes (panel A) and humidity sensation votes (panel B), correlating them with the building states and seasons. Analyzing the TSV votes (Figure 4-22A), the neutral percentage in winter stands at approximately 80%, surpassing that of summer by 30%. This discrepancy suggests that occupants of IUT de Nîmes buildings exhibit higher thermal satisfaction in a cold environment compared to a warm one. This observation aligns with the mean TSV values, specifically -0.01 for winter and 0.93 for summer, affirming the preference for cooler conditions during winter.

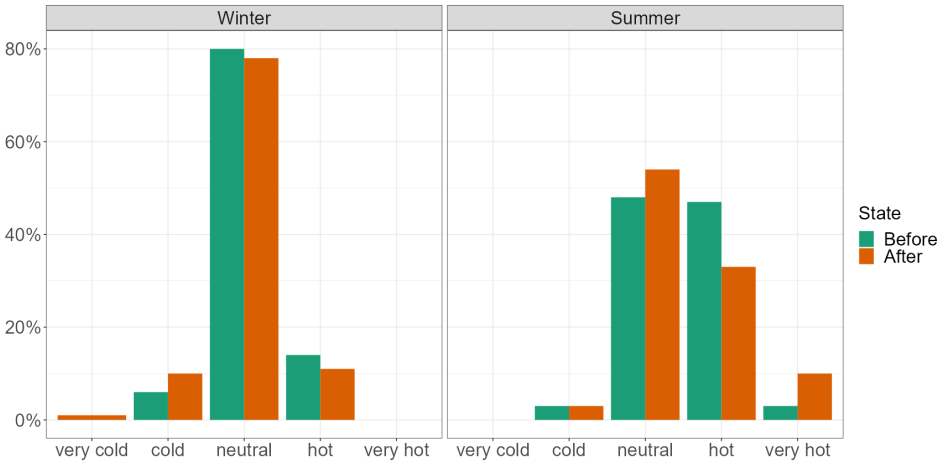
When comparing the discomfort votes percentages (very cold, cold, hot, and very hot) of the after with those of the before renovation, the votes are visually different, especially during summer for the hot category, which reduced by 10%, and the very hot category, which increased by 8%. This implies that the hot discomfort worsened following the renovation from a hot category to a very hot one.

Figure 4-22B shows that most HSV votes are neutral for both seasons, with approximately 80% in winter, which is 10% higher than in summer. In contrast to TSV, the distribution of HSV votes demonstrates consistency across seasons and states, indicating that respondents are less responsive to changes in relative humidity compared to indoor temperature.

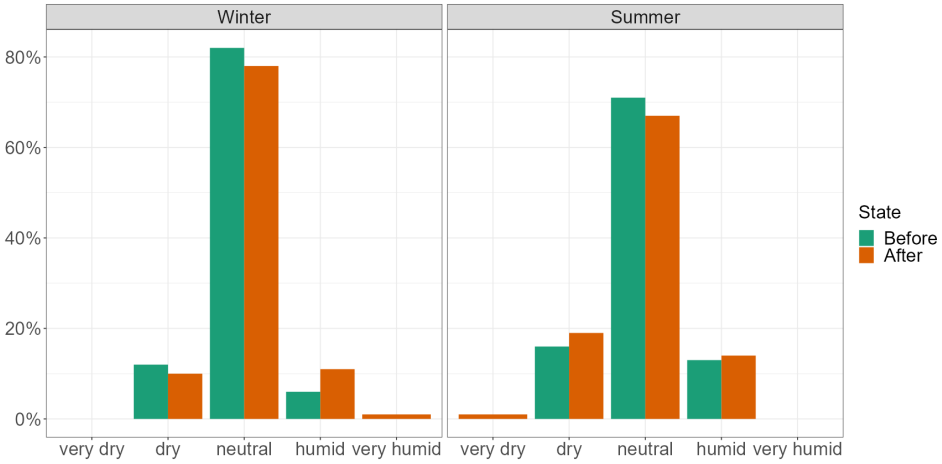
Validation through rational model

To conduct a comparative analysis of thermal sensation, the data acquired from surveys (TSV) and the calculated predicted mean vote (PMV) are examined as a function of operative temperature (T_{op}), illustrated in Figure 4-23.

The proposed regression lines of the Predicted Mean Vote (PMV) and Thermal Sensation Vote (TSV) concerning building states and seasons reveal that in winter, their progressions in relation to the operative temperature are closely aligned. However, during summer, a more pronounced gap emerges between the two models, both before and after renovation. This outcome suggests that the PMV model effectively estimates occupants' sensations in mild winter



(A) Thermal sensation vote



(B) Humidity sensation vote

Fig. 4-22. *Distribution of survey response in terms of (A) thermal sensation vote and (B) humidity sensation vote*

conditions, where temperatures range between 18°C to 22.5°C. Conversely, in highly elevated summer temperatures exceeding 25°C, the PMV model tends to predict a colder sensation than the actual experience, indicating an overestimation of occupants' warm tolerance.

As per the regression equations depicted in each panel of Figure 4-23, the neutral temperatures for the PMV during winter are determined to be 21.8°C and 21°C before and after renovation, respectively. Simultaneously, the neutral temperatures for the TSV during winter are 21°C and 20.5°C in the corresponding order. Moving to the summer season, the neutral temperatures for PMV are 26°C and 25.6°C before and after renovation, respectively, while for TSV, they are 24°C for both building states.

In summary, the neutral temperature deduced from the PMV always overestimates that

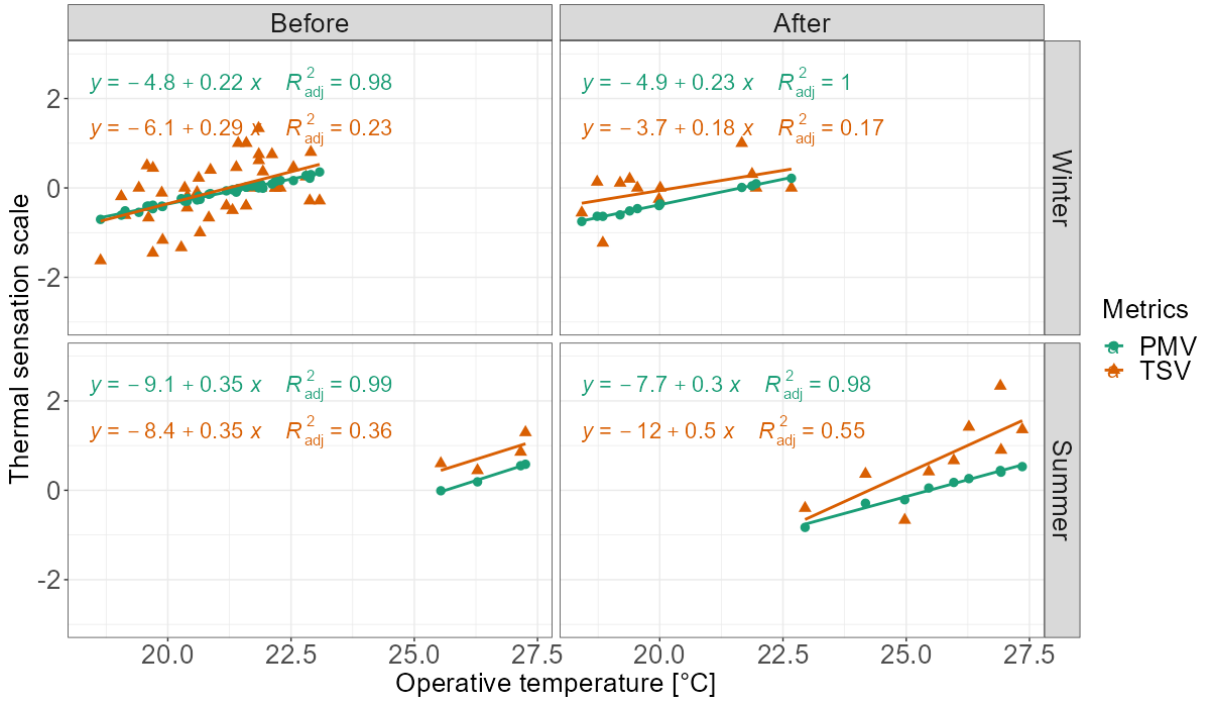


Fig. 4-23. *Thermal sensation votes versus predicted mean vote*

deduced from the TSV. However, this overestimate is small in winter but appears more prominent in summer. One potential explanation for this discrepancy is the acclimatization of individuals to warmer surroundings, a phenomenon significantly influenced by the outdoor temperature. The PMV model, however, fails to incorporate this aspect accurately. It is important to note that the average outdoor temperature during the survey moments was 27 ±2.7°C, closely aligning with the indoor temperature of 26 ±1°C. The minimal difference between the outdoor and indoor temperatures results in students not perceiving a noticeable cooling effect, thus expressing a persistent sensation of hot through their voting.

Upon comparing the temperature values post-renovation, the variance in the neutral temperature of TSV is less than 0.5°C in winter and 0.7°C in summer. These results show that the renovation has a negligible impact on the calculated (PMV) and the actual (TSV) comfort temperatures.

Validation through adaptive model

To establish a direct comparison between the field study and the standards EN 15251 [148] and ASHRAE Standard-55 [123], the designated comfort temperature is considered the operative temperature. These standards encompass thermal comfort models dependent on outdoor temperatures but are defined in distinct ways. Specifically, the EN15251 standard integrates a running mean outdoor air temperature from the preceding seven days (T_{rm}), as deter-

mined by the application of Equation IV.5.

$$T_{rm} = (T_{rm_1} + 0.8T_{rm_2} + 0.6T_{rm_3} + 0.5T_{rm_4} + 0.4T_{rm_5} + 0.3T_{rm_6} + 0.2T_{rm_7})/3.8 \quad \text{(IV.5)}$$

where
T_{rm} is the running mean temperature of the day (°C)
T_{rm_i} is the daily average outdoor air temperature of the ith preceding day (°C)

The ASHRAE standard utilizes the monthly mean outdoor air temperature (T_{om}), calculated as the average daily outdoor air temperature across all days within each month [123]. The daily outdoor temperature in both calculations is obtained from meteorological data.

Figure 4-24 presents a scatter plot depicting the recommended comfort zone analysis between T_{op} and outdoor temperature in two states, following the EN15251 Standard (Panel A) and the ASHRAE Standard (Panel B). The gray lines signify the comfort temperature determined by established criteria, while the segmented black lines represent the comfort zone limits defined by international standards. From an energy perspective, it is beneficial to remain within the lower range of the comfort zone, which facilitates energy consumption reduction.

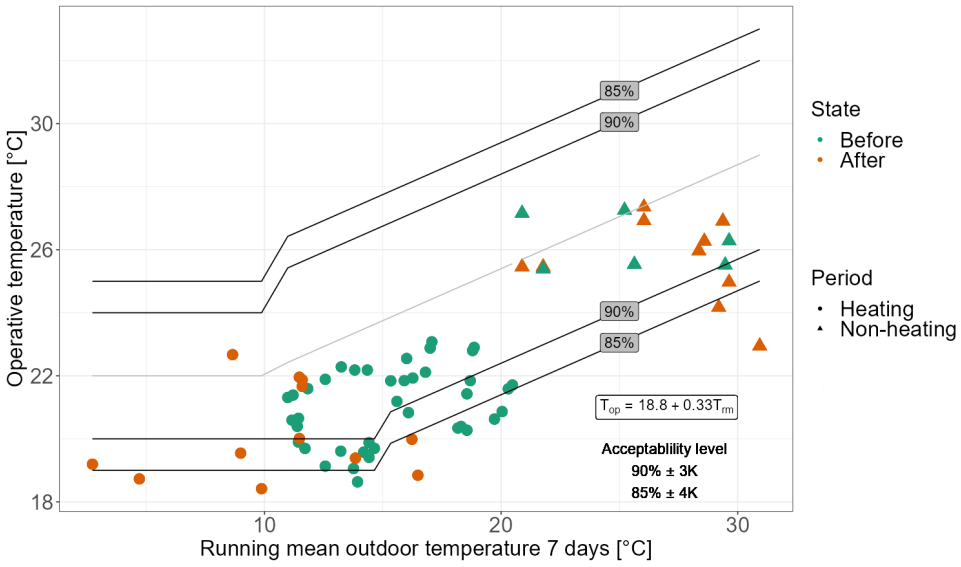
It should be noted that according to the EN 15251 standard, the 85% limits are applicable to non-renovated buildings, while the 90% limits apply to renovated buildings. As depicted in Figure 4-24A, in non-renovated buildings, only 15% and 0% of points fall outside the comfort zone during heating and non-heating periods, respectively, based on the 85% limits. In contrast, in renovated buildings, 58% and 30% of points fall outside the comfort zone during heating and non-heating periods, respectively, based on the 90% limits. The result shows that the EN 15251 standard is more rigorous for renovated buildings and appears excessive in relation to the students' votes, as nearly 80% of them perceived the thermal environment of the classrooms as neutral (Figure 4-23A).

According to the ASHRAE standard, no data points deviate beyond the 90% limits, which is defined as -0.5 $<$ PMV $<$ 0.5, with the exception of the heating period post-renovation, where it exceeds the lower limits by 25%. In comparison to the EN 15251 standard, the ASHRAE standard yields more favorable outcomes in evaluating thermal comfort in buildings.

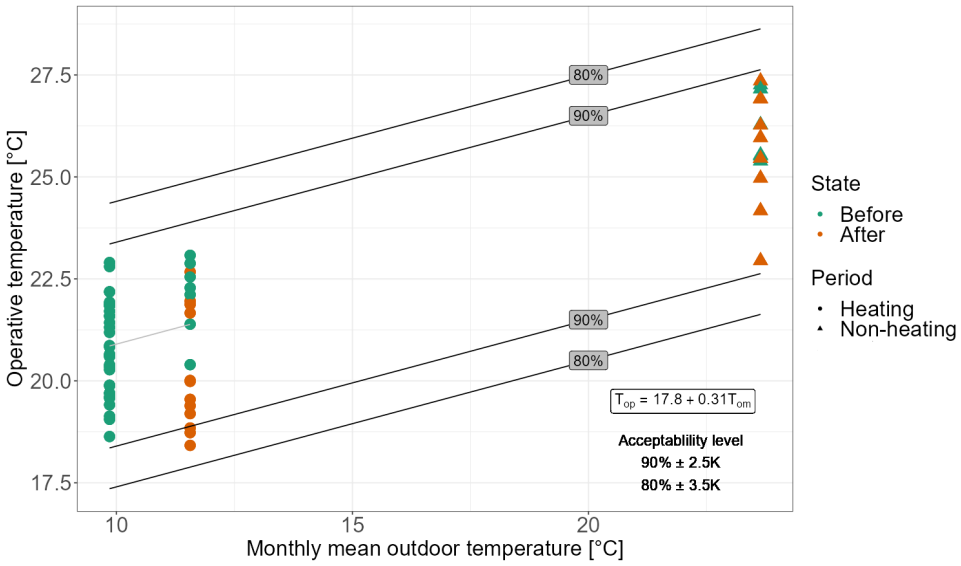
The results from both adaptive standards indicate that the post-renovated building exhibits poorer conformity to the comfort limit zone than the pre-renovated building. However, the ASHRAE model needs more adequate data points to validate the comfort temperature, as only three main points are available.

Thermal acceptability votes

Figure 4-25 illustrates a comparative analysis of thermal and humidity acceptability



(A) EN 15251 standard



(B) ASHRAE standard

Fig. 4-24. *Operative temperatures and adaptive assessment methods: (A) EN 15251 standard, and (B) ASHRAE standard*

votes' distribution derived from the acceptable category (TAV = +1 and HSV = +1). Notably, the alterations in the percentage of HSV votes are minimal in winter and summer, while TVS exhibits a noticeable increase of approximately 10%. Another noteworthy observation is that no acceptability votes change in post-renovation and remain consistently above 80%. This suggests that the acceptability metric, used to assess thermal comfort, is more forgiving than the sensation metric, particularly during summer.

Comparing different thermal comfort metrics

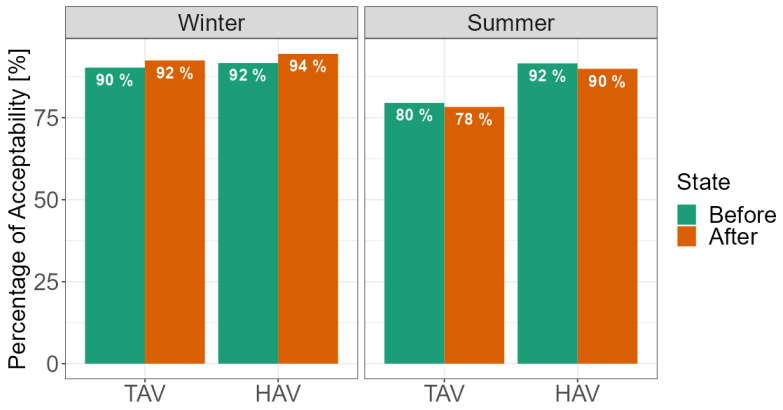


Fig. 4-25. *Percentage of acceptability from the acceptability sacle of temperature and humidity*

The thermal acceptability metric can be determined using the TSV method. When the value reaches a state of neutrality, it is presumed that the acceptability is deemed acceptable. Figure 4-26 presents a comparative analysis of the several approaches utilized for evaluating thermal comfort. When considering the middle three categories of the ASHRAE scale concerning the concepts of acceptability and preference, more than 80% of respondents perceive their classroom temperature as neutral. The thermal preference scale is more inclusive and diverse than the other options, which forces people to choose.

McIntyre [308] suggested that the neutral temperature, deemed acceptable by 80% of individuals, represents the desired temperature. However, in each state, the highest level of thermal satisfaction is achieved using the TAV scale (84% and 86% in before and after renovation, respectively), followed by the TSV scale with 61% and 69% for before and after renovation, respectively. Conversely, the thermal preference scale proves to be the most stringent metric for thermal satisfaction, as fewer than 60% of participants express a preference for "no change." This aligns with previous research indicating that the thermal preference scale consistently has a lower proportion compared to other scales [262, 278].

The comparison of scales underscores the apparent divergence in outcomes when assessing thermal sensation, particularly between thermal acceptance and thermal preference. This disparity is attributed to the flexibility inherent in different scale points. Individuals choosing extreme categories on the TSV scale may still perceive their thermal conditions as acceptable, even if these conditions do not align with their true preferences.

As a result, when evaluating the thermal comfort of respondents following the renovation, the TSV is shown to be the most significant discrepancy level compared to the other two metrics. Based on this metric, it is evident that 8% of respondents were more in neutral temperature after the renovation than before.

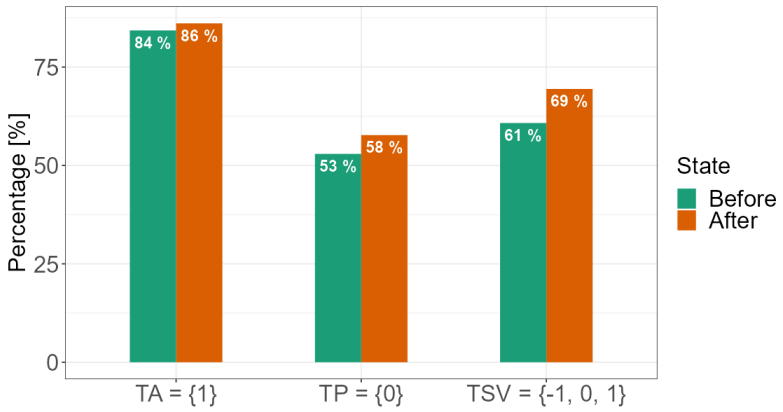


Fig. 4-26. *Percentage of acceptability from the acceptability sacle of temperature*

IV.4.4.3 Indoor air quality

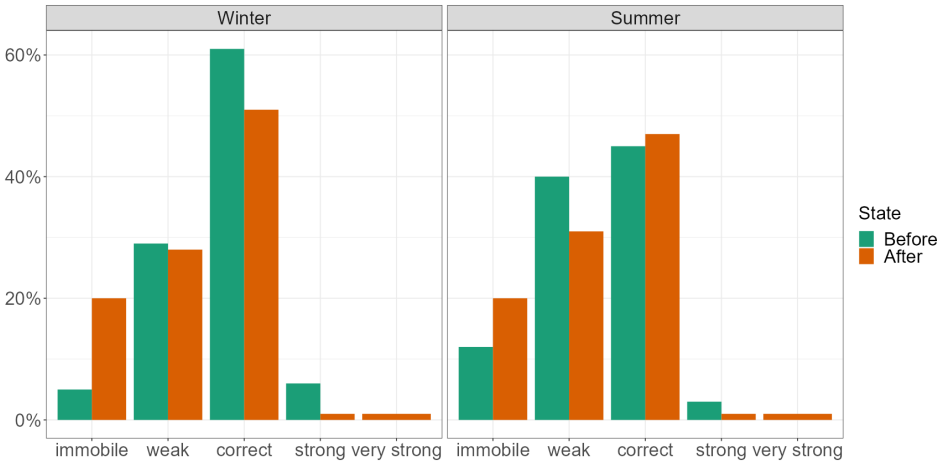
Air quality sensation votes

Figure 4-27 presents sensation votes for air movement (panel A) and environmental odor (panel B) to evaluate the CO_2 level in pre- and post-renovation buildings. The mechanical ventilation system supports natural ventilation throughout the occupied period in the renovated buildings. The CO_2 concentration profile before and after renovation was 400–1300 ppm and 415–1800 ppm during winter, 400–1000 ppm, and 400–1500 ppm during summer. The extreme CO_2 levels worsen due to the renovation strategy. This is further affirmed by the distribution of winter votes in panel A, where participants' sensation in the "correct" category reduced from 60% to 52%, and the "immobile" category increased from 5% to 20%.

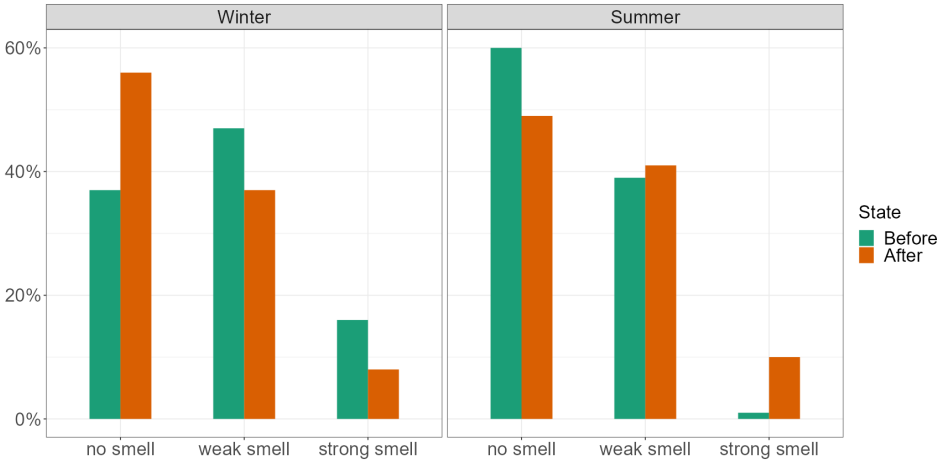
In the pre-renovation state, the windows and shutters (metallic) in the south were mainly closed in summer to prevent heat radiation. After renovation, the metallic shutters were replaced with PVC shutters, and sun protectors were installed. Consequently, renovated buildings allow students to open the windows more often for air exchange, leading to a more favorable air movement sensation, as shown in Panel A. On the contrary, Panel B illustrates an increase in "no smell" votes by 20% in winter, suggesting the opposite in terms of air movement. However, it is essential to note that this criterion, environmental odor, is influenced by factors such as classroom equipment and occupants' odors, in addition to air stuffiness caused by elevated CO_2 levels. Therefore, these criteria alone may be less accurate in evaluating a good or bad CO_2 concentration.

Air quality acceptability votes

Figure 4-28 presents the acceptability votes for air movement and environmental odor before and after renovation. Overall, the majority of respondents can accept the air movement



(A) Air-movement sensation vote



(B) Environmental-odor sensation vote

Fig. 4-27. *Distribution of survey response in terms of (A) air movement sensation vote and (B) environmental odor sensation vote*

and environmental odor in both seasons and both building states. However, a notable concern arises with the AAV (Acceptability of Air Velocity) in summer, where less than 80% of occupants are satisfied, indicating a need to increase the air exchange rate. Surprisingly, the intended improvement in the mechanical ventilation system to better control the airflow rate appears to have performed inversely, as more respondents are dissatisfied with it after renovation.

This issue prompted a detailed investigation into the CO_2 levels under three different functional modes of the ventilation system, as illustrated in Figure 4-29. The "natural ventilation" phase represents the studied period of CO_2 levels in non-renovated buildings, which, during that time, relied solely on natural ventilation. It is noteworthy that the design values of airflow rates for GC and GEII buildings are 3600 $m^3.h^{-1}$ and 2700 $m^3.h^{-1}$, respectively (equiv-

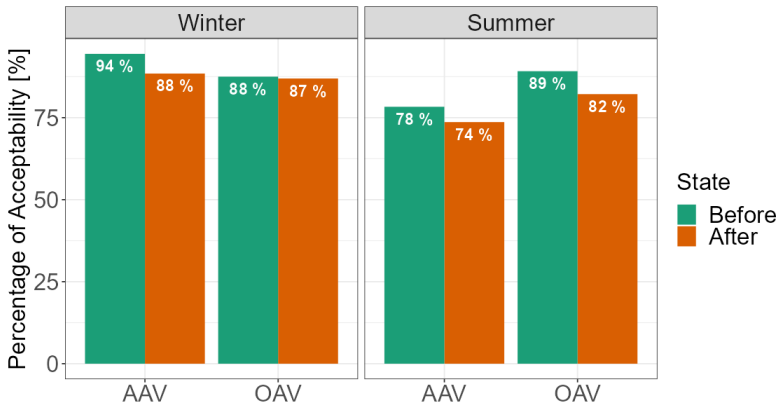


Fig. 4-28. *Percentage of acceptability from the acceptability scale of odor and air movement*

alent to 18 $m^3.h^{-1}$ per person) for maintaining healthy and comfortable indoor air quality.

However, ventilation tests conducted in the two buildings revealed that the ventilation system performed correctly in the GEII building following the renovation, providing an airflow rate of approximately 2800 $m^3.h^{-1}$, denoted as "Full ventilation". Conversely, the ventilation system in the GC building was found to be faulty following the renovation, delivering only 1800 $m^3.h^{-1}$, represented by "Half ventilation". Furthermore, the ventilation system in the GC building ceased operation entirely in the later months of 2023, depicted as "No ventilation".

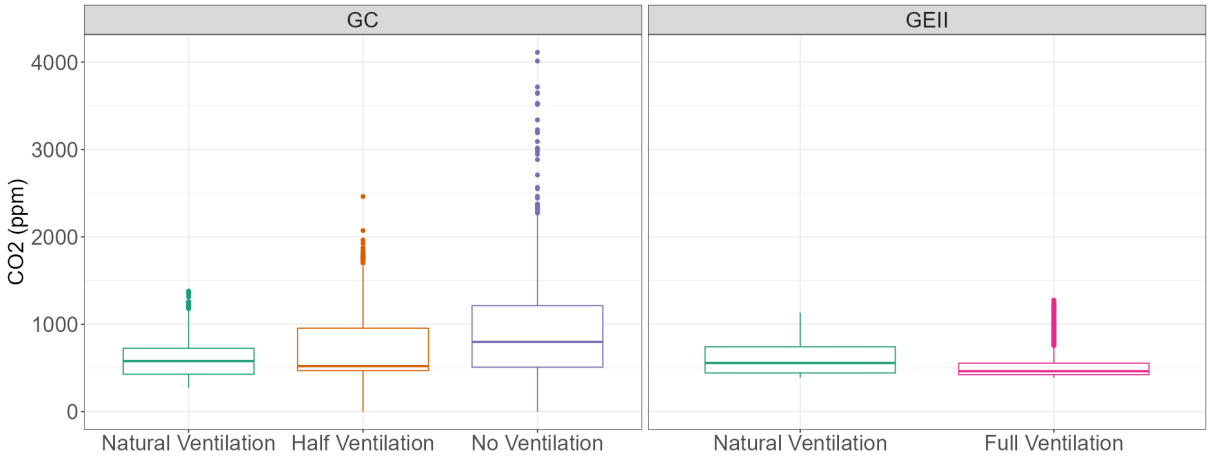


Fig. 4-29. *Comparing the CO_2 level concerning operation modes of ventilation of GC and GEII buildings during school hours (8h00 to 18h00) over five working days (Monday to Friday) during the winter season*

Natural ventilation: typical natural ventilation rate before the renovation
Half ventilation: faulty ventilation system in renovated GC building that provides a ventilation rate of approximately 1800 $m^3.h^{-1}$ over 3600 $m^3.h^{-1}$
No ventilation: When the ventilation system ceased operating entirely in the renovated GC building
Full ventilation: correct ventilation rate in renovated GEII building as the designed value, approximately 2800 $m^3.h^{-1}$ over 2700 $m^3.h^{-1}$

This figure demonstrates that the typical flow rates of naturally ventilated buildings (GC

and GEII) fall within the same range, averaging around 600 ppm with a maximum of 1100 ppm. In the half-ventilation mode, CO_2 concentrations average 500 ppm, with a maximum of 1000 ppm. However, in the no-ventilation mode, CO_2 levels increase significantly to an average of 850 ppm and a maximum of 2250 ppm. Moreover, the extreme values in the no-ventilation scenario reach up to 4000 ppm, 60% higher than they are in the half-ventilation mode (2500 ppm) and 167% higher than they are in the natural ventilation (1500 ppm). This suggests that when the ventilation system ceases during occupied periods, CO_2 levels can reach dangerous concentrations harmful to occupants' health in the renovated building. Conversely, when the ventilation system operates correctly, as observed in the full-ventilation mode, average and maximum values remain around 500 ppm, lower than those in the natural ventilation setting.

IV.4.5 Stratum level differences of investigated IEQ factors

The acquired subjective data underwent normality testing to determine the appropriateness of parametric tests for their analysis. Based on the results of the Shapiro-Wilk test, it can be concluded that the data set analyzed in this study does not exhibit a normal distribution. In order to examine the relationship between participants' votes and the pre- and post-renovation periods, researchers commonly use either the Mann-Whitney U test or the Wilcoxon Rank-Sum test. These statistical tests are suitable for comparing two independent groups of non-parametric data [309]. This test is used for comparing two categorical groups, especially for dealing with satisfaction surveys [300, 301, 306]. The results are given in Table 4-10. The effect size statistics obtained from the Mann-Whitney test offer insights into how one group demonstrates higher-ranked data than another. This study's effect size is computed using the *wilcox_effsize* method [310]. This method provides a quantitative measure of the probability that a value from one group is more significant than another. According to RStudio's interpretation of effsize scores, they fall into the following categories: 0.10 - $<$ 0.3 (small effect), 0.30 - $<$ 0.5 (moderate effect), and $>=$ 0.5 (large effect).

		Sensation vote			**Acceptability vote**		
		p-value	**p.signif**	**effsize**	**p-value**	**p.signif**	**effsize**
Thermal environement	Temperature	0.02	**	0.08 (small)	0.01	**	0.09 (small)
	Humidity	0.54		0.02 (small)	0.31		0.03 (small)
Air quality	Air movement	0	***	0.25 (small)	0	***	0.10 (small)
	Odor	0.59		0.02 (small)	0.32		0.04 (small)

Table 4-10. *Mann Whitney test statistics of participants' thermal environment and air quality votes in terms of sensation and acceptability before and after renovation*

According to the results presented in Table 4-10, the Mann-Whitney test reveals significant differences in temperature votes (TSV and TAV) as well as air movement votes (ASV

and AAV) between before and after renovation, with p-values lower than 0.05. This outcome implies that students' perceived comfort and acceptability in the renovated building differ from that in the non-renovated building. It underscores the substantial impact of energy-efficient renovations on students' reactions to the indoor environment.

Nevertheless, it is crucial to note that the effect size scores, which quantify the magnitude of observed differences in respondents' votes between renovated and non-renovated states, are relatively small. This suggests that while statistically significant differences exist, these changes may be subtle, discernible primarily to experts, and may not be readily perceptible by the general occupants.

IV.4.6 Conclusion

This study investigated students' perception and acceptability of Indoor Environmental Quality (IEQ) in both renovated and non-renovated school buildings. The two main results can be summarized as the following:

i) Perceived Comfort in IUT de Nîmes Buildings:

- During winter, the neutral vote percentage reaches approximately 80%, indicating a higher level of thermal satisfaction in colder environments than warmer ones.

- The PMV model effectively estimates sensations in mild winter (18°C to 22.5°C). However, in elevated summer temperatures exceeding 25°C, the model tends to predict a colder sensation than experienced, suggesting a potential overestimation of occupants' warm tolerance.

ii) Impact of Energy-Efficient Renovation on Student Comfort Votes:

- There is an 8% increase in thermal discomfort votes during summer, indicating a worsening of hot discomfort from the hot to the very hot category following the renovation.

- According to the PMV fitted model, the neutral temperatures in winter slightly decrease from 21.8°C (pre-renovation) to 21°C (post-renovation). Similarly, the neutral temperatures in summer decrease from 26°C (pre-renovation) to 25.6°C (post-renovation).

- Following the EN 15251 standard's comfort zone criteria ($-0.5 < \text{PMV} < 0.5$), 50% and 16% of data points in heating and non-heating periods, respectively, indicate discomfort before the renovation. These values increase to 58% and 30%, respectively, after the renovation. According to the ASHRAE standard, none of the data points fall out of the comfort zone, except for the heating period after renovation, which exceeds the limits by 25%.

- The Mann-Whitney test found statistical significance in the perceived and acceptable temperature and air-draft between the two states, indicating the impact of energy-efficient reno-

vation on respondents' votes. However, these changes are minimal and may only be noticeable to experts.

Overall, the results reveal higher thermal satisfaction in colder environments during winter. While influencing thermal discomfort and neutral temperatures, the energy-efficient renovations result in subtle changes, primarily discernible to experts. The study underscores the necessity for a comprehensive grasp of IEQ factors, particularly within building renovations, to guarantee that improvements align with occupants' comfort expectations.

Chapter V

Energy

"All sorts of things can happen when you're open to new ideas and playing around with things"

— STEPHANIE KWOLEK

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V.1 Introduction

This chapter conducts a comprehensive analysis and discusses energy consumption at IUT de Nîmes to evaluate the buildings' energy performance before and after the site's renovation. The analysis focuses on reviewing historical records of electricity and heating energy consumption, as documented in the energy bills from EDF and NIMERGIE companies. By examining these consumption patterns, the study aims to gain insights into the overall energy dynamics and assess the impact of the COVID-19 pandemic on energy reduction. Furthermore, the chapter includes an estimation of the heat demand for each building using the degree-day method, followed by a comparison with the measured heat demand.

V.2 IUT de Nîmes

V.2.1 IUT de Nîmes building information

The electricity network serves IUT de Nîmes via a single delivery point for the entire site and its uses. The site has a single Green Rate A5 subscription, Average Use, at the EDF-regulated rate. Regarding heating, the IUT de Nîmes campus is linked to the Nîmes heating network (CU de Nîmes-NIMERGIE) through a single substation (101 IUT) situated north of the site.

As outlined in Chapter 2, the campus comprises five main buildings (see Table 5-1). In addition, there is a small housing building adjacent to the campus, and its energy consumption is monitored using the same energy meter as the campus. To gain a comprehensive understanding of the overall energy consumption of the entire campus, it is essential to know the nature of each building and its activities.

The BC building is composed of three sections. The western part features two levels organized around a patio, primarily housing administrative offices, meeting rooms, classrooms, and a library. On the eastern side, there are three levels dedicated to classrooms. The northern side includes two lecture halls. This building has various office equipment, including 40 desktop computers, 10 printing machines, one local server, 100 classroom desktops, and 10 video projectors.

The GMP building consists of two sections. The southern section has two levels, which mainly accommodate classrooms and offices. This section has 18 office desktops, 5 printing machines, one local server, 160 classroom desktops, and 18 video projectors. The northern side has one level, mainly used for technical practice (TP) rooms and workshop halls equipped with heavy mechanical machines specific to the specialty taught. Due to significant uncertainty regarding their energy consumption, an inventory of these machines is not conducted, and their

Building	Full name	Year of construction	Surface area (m2)			Floor level	Total floor height (m)	Principal activities
			Teaching	Atelier	Total			
BC	Building central - Administration	1969	-		5509	3	7.8	Office - Teaching
GMP/SGM	Mechanical engineering	1968	3804	3490	7294	2	5.2	Teaching - Atelier
GC	Civil Engineering	1969	3102	2568	5670	2	5.2	Teaching - Atelier
GEII	Electrical Engineering and Industrial Computing	1968	1752	2527	4279	2	5.2	Teaching - Atelier
GEA	Management Companies and Administration	1998	-		1547	2	5.2	Office - Teaching
Housing		1969	-		627	1	2.6	Residential

Table 5-1. *Building description summary*

energy usage is estimated at a flat rate.

Similar to the GMP building, the GC and GEII buildings comprise two sections. The northern sides feature two levels primarily dedicated to classrooms and offices. The southern sides have one level, host TP rooms, and workshop halls with various mechanical machines installed specific to the specialty taught. The GC building has 15 office desktops, 6 printing machines, 15 video projectors, one local server, and 130 classroom desktops. Meanwhile, the GEII building features 7 office desktops, 4 printing machines, 95 classroom desktops, and 12 video projectors.

The GEA building comprises an amphitheater and classrooms on the ground floor. The upper floor features an office area and a few classrooms. The entire layout is organized around a spacious hall open on both levels. This building has 10 office desktops, one local server, 25 classroom desktops, and 5 video projectors.

V.2.2 Important timeline of IUT de Nîmes campus

Figure 5-1 summarizes the critical events, including the COVID-19 pandemic and renovation periods, in IUT de Nîmes from 2020 to 2023 that impact energy usage. Following the global outbreak of COVID-19, IUT de Nîmes follows the confinement measures set by the French health environment to avoid physical classes from mid-March to mid-June 2020. This pandemic-induced period results in a notable decrease in energy consumption, as elaborated in Section V.3.4. A similar impact on energy consumption is anticipated during the second COVID lockdown, extending from early November 2020 to mid-January 2021, due to limited in-person activities and reduced occupancy.

Between May and October 2021, the GEII building underwent an energy-efficient reno-

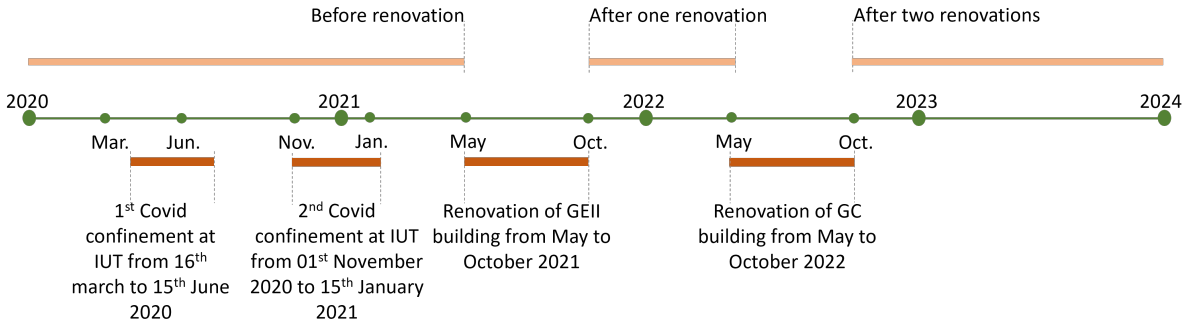


Fig. 5-1. *Timeline of IUT de Nîmes campus related to COVID-19 lockdowns and renovation projects that impacted energy usage*

vation, as detailed in Chapter 2, Section 2.3. During the renovation period, the indoor climate data for this building may not accurately represent typical thermal conditions, given that the building was practically vacant with windows left permanently open. The same scenario occurred for the GC building between May and October 2022, where the ongoing renovation activities affected the indoor climate data.

The post-renovation phase, from October 2022 to the present day, marks a period of potential energy optimization both at the whole campus and individual building levels.

V.3 Assessment and analysis of energy consumption

V.3.1 Electrical energy consumption

V.3.1.1 History of electricity consumption

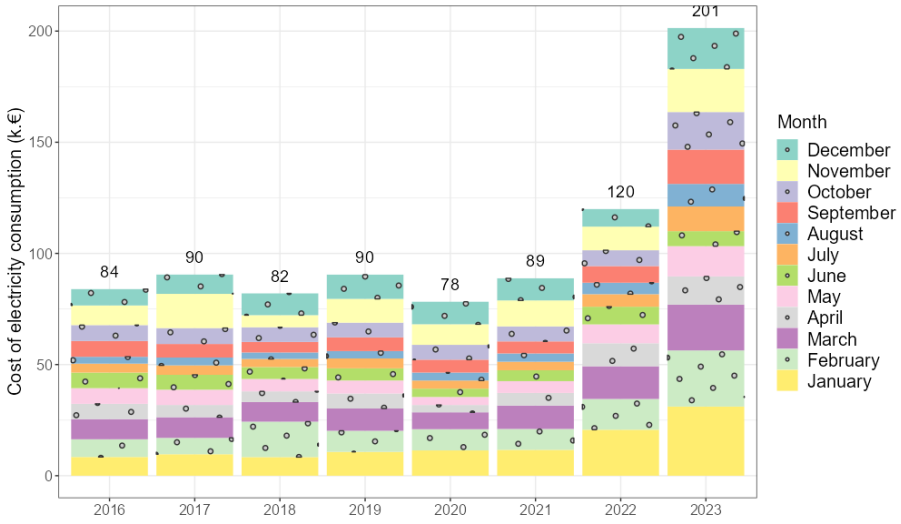
EDF monthly electric bills comprehensively summarize key parameters, providing detailed electricity usage and associated costs (refer to Appendix D.1 for a full detail of the electric bill). Figure 5-2 depicts the global electricity consumption based on the EDF records, summarized from 2016 to 2023 in megawatt-hours (MWh) for panel A and kilo.euro TTC (k€) for panel B.

Except for 2023 and the pandemic-affected year of 2020, it is apparent that the annual electricity consumption of the IUT de Nîmes campus falls within the range of 600 MWh to 700 MWh. The monthly consumption during academic periods (September to July) remains relatively consistent, averaging around 60 MWh monthly. Conversely, electricity consumption is typically reduced by half over the summer break from July to August.

In recent years, electricity consumption costs have experienced a significant increase.



(A) Electricity quantity



(B) Electricity cost

Fig. 5-2. *Monthly electrical energy consumption for years 2016 - 2023 (A) quantity and (B) cost*

While the typical cost from 2016 to 2021 (excluding 2020) stands approximately at €130/MWh, it rises to €176/MWh in 2022 and further increases to €372/MWh in 2023. EDF reports that "the price of electricity in €/MWh on the European wholesale electricity market surged in 2021. Specifically, after 2022, the price of electricity doubles, surpassing the symbolic €400/MWh mark in December 2021 for the first time in its history. In 2022, the price of electricity remained exceptionally high, reaching over €1100/MWh at the end of August" [311].

V.3.1.2 Electricity consumption before and after renovation

Figure 5-3 compares both the electricity consumption in 2022 (after the renovation of the GEII building) and in 2023 (after the renovation of the GEII and GC building) with electricity consumption on average before the renovation (2016–2019).

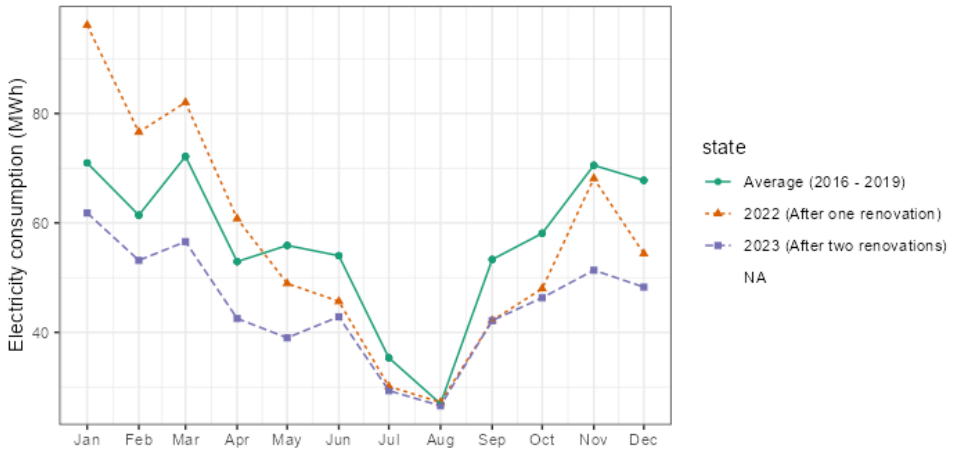


Fig. 5-3. *Comparison of monthly electricity consumption of IUT de Nîmes campus between the pre-renovation and post-renovation years*

In examining the monthly electricity consumption patterns, a consistent trend emerges: generally, electricity consumption after the renovation falls behind that observed before the completion of the renovation projects. An exception to this pattern is noticeable from January to April, where electricity consumption in 2022 stands out as significantly higher. Furthermore, a distinct gap is apparent when comparing the consumption of 2023 with the other two, suggesting the effectiveness of the two renovation projects in reducing overall electricity consumption.

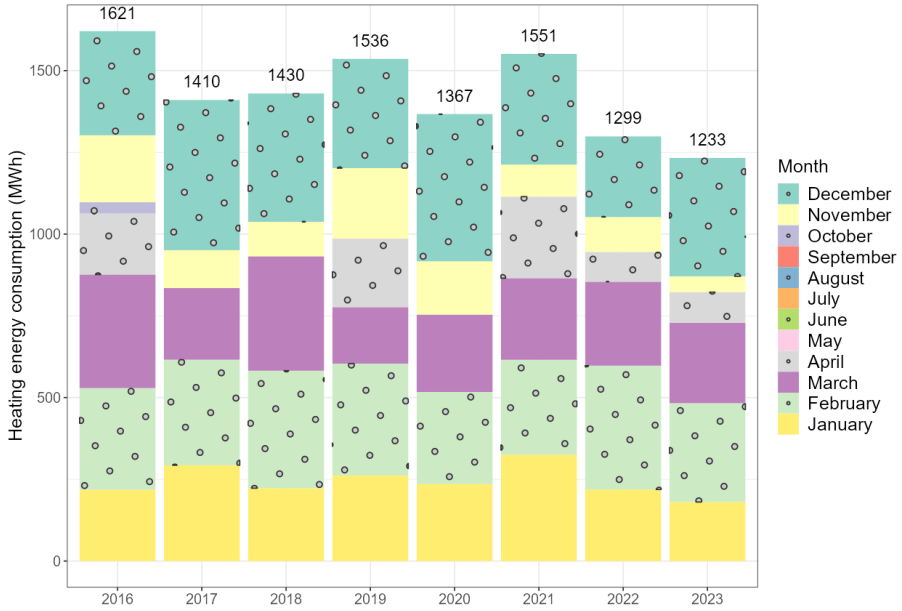
V.3.2 Heating energy consumption

V.3.2.1 History of heating energy consumption

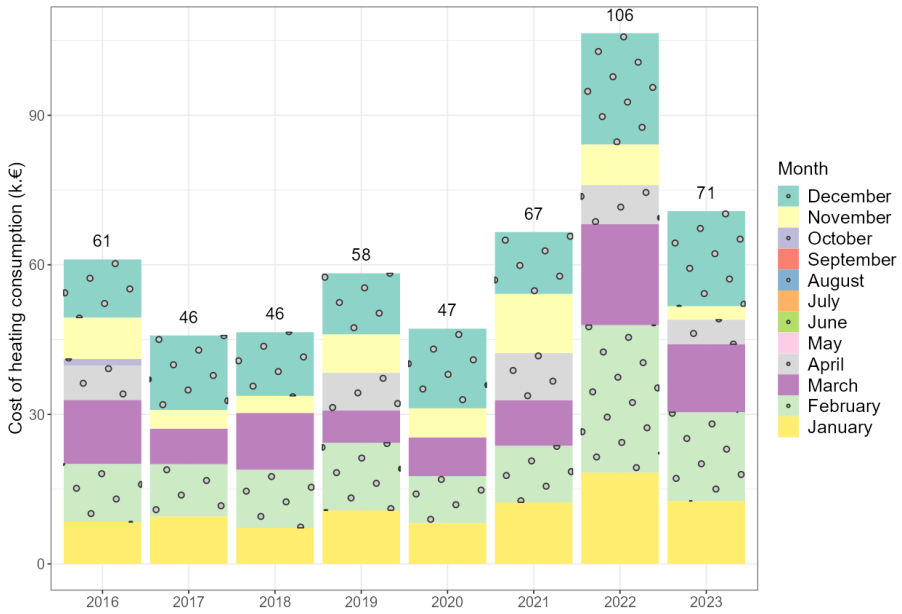
The campus's heating consumption history is analyzed based on the energy bills provided by NIMERGIE from 2016 to 2023 (refer to Appendix D.2 for a full detail of the heating energy bill). The heating system traditionally operates from January to March and from November to December each year. However, the system's activation could be influenced by outdoor temperatures, potentially extending its operation until April or starting as early as October.

The annual quantities and energy consumption costs are depicted in Figure 5-4, panels A and B, respectively. The average energy consumption from 2016 to 2021 (excluding 2020) is 1500 MWh annually, costing €56k annually. In 2022, the energy consumption was reduced

to 1299 MWh, showcasing the significant impact of energy-efficient renovation on conserving heating energy. However, the heating consumption price increases to €106k due to elevated energy prices.



(A) Heating energy quantity



(B) Heating energy cost

Fig. 5-4. *Monthly heating energy consumption for years 2016 - 2023 (A) quantity and (B) cost*

V.3.2.2 Heating consumption before and after renovation

Figure 5-5 illustrates the comparison of monthly heating energy consumption in 2022 (after the renovation of the GEII building) and 2023 (after the renovation of the GC building) with heating consumption on average before the renovation (2016–2019).

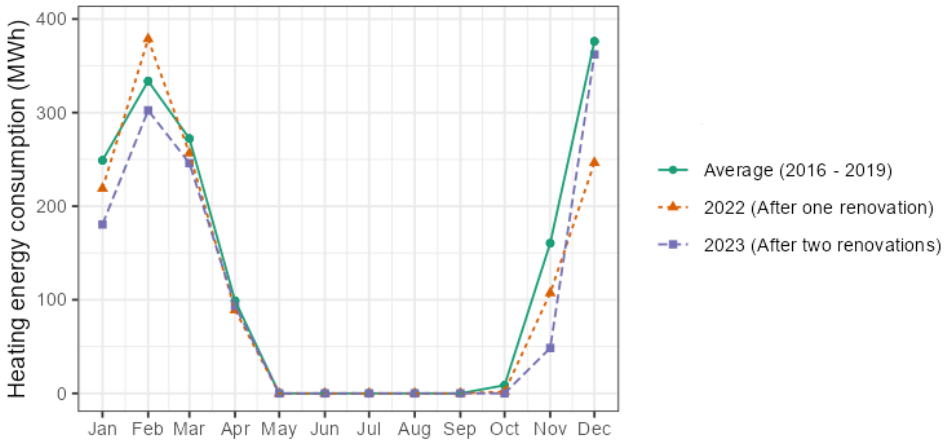


Fig. 5-5. *Comparison of monthly heating energy consumption of IUT de Nîmes campus between the pre-renovation and post-renovation years*

A similar pattern is observed when examining the evolution of electrical and heating energy consumption. Generally, the average consumption of preceding years tends to surpass that observed after renovation, with one notable exception at the beginning of 2022, specifically in February for heating energy. This is caused by a leak in heating distribution pipes in early 2022, leading to the heater continuing to consume energy without delivering heat to the main buildings. As a result, occupants have to rely on reversible air conditioners for heating during this period.

The annual heating consumption in 2022 and 2023 is reduced by 200 MWh and 266 MWh, respectively, compared to the average heating consumption of the previous years. These quantities reflect a 13% and 17% reduction thanks to the renovation.

V.3.3 Electricity consumption by buildings

To obtain a comprehensive understanding of overall electrical energy consumption, this section delves into the electricity usage of individual buildings on campus. The data for this analysis is derived from hourly electric meters, providing real-time consumption details for each building. However, the measured values may not precisely match the figures recorded in EDF bills. Discrepancies could arise due to measurement accuracy, additional charges included in the bills, and minor variations in measuring cycles.

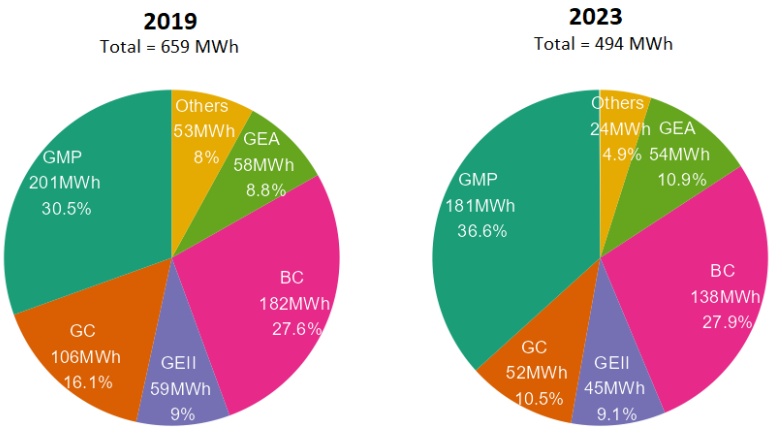


Fig. 5-6. *Distribution of electricity consumption by buildings in 2019 (before the renovation) and 2023 (after the renovation of GEII and GC buildings). The "Others" represented other electricity consumption such as the cafeteria, housing, and substation*

Figure 5-6 reveals that the GMP building consumes the most energy, accounting for approximately 30%–40% of the site's electricity consumption (i.e., around €27k in 2019 and €67k in 2023). This building serves as the primary energy consumer for the site, attributed not only to its largest floor area but also to its heavy equipment (machine tools, compressors, etc.) and its largest thermal envelope. According to users, the workshop halls are often overheated due to the old air heaters and remain overheated even when not in use.

The BC building is the second-largest energy consumer, constituting approximately 28% of the site's consumption (approximately €25k in 2019 and €51k in 2023) due to the use of split systems for central heating.

In 2019, the GC and GEII buildings collectively consumed substantial amounts of electricity, accounting for 16% and 9% of the total consumption, equivalent to around €14k and €8k in the given order. By 2023, their share in total consumption reduces, with the GC and GEII buildings representing 10.5% and 9%, resulting in bills of €19k and €17k, respectively. Remarkably, after renovation, energy consumption decreased by 51% and 24% compared to the levels observed in 2019 for the GC and GEII buildings, respectively.

Following the refurbishment, there is not only a reduction in heating consumption but also significant savings in electrical energy due to efficient automated lighting. However, as part of the renovation, the newly installed mechanical ventilation contributes to the rise in electricity usage. While the mechanical ventilation system operates effectively in GEII, its performance is less optimal in GC. Particularly in the late months of 2023, the mechanical ventilation in GC ceased to operate entirely, which may explain the difference in energy savings between the two

renovated buildings.

V.3.4 Variation of energy consumption during COVID-19 pandemic

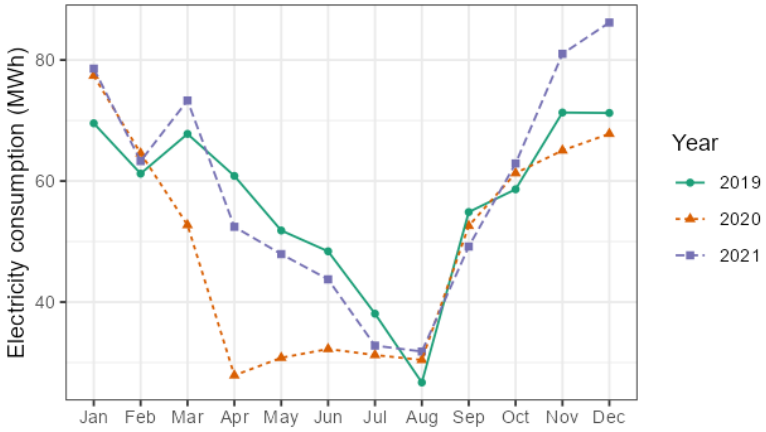
Due to the COVID-19 pandemic, IUT de Nîmes was closed on March 16, 2020, and reopened on June 15, 2020, just before the summer vacation in July, which lasted three weeks. In response to the second lockdown from November 1, 2020, to January 15, 2021, IUT de Nîmes adopted a hybrid education system that combined virtual and in-person learning.

TThe study program of IUT de Nîmes consists of classes in three formats: Cours magistraux (CM), Travaux dirigés (TD), and Travail personnel (TP), with respective teaching hour percentages of 15%, 48%, and 37%. TP involves practical work with groups of 10–15 students in technical practice rooms and workshop halls, while TD serves as a pedagogical framework for applying and clarifying lectures, typically with 20–30 students in regular classrooms. CM consists of large lectures for 100–150 students in lecture halls. During the second lockdown, CM and TD transformed to virtual learning while TP was on-site learning, ensuring safety and compliance with lockdown measures. Moreover, as the post-second lockdown phase extended from January to July 2021, social distancing measures persisted, necessitating the continuation of online learning for CM classes. However, employees have resumed their on-site work since the end of the first lockdown.

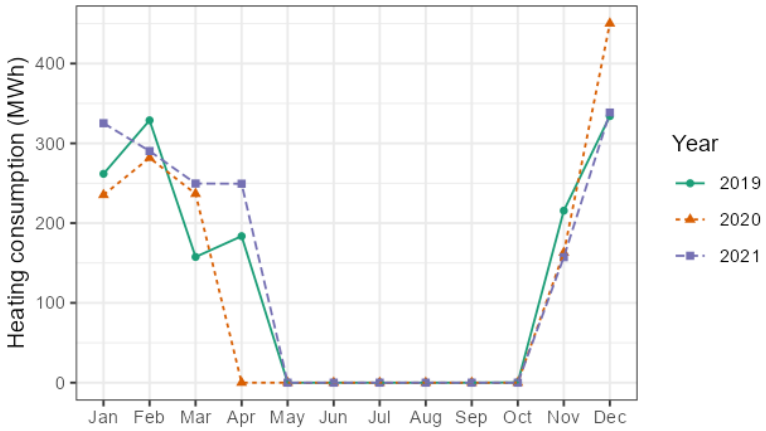
Figure 5-7A demonstrates a consistent decline in electricity consumption of the entire campus from March to August, followed by a sharp increase from August to October each year. The electricity usage in April 2020 is twice as low as in 2019 and 2021. During the first lockdown from March to June 2020, this period's average monthly electric energy consumption was 36 MWh, reflecting a decrease of 37% compared to the same period in 2019.

Figure 5-7B shows a significant difference in heating energy consumption between March and April of 2020 and the same months in 2019 and 2021. This is due to the early cessation of heating operations during the COVID lockdown.

Figure 5-8A presents the total energy usage per year from 2019 to 2021. The annual differences between 2019 and 2020 are relatively modest, leading to a decline of 86 MWh in electricity consumption and 115 MWh in heating energy usage. Figure 5-8B illustrates electricity and energy usage over three months, specifically from March to June 2019, 2020, and 2021. This timeframe is chosen to comprehensively analyze energy fluctuations following the first COVID-19 lockdown. The total usage during this duration in 2020 is 144 MWh, which is 37% and 51% lower than in 2019 (229 MWh) and 2021 (217 MWh), respectively. This suggests that 63% (equivalent to €18,000) of the typical electricity consumption persists, even though the buildings are not occupied.



(A) Electrical energy consumption

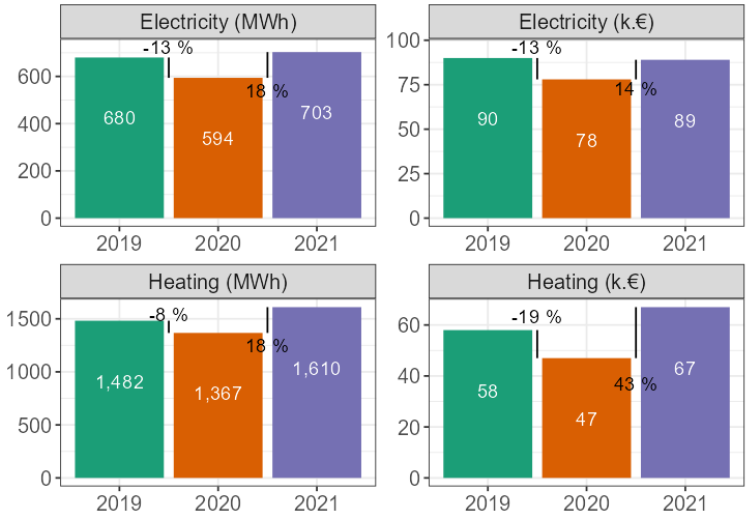


(B) Heating energy consumption

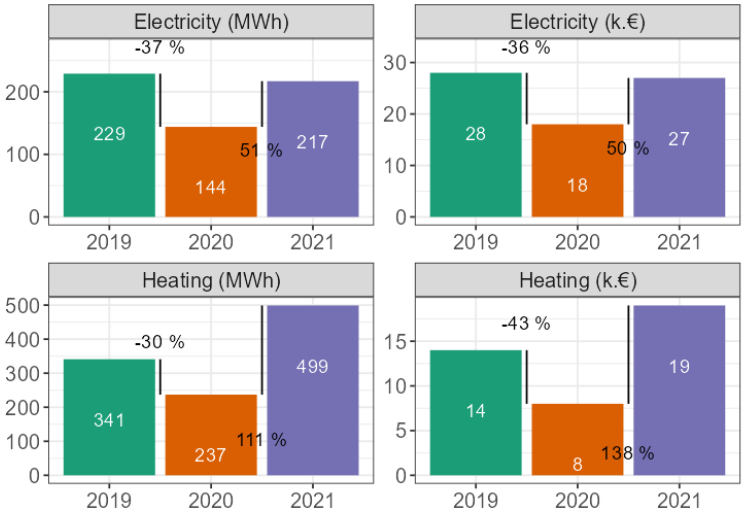
Fig. 5-7. *Monthly energy consumption of the IUT de Nîmes campus in 2019 (before COVID-19), 2020 (during COVID-19), and 2021 (after COVID-19) of (A) electricity and (B) heating*

During the first COVID lockdown, the campus still consumes electricity when completely unoccupied, suggesting a monthly allocation of at least 30 MWh for maintenance. Essential energy is required to operate local servers, distribution systems, and HVAC systems, ensuring a healthy environment upon the return of users. However, some energy is unnecessarily used for nonessential equipment, such as computers, TP machines, etc., left plugged in. To address energy waste, a more thorough investigation is recommended to identify all nonessential equipment that could be unplugged when a building is not in use.

During the second lockdown from November 1, 2020, to January 15, 2021, 63% of teaching sessions were held online. Surprisingly, the overall energy demand during this period is only 9% less than it was in 2019, indicating a weaker correlation between electric energy demand and the occupancy rate. Indeed, despite the predominant absence of students from the site,



(A) Annual consumption



(B) Three-month consumption

Fig. 5-8. *Comparing the electricity and heating consumption along with their corresponding energy costs across A) an annual timeframe and B) a three-month span from March to June, reflecting the first lockdown period*

most employees resumed on-site work, while the rest adopted hybrid work arrangements. Unlike classrooms, which typically accommodate 20–30 students in a single space, each employee has an individual office. In common areas, offices are equipped with various energy-consuming devices, such as computers, coffee machines, refrigerators, and microwaves. Consequently, decreasing the on-site presence of employees will likely lead to a substantial reduction in energy consumption.

V.4 Analysis of heat demand

V.4.1 Estimated heat demand

V.4.1.1 Degree-day method

The degree-day value serves as an indicator for the energy consumption of buildings, representing a traditional yet straightforward method employed in the heating, ventilation, and air-conditioning (HVAC) industries to estimate the heating and/or cooling energy demand [312, 313] and to evaluate the building energy performance [314]. In major building renovations, users can adjust energy levels based on an analysis of the HVAC system [315].

Under static conditions, the heat losses from a specific building correlate directly with the differences between the building's outdoor temperatures and a reference temperature (base temperature). Below this threshold temperature, buildings necessitate space heating energy to maintain thermal comfort conditions [316, 317]. Commonly, degree days for a location are calculated as the sum of the positive differences between the reference temperature and the daily average outdoor temperature, considering all days in a given period [313].

This study utilizes a quasi-stationary monthly calculation of heat loss and usable heat gains for the building [318], expressed in equation V.1, to calculate heat demand for IUT de Nîmes buildings.

$$Q_h = Q_1 - \eta \times Q_g \tag{V.1}$$

Where:
Q_h : total heat demand (kWh)
Q_1 : total heat loss (kWh), defined in equation V.2
Q_g : total heat gain (kWh), defined in equation V.6
η : the utilisation factor, defined in equation V.9
Total heat loss Q_1 of a national level that incorporates the use of degree days is:

$$Q_1 = H \times DJU_{18} \times 0.024 \tag{V.2}$$

Where :
H : total heat loss coefficient of the building ($W.K^{-1}$)
$H = H_T + H_V$
H_T is the specific transmission loss through each building fabric ($W.K^{-1}$), namely, walls, windows, roofs, and floors. It is calculated as:

$$H_T = \sum b_i \times U_i \times S_i + \sum b_i \times \Psi_i \times l_i \tag{V.3}$$

where b_i is the reduction factor of the fabric's temperature depending on the condition that the element is exposed to, b = 1 for exterior, and b $<$ 1 for non-heating space, i.e., crawl space. U_i is the transmission coefficient ($W.m^{-2}.K^{-1}$) and S_i is the transmission surface area (m^2). Ψ is the thermal bridge coefficient ($W.m^{-1}.K^{-1}$), and l is the transmission length (m).
H_V is the specific heat loss through ventilation ($W.K^{-1}$), calculated as follows:

$$H_V = \dot{V} \times \rho_a \times c_a \tag{V.4}$$

where $\dot{V}$ is the air flow rate through the building ($m^3.h^{-1}$); including air flow through unheated space, and $\rho_a c_a$ is the heat capacity per volume = 0.34 $Wh.m^{-3}.K^{-1}$.
DJU_{18} is the unified degree day on a base of 18°C of the Nîmes Courbessac region during the heating period from January to March and from November to December (refer to Chapter 2, Section 2, for a detailed DJU definition).

$$DJU_{18} = \int \left(18 - \frac{Tej_{max}(t) + Tej_{min}(t)}{2}\right).dt \tag{V.5}$$

where Tej_{max} is the maximum daily outdoor temperature (°C), Tej_{min} is the minimum daily outdoor temperature (°C) and t is time (day).

Available heat gains Q_g are the combination of solar heat gain through windows Q_s (kWh) and internal heat gain Q_i (kWh) released by human body heat, thermal machines, computers, servers in educational buildings. The Q_s and Q_i are evaluated monthly during heating.

$$Q_g = Q_s + Q_i \tag{V.6}$$

Where:
Q_s: solar gains for each window facing different orientations (kWh).
Q_s for a window is calculated from the solar incident through a type of window glass, a free horizon, and the same orientation of the corresponding windows as :

$$Q_s = F \times S_i \times I_s \tag{V.7}$$

where F ($F = F_s F_a F_g$) is the reduction factor of the insolation through the actual window anticipates the effect of shadows F_s, the area the frame F_a and the glass type F_g. S_i is the transmission

surface area (m^2) and I_s is the insolation through the reference pan ($kWh.m^{-2}$).
Q_i: internal heat gain (kWh)
Q_i for each month over the heating period is calculated as:

$$Q_i = 0.024 \times D \times S_e \times \Phi_i \tag{V.8}$$

where D is the number of days of the month, S_e is the total heated floor surface area of the building (m^2), and Φ_i is the power density of internal heat gain ($W.m^{-2}$).

Not all available free energy gains can be effectively utilized for heating the building. This is attributed to an excess of temperatures in certain periods, which can often be traced back to the substantial solar gains in periods with elevated external temperatures. The utilization of the heat gained in the course of the heating season depends on the time constant of building τ (h) and the total heat gain as a ratio of the total heat loss γ. The utilization factor for the heat gain η indicates how much potential heat gain can be utilized. The residual heat gain is mitigated through the implementation of solar shades and curtains, accompanied by enhanced ventilation. Typically, the model calculates the utilization factor η for the free gain as:

$$when\ \gamma = 1,\ \eta = \frac{a}{1+a}\ ;\ when\ \gamma \neq 1,\ \eta = \frac{1-\gamma^a}{1-\gamma^{a+1}} \tag{V.9}$$

where γ is the relative heat gain $\gamma = \frac{Q_G}{Q_l}$, and $a = 1 + \frac{\tau}{16}$.

V.4.1.2 Estimated heat losses through building fabrics

In winter, the outdoor temperature is lower than the indoor temperature, indicating the cause of heat loss. The advantage of having an insulated building lies in reducing heat loss through the building fabric by enhancing its thermal resistance. Moreover, an insulated building maximizes the utilization of internal loads derived from human heat release, lighting systems, internal devices, etc. The remaining heat requirement is then supplied by the heating system operating within the building.

Considering this, when the heating system is disregarded, internal heat gains alone can sustain a comfortable temperature without additional energy consumption up to a certain point. However, there will be times when the indoor temperature falls below the threshold temperature, necessitating a heating appliance to reach the comfort temperature.

Figure 5-9 portrays the estimated transmission loss through building fabrics before and after renovation of the teaching section in the GC building (panel A), GEII building (panel B), and GMP building (panel C). This estimation is based on equation V.3.



(A) GC building

(B) GEII building

(C) GMP building

Fig. 5-9. *Comparison of transmission loss through building fabrics before and after renovation of teaching section in the following building: (A) GC building; (B) GEII building; and (C) Future GMP building*

After the renovations, the total heat losses in the GC and GEII buildings decrease by 57% and 60%, respectively. Applying the same renovation measures to the GMP building could potentially result in a significant improvement, with an estimated reduction in the total heat loss coefficient to 3000 $W.K^{-1}$, marking a 56% decrease from the current state.

It is worth noting that the renovation of the GC and GEII building envelopes involves solely the addition of external wall insulation and the replacement of old low-emissivity windows. Consequently, insulated walls demonstrate the most significant reduction in heat losses at 90%, followed by upgraded windows at 60%.

V.4.1.3 Estimated heating saving

For this study, the usable free heat gains Q_g remain the same between the pre- and post-renovated buildings. Therefore, the changes before and after in heat demand Q_h are placed

on the difference in total heat loss Q_1. The equation of heat demand saving ΔQ_h is expressed in equation V.10.

$$\Delta Q_h = \Delta H \times DJU \times 0.024 \tag{V.10}$$

The calculation is applied to ventilation and upgraded building envelopes: walls and windows. Table 5-2 presents the quantity of heating saving ΔQ_h of the entire buildings using the ΔH and a DJU_{18} of 1290°C.day. This DJU_{18} is the average value from January to March and from November to December for three consecutive years (2021, 2022, and 2024).

Entire building	**Elements**		$\Delta H(W.K^{-1})$	**Heat demand saving (MWh)**	**Saving Percentage by building fabric (%)**
GEII	Envelope	Wall	3830	118	75
		Window	670	21	13
		Thermal bridges	206	6	4
	Ventilation		413	13	8
	Total		**5119**	**158**	**-**
GC	Envelope	Wall	4691	145	71
		Window	877	27	13
		Thermal bridges	265	8	4
	Ventilation		731	23	11
	Total		**6564**	**203**	**-**
GMP	Envelope	Wall	5916	183	72
		Window	1064	33	13
		Thermal bridges	318	10	4
	Ventilation		897	28	11
	Total		**8194**	**254**	**-**

Table 5-2. *Estimated heating demand savings following the renovation of the entire GEII, GC and GMP buildings during heating period from November to March*

Table 5-2 shows that the renovation is estimated to reduce the heating demand by 158 MWh (36.9 $kWh.m^{-2}$), 203 MWh (35.8 $kWh.m^{-2}$), and 254 MWh (34.8 $kWh.m^{-2}$) in GEII, GC, and GMP buildings, respectively, during five months of heating period. By removing permanent openings for natural ventilation (replaced by single-flow mechanical ventilation), the heating requirement conserved from this factor contributes 8%, 11%, and 11% of the total savings in the respective buildings. In naturally ventilated schools, air renewal relies on manually opening windows and doors in classrooms [244]. In winter, it can be observed that both teachers and students exhibit a lack of motivation to manually open windows, as reported in academic studies [241, 319]. Consequently, retrofits incorporating automatically controlled ventilation have been found to present greater dependability than traditional window opening methods when enhancing air quality within the classroom [242].

Therefore, the ventilation system implemented in the present study serves the dual purpose of diminishing thermal dissipation and controlling airflow rate. The mechanism ensures a

consistent and sufficient airflow supply in compliance with the recommended healthy regulation value of 18 m^3/h per person throughout occupied periods and ceases operation when unoccupied. Regarding the building envelope, external wall insulation emerges as the most impactful method for minimizing heat loss, accounting for approximately 70% of the total savings.

Teaching Section	Elements		$\Delta H(W.K^{-1})$	Heat demand saving (MWh)	Saving Percentage by building fabric (%)
GEII	Envelope	Wall	1867	58	65
		Window	446	14	16
		Thermal bridges	143	4	5
	Ventilation		413	13	14
	Total		**2869**	**89**	**-**
GC	Envelope	Wall	2731	85	63
		Window	653	20	15
		Thermal bridges	202	6	5
	Ventilation		731	23	17
	Total		**4318**	**134**	**-**
GMP	Envelope	Wall	3112	96	62
		Window	744	23	15
		Thermal bridges	228	7	5
	Ventilation		897	28	18
	Total		**4981**	**154**	**-**

Table 5-3. *Estimated heating demand savings following the renovation of the teaching section in GEII, GC and GMP buildings during heating period from November to March*

Table 5-3 summarizes the heat demand savings in the teaching sections of GEII, GC, and GMP buildings. In these buildings, the savings amount to 89 MWh (50 $kWh.m^{-2}$), 134 MWh (43 $kWh.m^{-2}$), and 154 MWh (40 $kWh.m^{-2}$), respectively, during five months of heating period. These teaching sections contribute significantly, accounting for 57%, 67%, and 62% of the total savings from each building, respectively.

V.4.2 Measured heating energy consumption

V.4.2.1 Data interpolation

After renovation, the actual heating energy consumption meter started operating in November 2023. Nevertheless, several gaps or missing data points exist, particularly in the GEII and GMP buildings. To tackle this problem, a linear interpolation method is employed to estimate and fill in the missing values, generating an hourly consumption profile as illustrated in Figure 5-10.

This interpolation technique facilitates the creation of a continuous and more extensive dataset, ensuring a more precise depiction of the heating energy consumption patterns in the

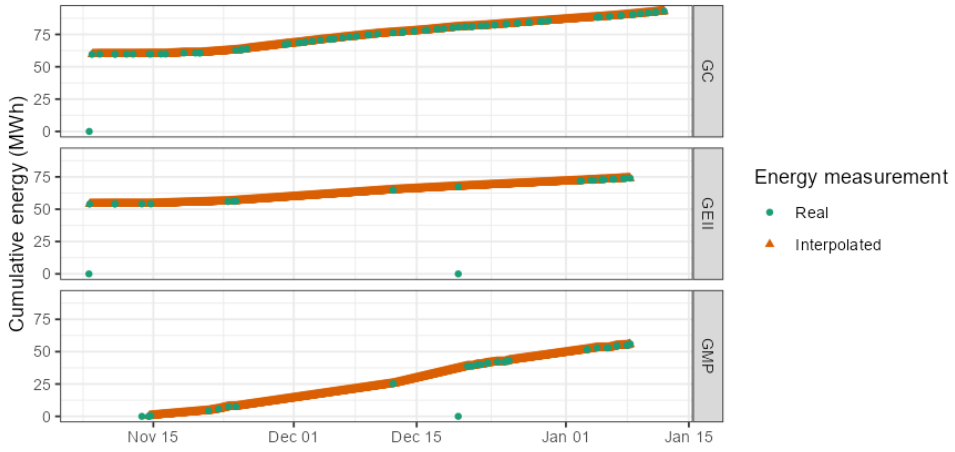


Fig. 5-10. *Cumulative heating energy, derived through interpolation of actual measurements, from November 2023 to January 2024 in the GC, GEII, and GMP buildings*

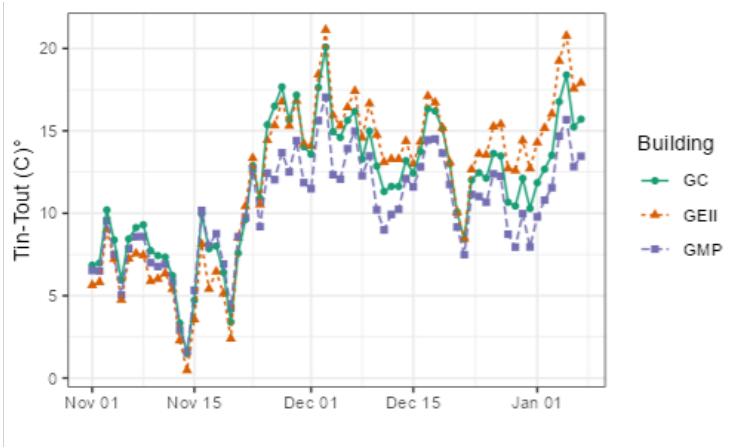
GEII and GMP buildings, even in the presence of occasional gaps in the original data. This figure indicates that the interpolation method successfully estimates the missing values, seamlessly aligning with the original trend of cumulative energy lines.

V.4.2.2 Evolution of indoor and outdoor temperature during the heating consumption measurement period

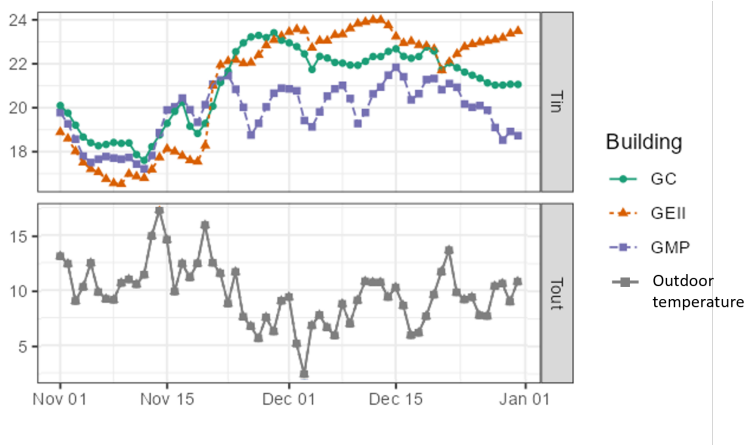
Figure 5-11 presents two aspects related to temperature variations. Panel A depicts the differences between indoor and outdoor temperatures, providing insights into the thermal conditions during the heating period from November 01, 2023, to January 07, 2024. Meanwhile, Panel B showcases the evolution of both indoor and outdoor temperatures throughout the same heating period, offering a visual representation of how these temperatures change over time.

Overall, Figure 5-11A shows that the temperature discrepancies are the biggest in the GEII building, followed by the GC building and then the GMP building, specifically from 15th of November onward when the heating operation started. This suggests that the GEII tended to have the highest indoor temperature, whereas the GMP building exhibits the lowest. However, a higher indoor temperature does not necessarily imply that the comfort temperature range is obtained.

Therefore, Figure 5-11B delves into the progression of indoor temperatures. Notably, the GMP building shows the most substantial weekly variation in indoor temperature, ranging from a minimum of 19°C to a maximum of 22°C. This indicates a significant fluctuation in the temperature difference between the indoor and outdoor environments within this building over the week. In contrast, GC and GEII buildings maintain relatively milder temperature gaps,



(A) Difference between indoor and outdoor temperature



(B) Indoor and outdoor temperature

Fig. 5-11. *The evolution of (A) the difference between indoor and outdoor temperature of GC, GEII and GMP buildings and (B) outdoor temperature and indoor temperature of GC, GEII and GMP teaching sections*

staying mostly constant at 23.5°C and 22.5°C, respectively.

The observed progressions are linked to the fact that the GMP building is not insulated, causing a remarkable decrease in temperature due to substantial heat losses when the heating temperature threshold is decreased during weekends. Conversely, the temperature increases sharply when the heating temperature threshold increases to a comfortable level on Mondays. In contrast, the renovated buildings show lower sensitivity to outdoor temperatures, with their temperatures gradually decreasing during the weekend. However, it seems that the renovated buildings may sometimes experience occasional overheating in their spaces.

Another observation surfaces in the GEII building when its indoor temperature evolves stably at 23°C throughout the winter break (from December 22, 2023, to January 07, 2024), signifying that the heating system maintains the same energy intensity. This underscores a no-

table issue associated with ineffective energy management in existing buildings, even those that have undergone renovations. Various factors contribute to this challenge, including difficulties in temperature regulation and the lack of robust monitoring and control systems.

V.4.2.3 Potential heating saving by lowering comfort temperature threshold

Considering the possibility of overheating in the renovated buildings (GC and GEII), which could result from elevated heating temperature thresholds, it is crucial to lower these thresholds. This is necessary not only to attain an optimal comfort temperature but also to enhance energy conservation.

The difference in energy consumption following the reduction in temperature threshold is calculated as follows:

$$\Delta Q_h = H \cdot \Delta DJU \cdot 0.024 \tag{V.11}$$

As shown in Figure 5-9, the coefficients of heat losses through building fabrics for renovated GC, GEII, and GMP buildings are 2.6 $kW.K^{-1}$, 1.6 $kW.K^{-1}$ and 3.2 $kW.K^{-1}$, respectively. Applying Equation V.11, the potential heat savings from lowering the heating set-point are summarized in Table 5-4.

Reduced heating temperature threshold (°C)	**ΔDJU * 0.024 (k°C.h)**	$\Delta Q_h(MWh)$			
		Building	*GC*	*GEII*	*GMP*
		$H\ (kW.K^{-1})$	*2.6*	*1.6*	*3.2*
1	3.6	-	9	6	12
2	7.2		19	12	23
3	10.8		28	17	35

Table 5-4. *Calculated potential heat saving by lowering heating temperature thresholds in renovated GEII, GC, and GMP buildings. The investigated duration (5-month heating period) is considered to be 150 days*

Consequently, reducing the heating set-point by 1°C results in additional annual energy savings of 9 MWh for the GC building and 6 MWh for the GEII building during the five months of the heating period. This result emphasizes the potential for additional energy conservation beyond the gains obtained through the initial renovation, highlighting the effectiveness of the indoor temperature control strategy.

V.4.3 Evaluating actual heat loss density (K in $W.m^{-2}.°C^{-1}$) of renovated and non-renovated buildings

Figure 5-12 depicts the relationship between weekly energy consumption per usable surface area and weekly heating degree hours for both renovated teaching sections (GC and GEII buildings) and the non-renovated teaching section (GMP building) from December 22, 2023, to January 7, 2024. Notably, the regression line for the GC building shows a shallow slope (0.69) compared to that of the GMP building (1.15), indicating that renovated building consumed approximately 40% less energy than the non-renovated building. The similar slopes of regression lines for GC and GEII buildings (0.69 versus 0.73, respectively) suggest comparable consumption levels, given their identical renovation measures.

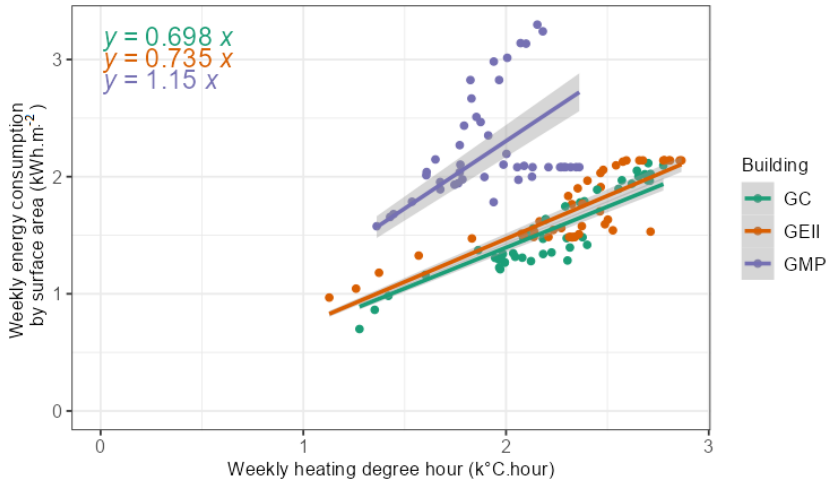


Fig. 5-12. *The relationship of weekly energy consumption by usable surface area and weekly heating degree hour of GC, GEII and GMP teaching sections from December 22, 2023 to January 7, 2024*

The observed trend further indicates that energy consumption increases with heating degree hours. It is crucial to acknowledge that, in theory, this relationship is not strictly linear due to the variability of free heat gain influenced by internal activities and weather conditions. However, the linear interpolation used in this study assumes no free heat gain, with the interpolation coefficient characterizing the energy loss of the building.

V.4.4 Comparison between estimated and measured heating energy consumption

To accurately compare energy consumption between renovated and non-renovated buildings, the analysis is conducted during conditions with minimal internal heat gains. This is exemplified

in Table 5-5, which presents the calculated values for the winter vacation period from December 22, 2023, to January 07, 2024. During this timeframe, the buildings are entirely unoccupied, eliminating internal heat gains from occupants' activities. Moreover, the windows and shutters are entirely closed, removing solar gains.

Building (Teaching section)	**Energy consumption per surface area** ($Wh.m^{-2}$)	**Heating degree hour (°C.h)**	**Measured K** [a] ($W.m^{-2}.°C^{-1}$)	Δ **Q**$_{h.GC}/Q_h$ [b]	**Estimated K** ($W.m^{-2}.°C^{-1}$)	**K error (Estimated K Vs. Measured K**
GEII	3277	5645	0.58	14%	0.92	59%
Supposed GEII [c]	2852	*4914*	0.58	2%	-	
GC	2802	*4914*	0.57	-	0.86	51%
GMP	3981	4211	0.95	30%	1.91	102%
Supposed GMP [c]	4646	*4914*	0.95	40%	-	

[a] K represents heat loss density

[b] percentage of energy consumption savings of the building compared to GC building

[c] calculated values to obtain the same comfort temperature as GC building with the same degree-hour

Table 5-5. *Energy consumption of teaching section in GEII, GC (renovated buildings) and GMP (non-renovated building), and heat losses coefficient during winter break from December 22, 2023 to January 07, 2024*

During the investigated period, the actual heating energy consumption per unit usable area for GEII, GC, and GMP teaching sections is 3277 $Wh.m^{-2}$, 2852 $Wh.m^{-2}$, and 3981 $Wh.m^{-2}$, respectively. In this context, GC exhibits 30% lower energy consumption than the GMP building. However, a direct comparison of these consumption figures is not accurate due to variations in indoor temperatures, as indicated by heating degree hour values. Specifically, the GC, GEII, and GMP buildings have 4914°C.h, 5645°C.h and 4211°C.h, respectively.

To conduct a more accurate comparison, hypothetical scenarios labeled as "supposed GMP" and "supposed GEII" are derived. These scenarios are calculated by using the heating degree hours of the GC building (4914°C.h) as a reference, ensuring consistent comfort temperatures across all three teaching sections. As a result, when striving to maintain an equivalent comfort level without the influence of internal heat gains, it is determined that GC consumes 40% less energy than the GMP building.

Additionally, the table facilitates a comparison between the calculated heat loss density coefficient (Estimated K), derived from equation V.3, and the actual heat loss density coefficient (Measured K), determined through the measured energy consumption and observed heating degree hours. The results reveal that the estimated K values are higher than measured K values by approximately 55% in renovated buildings (51% and 59% for GC and GEII buildings, respectively) and by 102% in the non-renovated building (GMP). The discrepancies between the estimated values and the measured values can be explained by two potential hypotheses: (i) heat gains exist mainly in the non-renovated building (GMP) where the shutters are broken, but only slightly in the renovated buildings (GC and GEII) where the windows have remained

closed, and (ii) the U-values of the opaque surfaces of the buildings before renovation have been overestimated.

V.5 Conclusion

This chapter delves into analyzing electricity and heating energy consumption patterns in renovated and non-renovated buildings within the IUT de Nîmes, providing valuable insights. The fundamental discoveries and conclusions drawn from this investigation can be summarized as follows:

- Reduction in electricity consumption: The introduction of automated lighting in two renovated buildings significantly decreases overall electricity usage. However, it is essential to note that this reduction may also be influenced by the decreased usage of air conditioners in the summer. Unfortunately, a precise evaluation of the impact on air conditioner consumption is challenging due to the absence of electric meters on these devices.

- Reduction in heating consumption: After the completion of the renovation projects, there is a notable decrease in the overall heating energy consumption, highlighting the effectiveness of energy-efficient renovation measures in preserving heat demand. Nevertheless, it is observed that the indoor temperature in renovated buildings occasionally reaches overheating levels, indicating issues with energy management efficiency. Further energy conservation and ensuring an optimal comfort temperature can be done by lowering the set temperature of the thermostatic valves and adjusting them according to the indoor temperature.

- Heat demand savings estimations: Employing the degree-day method, the estimated heat demand savings for the renovated buildings during five months of heating period is determined to be 158 MWh (37 $kWh.m^{-2}$) for the GEII building and 203 MWh (36 $kWh.m^{-2}$) for the GC building, and 254 MWh (35 $kWh.m^{-2}$) for the future renovated GMP building.

- Heating energy consumption: The analysis of measured heating consumption (during two weeks of unoccupied period) enables an assessment of heating energy consumption savings, revealing that the renovated building consumes approximately 40% less than the non-renovated building. Moreover, the results also show that the estimated heat demand significantly overestimates the U-value of opaque surfaces of non-renovated building by 102%. This overestimation is less pronounced in renovated buildings, approximately 55%.

Moreover, the renovated GC and GEII buildings nevertheless have different consumption levels (2.8 $kWh.m^{-2}$ vs. 3.2 $kWh.m^{-2}$ during two weeks of unoccupied period) due to unequal indoor temperature management. The potential savings for both GC and GEII buildings can be realized by regulating the indoor temperature during the unoccupied period.

These results underscore the significant advantages of energy-efficient renovations, demonstrating notable reductions in electricity and heating energy consumption. The provided data adds valuable insights for shaping future energy management strategies and reinforces the positive outcomes associated with sustainable building practices.

General Conclusion

"Shoot for the moon. Even if you miss,
you'll land among the stars."

— NORMAN VINCENT PEALE

Conclusion

Building renovation is critical to sustainable development, addressing energy efficiency, environmental impact, and Indoor Environmental Quality (IEQ). The optimizing building envelopes, upgrading HVAC systems, and considering occupant well-being, they contribute to scholarly discussions on sustainable urbanization, climate change mitigation, and human-centric design.

Upon reviewing the existing literature, it became evident that the number of field studies up to date is insufficient in assessing the impact of energy-efficient measures on IEQ and occupant satisfaction within real building settings. The principal objective of this dissertation is to conduct a comprehensive analysis of the energy performance of school buildings after energy-efficient renovation and its effects linked to indoor climate and users' comfort in the Mediterranean climate.

The study found that the level of CO_2 in pre-renovated buildings occasionally exceeded the recommended acceptable range of 1000 ppm. The results underscore the substantial impact of occupant behavior on indoor climate dynamics, particularly in relation to window usage. While opening windows can reduce CO_2 levels, it causes a rapid loss of the cool indoor air in summer and heat loss in winter. The study recommends a strategy that involves partially or entirely opening windows during short breaks of around 10 minutes. The research highlights the crucial significance of exchange air rates within the mechanical ventilation system in the post-renovated building. Given that the renovated building is now highly air-tight, it emphasizes the necessity for routine verification of the ventilation system to ensure adequate air flow rate to prevent elevated CO_2 concentrations and mitigate building sick syndrome. This concern arises from the observed extreme levels of CO_2 in the renovated building during occupied peri-

ods, which can reach up to 4000 ppm when the ventilation system ceases completely. This CO_2 level is 60% higher than when the system operates at half the designed airflow rate (approximately 9 $m^3.h^{-1}$ per person), and 167% higher than the CO_2 level during natural ventilation (approximately 18 $m^3.h^{-1}$ per person).

Analysis of thermal sensation votes, air-draft sensation votes, and humidity sensation votes of students within IUT de Nîmes existing buildings reveals that most respondents were comfortable in winter but remarkably uncomfortable in summer. Workshops exhibit more discomfort due to architectural design and additional heat sources (mechanical machines). Despite limited control over HVAC systems, occupants favored "increasing ventilation" as a strategy for coping with hot environments. The study highlights the need for user-friendly environmental modifications to enhance occupant comfort and satisfaction.

Through the degree-day method, the heat demand savings in the investigated buildings are estimated to be approximately 34 $kWh.m^{-2}$ during five months of the heating period following the renovation. However, this calculation assumes no change in free heat gains between the after and before renovation.

Based on the measured energy consumption during two weeks of the unoccupied period (when the shutters and windows remain closed), which potentially removes the free heat gains, the result shows that the renovated building consumes 40% less energy than the non-renovated one (2.8 $kWh.m^{-2}$ versus 4.6 $kWh.m^{-2}$). The significant decrease in heating energy consumption after renovation suggests the efficacy of energy-efficient measures in managing heat demand.

Furthermore, non-renovated buildings have been observed to experience space overheating during winter due to the lack of heating set points and the presence of free heat gains (internal and solar), which can be substantial in the Mediterranean region. The renovation of the heating system has allowed indoor temperatures to be regulated by thermostatic valves, which helps to reduce heating consumption. However, this does not entirely prevent overheating in certain highly exposed rooms.

In addition, reducing the set temperature in renovated buildings further conserves energy consumption and upholds optimal comfort temperatures. According to thermal sensation assessments, adjusting heating set-points to 18°C does not affect respondents' thermal comfort in classrooms, as they demonstrate increased tolerance to cooler environments. However, this strategy is less effective for offices and workshops, where lower occupancy rates result in limited internal heat gain, necessitating the use of additional heating devices.

In conclusion, the energy-efficient renovation significantly reduced building energy consumption, slightly negatively impacting indoor climate values, particularly CO_2. Although these values are now on the edge of the recommended comfort zone, they remain within acceptable

ranges according to building standards. Minimal changes in indoor climate did not significantly affect occupant satisfaction regarding their sensation, acceptability, and preference of thermal environment and air quality. The incorporation of real-world scenarios provided valuable insights into renovation outcomes, offering a nuanced understanding of occupant behavior, unexpected challenges, and the actual performance of implemented measures. This holistic perspective is important for refining energy-efficient strategies and ensuring their effectiveness in diverse and dynamic settings.

Limitations

Despite the comprehensive nature of this study, several limitations have been encountered that are important to acknowledge and consider in interpreting the findings. These limitations encompass both data-related challenges and constraints associated with the research methodology.

• *Missing electricity data during the COVID-19 period*

The unavailability of electricity consumption data from March to October 2020 presents a substantial limitation. This period was pivotal for studying the impact of the COVID-19 pandemic on building energy consumption. The data during this time could have provided crucial insights into the nature of energy consumption at IUT de Nîmes during unoccupied periods, allowing for a more comprehensive understanding of the effects of the pandemic on energy use.

• *Absence of Heating Meter*

The absence of heating meter data impedes the ability to access the heating consumption of individual buildings. This limitation restricts the capacity to thoroughly compare energy consumption before and after renovation, making it challenging to validate the energy savings resulting from the renovation measures.

• *Inaccurate Heating Invoices*

Inaccurate heating invoices from the energy provider company, attributed to an old heating system leakage, hinder real heating energy consumption evaluation. This discrepancy between billed consumption and actual usage can lead to a misleading representation of the energy performance of the buildings.

• *Missing Physical Data*

The absence of physical data for almost one year, from April 2022 to January 2023, significantly impacts the study. This missing data renders the survey conducted during the summer before the renovation of the GC building unusable, which is a fundamental element of this thesis.

• *Lack of Key Measured Variables*

The lack of key measured variables, such as airspeed, mean radiant temperature, and globe tem-

perature, limits evaluating thermal comfort using Rational models. This absence necessitates several assumptions in calculating thermal comfort, potentially resulting in a higher degree of inaccuracy in the assessment.

• *Survey Timing and Acclimatization*

As the survey relies on teachers' permission, some surveys were conducted during the transition period (for instance, immediately after the arrival of students), which does not align with the requirements of the thermal comfort models based on steady state. The model stipulates that respondents should be seated for at least 20 minutes before completing the survey to ensure proper acclimatization, which may not be achieved during the transitional state surveys.

These limitations are essential to consider when interpreting the results and conclusions of this study. They underscore the need for careful and nuanced interpretation of the findings concerning the potential sources of bias and constraints that may influence the outcomes.

Perspectives

Four main themes can be developed for the continuation of this work.

• *Mechanical ventilation system*

The outcomes of this dissertation stress the inefficacy of the mechanical ventilation system following the renovation, delineating multifaceted challenges. Firstly, the practical implementation of the design system is compromised by the absence of ventilation performance tests and control mechanisms, revealing a disparity between the intended functionality in the design and the system's real-setting performance.

Secondly, the ventilation system's inadequate regulation, leading to unnecessary operation in vacant spaces and consequent electricity wastage, necessitates future investigations into advanced CO_2-sensing ventilation systems. These systems dynamically adjust airflow based on CO_2 levels, offering an energy-efficient approach. They can also monitor CO_2 levels and airflow in real-time via user-friendly applications, ensuring optimal system functionality. This approach [320–322], cost-effective compared to heating expenses, ultimately enhances indoor air quality in university buildings.

Lastly, there is persistent thermal discomfort in the post-renovated building, particularly during the summer season from May to September (occupied periods). The proposed future study should delve into the intricacies of implementing and optimizing nocturnal overventilation as a potential strategy to remove the heat accumulated by the building during the day. Moreover, this study should take into account factors such as its impact on thermal comfort, energy consumption, and overall indoor environmental quality.

• *Heating regulation*

The study reveals that the improved heating system in renovated buildings still lacks a regulation strategy. The remaining issues are (i) overheating space despite integrating thermostatics and (ii) permanent heating space when the windows are open, which leads to energy wastage. Future research should emphasize advanced heating regulation, utilizing per-room thermostatic valves controlled by window sensors. These interconnected valves, equipped with window status detection (open/closed), aim to optimize energy use and ensure precise temperature control in each room.

• *Simplified occupants scenarios in questionnaire survey*

This study aimed to capture the realistic behaviors of occupants in many classrooms, providing a comprehensive understanding of the building environment. However, this approach yielded complex results, interpreting challenging due to intercorrelations between factors. For instance, survey timestamps (survey completion immediately upon entering the classroom) may influence respondents' thermal comfort votes, impacting their judgment of indoor conditions. Additionally, assessing the impact of energy-efficient renovations on thermal comfort needs to be more precise, as direct comparisons were not made in the same rooms with the same respondents. The author acknowledges that employing a simplified questionnaire survey scenario could enhance accuracy. Nonetheless, a simplified scenario by persuading student groups to participate in repeated surveys within a few classrooms may be difficult and risk deviating the nature of respondents from the "typical student". Furthermore, the study highlights the variability in indoor environments across different classrooms, indicating that a simplified approach with a few classroom selections may not precisely capture the diversity of the entire building.

• *More comprehensive instrumentation*

Thermal comfort and air quality evaluation should be improved by addressing clothing insulation and metabolic rate in the questionnaire survey and implementing corresponding sensors to mean radiant temperature and airspeed.

Additionally, addressing missing values in climate sensors is crucial, and the assessment should include identifying missing and incorrect technical data through network traffic classification [323, 324].

Further development is essential for energy consumption analysis. Incorporating additional electric meters to monitor individual consumers, such as mechanical machines, office equipment, air-conditioners, lighting, mechanical ventilation, and local servers, would provide intricate insights into energy usage patterns. This detailed data is pivotal for identifying influential energy factors and formulating effective electricity management strategies.

The heating consumption is also to be developed. Challenges persist in heating consumption assessment. With meters implemented post-renovation and covering larger areas like

teaching and workshop sections, assessing the renovation's impact on actual heating energy consumption is limited. To address this, heating meters should be integrated into smaller spaces like classrooms, offices, and workshops. Utilizing detailed data, artificial intelligence approaches such as Support Vector Machines (SVM) or Artificial Neural Networks (ANN) can enhance the accuracy of energy consumption predictions, facilitating energy control and management strategies.

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Appendices

A. Solar radiation calculation

A.1 Introduction

This annex exclusively comprises excerpts from the book *Solar Engineering of Thermal Processes* by John A. Duffie and William A. Beckman, published in 1980 [197]. However, this annex presents solely the pertinent elements essential for calculating the hourly vertical solar radiation from the horizontal plane, known as Solar Radiation (SR) in Chapter 3 Part 2 (Section III.3.3). Later in this annex, the SR is written in terms of I_T (Irradiation on titled plane), as detailed in Section A.3.7.1 for the Isotropic Sky Model and Section A.3.7.2 for the Perez Model.

For comprehensive details, readers should refer to PART I FUNDAMENTALS of the book *Solar Engineering of Thermal Processes*, which includes Section 1 on Solar Radiation and Section 2 on Available Solar Radiation.

A.2 Meteorological data

The meteorological data used in the calculation are as follows :
- Calculation period: June 21 to September 21, 2020
- Radiation Data: Use total horizontal only (designated as “GLO” Hourly Global Radiation in meteorological data [325])
- Location: Nîmes Courbessac weather station (43.86°N, 4.41°E)

A.3 Calculation details

A.3.1 Variation of extraterrestrial radiation

Variation of the earth-sun distance does lead to variation in extraterrestrial radiation flux in the range of ±3.3%. A simple equation with accuracy adequate for most engineering calculations is given by Equation A.1.

$$G_{on} = G_{sc}(1 + 0.033 \cos \frac{360n}{365}) \tag{A.1}$$

where G_{on} is the extraterrestrial radiation incident on the plane normal to the radiation on the nth day of the year.

A.3.2 Direction of beam radiation

The geometric relationships between a plane of any particular orientation relative to the earth at any time (whether that plane is fixed or moving relative to the earth) and the incoming beam solar radiation, that is, the position of the sun relative to that plane, can be described in terms of several angles [326]. Some of the angles are indicated in Figure 1-1.

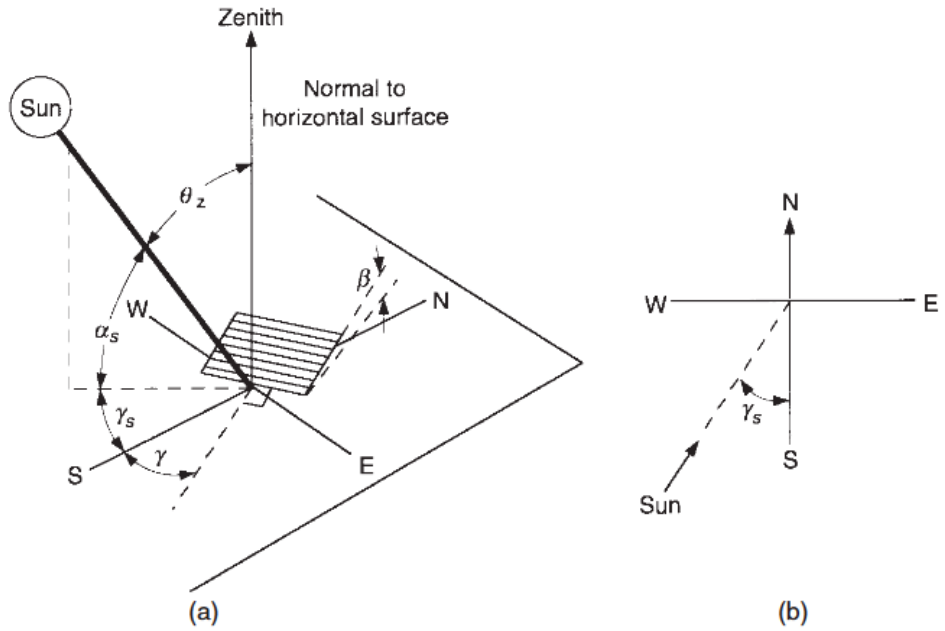


Fig. 1-1. (a) Zenith angle, slope, surface azimuth angle, and solar azimuth angle for a tilted surface. (b) Plan view showing solar azimuth angle.

The angles and a set of consistent sign conventions are as follows:

ϕ **Latitude**, the angular location north or south of the equator, north positive; -90° $\leq \phi \leq$ 90°.

δ **Declination**, the angular position of the sun at solar noon (i.e., when the sun is on the local meridian) with respect to the plane of the equator, north positive; -23.45° $\leq \delta \leq$ 23.45°.

β **Slope**, the angle between the plane of the surface in question and the horizontal; 0° $\leq \beta \leq$ 180°. ($\beta >$ 90° means that the surface has a downward-facing component.)

γ **Surface azimuth angle**, the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive; -180° $\leq \gamma \leq$ 180°.

ω **Hour angle**, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour; morning negative, afternoon positive.

θ **Angle of incidence**, the angle between the beam radiation on a surface and the normal to that surface.

Additional angles are defined that describe the position of the sun in the sky:

θ_z **Zenith angle**, the angle between the vertical and the line to the sun, that is, the angle of incidence of beam radiation on a horizontal surface.
α_s **Solar altitude angle**, the angle between the horizontal and the line to the sun, that is, the complement of the zenith angle.
γ_s **Solar azimuth angle**, the angular displacement from south of the projection of beam radiation on the horizontal plane, shown in Figure 1-1. Displacements east of the south are negative, and those west of the south are positive.

The declination δ can be found from the approximate equation of Cooper [327]:

$$\delta = 23.45 \sin\left(360\frac{284+n}{365}\right) \tag{A.2}$$

Where the day of the year n can be conveniently obtained with the help of Table 1-1.

Month	***n* for ith Day of Month**	**For Average Day of Month**		
		Date	**n**	δ
January	i	17	17	-20.9
February	31 + i	16	47	-13.0
March	59 + i	16	75	-2.4
April	90 + i	15	105	9.4
May	120 + i	15	135	18.8
June	151 + i	11	162	23.1
July	181 + i	17	198	21.2
August	212 + i	16	228	13.5
September	243 + i	15	258	2.2
October	273 + i	15	288	-9.6
November	304 + i	14	318	-18.9
December	334 + i	10	344	-23.0

Table 1-1. Recommended Average Days for Months and Values of n by Months *

* From Klein [328]. Do not use for $|\Phi| > 66.5°$.

Equations relating the angle of incidence of beam radiation on a surface, θ, to the other angles are:

$$\begin{aligned}\cos\theta = &\sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma \\ &+ \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega \\ &+ \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \tag{A.3}$$

and

$$\cos\theta = \cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos(\gamma_s - \gamma) \tag{A.4}$$

The angle θ may exceed 90°, which means that the sun is behind the surface. Also, when using Equation A.3, it is necessary to ensure that the earth is not blocking the sun (i.e., that the hour angle is between sunrise and sunset).

For horizontal surfaces, the angle of incidence is the zenith angle of the sun, θ_z. Its value must be between 0° and 90° when the sun is above the horizon. For this situation, $\beta = 0$, and Equation A.3 becomes:

$$\cos\theta_z = \cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta \tag{A.5}$$

The solar azimuth angle γ_s can have values in the range of 180° to -180°. For north or south latitudes between 23.45° and 66.45°, γ_s will be between 90° and -90° for days less than 12h long; for days with more than 12h between sunrise and sunset, γ_s will be greater than 90° or less than -90° early and late in the day when the sun is north of the east-west line in the northern hemisphere or south of the east-west line in the southern hemisphere. For tropical latitudes, γ_s can have any value when δ - ϕ is positive in the northern hemisphere or negative in the southern, for example, just before noon at ϕ = 10° and δ = 20°, γ_s = -180°, and just after noon γ_s = +180°. Thus γ_s is negative when the hour angle is negative and positive when the hour angle is positive. The sign function in Equations A.6 is equal to +1 if ω is positive and is equal to -1 if ω is negative:

$$\gamma_S = \text{sign}(\omega) \left| \cos^{-1}\left(\frac{\cos\theta_z \sin\phi - \sin\delta}{\sin\theta_z \cos\phi} \right) \right| \tag{A.6}$$

Equation A.5 can be solved for the **sunset hour angle** ω_s , when θ_z = 90°:

$$\cos\omega_s = -\frac{\sin\phi \sin\delta}{\cos\phi \cos\delta} = -\tan\phi \tan\delta \tag{A.7}$$

A.3.3 Ratio of beam radiation on tilted surface to that on horizontal surface

For purposes of solar process design and performance calculations, it is often necessary to calculate the hourly radiation on a tilted surface of a collector from measurements or estimates of solar radiation on a horizontal surface. The most commonly available data are total radiation for hours or days on the horizontal surface, whereas the need is for beam and diffuse radiation on the plane of a collector.

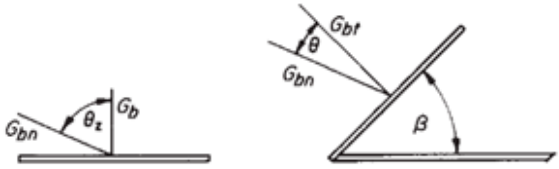


Fig. 1-2. Beam radiation on horizontal and tilted surfaces

The geometric factor R_b, the ratio of beam radiation on the tilted surface to that on a horizontal surface at any time, can be calculated exactly by appropriate use of Equation A.3. Figure 1-2 indicates the angle of incidence of beam radiation on the horizontal and tilted surfaces. The ratio $G_{b,T}/G_b$ is given by:

$$R_b = \frac{G_{b,T}}{G_b} = \frac{G_{b,n}\cos\theta}{G_{b,n}\cos\theta_z} = \frac{\cos\theta}{\cos\theta_z} \tag{A.8}$$

and $\cos\theta$ and cos $\cos\theta_z$ are both determined from Equation A.3 (or from equations derived from Equation A.3).

A.3.4 Extraterrestrial radiation on a horizontal surface

Several types of radiation calculations are most conveniently done using normalized radiation levels, that is, the ratio of radiation level to the theoretically possible radiation that would be available if there were no atmosphere. For these calculations, we need a method of calculating the extraterrestrial radiation. At any point in time, the solar radiation incident on a horizontal plane outside of the atmosphere is the normal incident solar radiation as given by Equation A.1 divided by R_b:

$$G_o = G_{sc}\left(1+0.033\cos\frac{360n}{365}\right)\cos\theta_z \tag{A.9}$$

where G_{sc} is the solar constant and n is the day of the year. Combining Equation A.5 for cos θ_z with Equation A.9 gives G_o for a horizontal surface at any time between sunrise and sunset:

$$G_o = G_{sc}\left(1+0.033\cos\frac{360n}{365}\right)(\cos\phi\cos\delta\cos\omega+\sin\phi\sin\delta) \tag{A.10}$$

It is often necessary for calculation of daily solar radiation to have the integrated daily extraterrestrial radiation on a horizontal surface, H_o. This is obtained by integrating Equation A.10 over the period from sunrise to sunset. If G_{sc} is in watts per square meter, H_o in daily joules per square meter per day is:

$$\begin{aligned} H_o = &\frac{24\times 3600 G_{sc}}{\pi}\left(1+0.033\cos\frac{360n}{365}\right) \\ &\times\left(\cos\phi\cos\delta\sin\omega_s+\frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \end{aligned} \tag{A.11}$$

where ω_s is the sunset hour angle, in degrees, from Equation A.7.

It is also of interest to calculate the extraterrestrial radiation on a horizontal surface for an hour period. Integrating Equation A.10 for a period between hour angles ω_1 and ω_2 which define an hour (where ω_2 is the larger):

$$I_o = \frac{12 \times 3600}{\pi} G_{sc} \left(1 + 0.033 \cos \frac{360n}{365}\right) \times \left[\cos\phi \cos\delta \left(\sin\omega_2 - \sin\omega_1\right) + \frac{\pi\left(\omega_2 - \omega_1\right)}{180} \sin\phi \sin\delta\right] \tag{A.12}$$

(The limits ω_1 and ω_2 may define a time other than an hour.)

A.3.5 Distribution of clear and cloudy days and hour

The frequency of the occurrence of periods of various radiation levels, for example, of good and bad days, is of interest in two contexts. First, information on the frequency distribution is the link between two kinds of correlations, that of the daily fraction of diffuse with daily radiation and that of the monthly average fraction of diffuse with monthly average radiation. Second, the concept of utilizability; it depends on the frequency distributions. An hourly clearness index k_T can be defined as:

$$k_T = \frac{I}{I_o} \tag{A.13}$$

The data I is from measurements of total solar radiation on a horizontal surface, that is, the commonly available pyranometer measurements. I_o is calculated using equation A.12.

A.3.6 Beam and diffuse components of hourly radiation

The split of total solar radiation on a horizontal surface into its diffuse and beam components is of interest in two contexts. First, methods for calculating total radiation on surfaces of other orientations from data on a horizontal surface require separate treatments of beam and diffuse radiation (see Section A.3.7.1). Second, estimates of the long-time performance of most concentrating collectors must be based on estimates of availability of beam radiation. The present methods for estimating the distribution are based on studies of available measured data; they are adequate for the first purpose but less than adequate for the second. The usual approach is to correlate I_d/I, the fraction of the hourly radiation on a horizontal plane which is diffuse, with k_T , the hourly clearness index.

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.09k_T & \text{for } k_T \leq 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 & \text{for } 0.22 < k_T \leq 0.80 \\ -16.638k_T^3 + 12.336k_T^4 & \\ 0.165 & \text{for } k_T > 0.8 \end{cases} \tag{A.14}$$

A.3.7 Radiation on sloped surface

We turn next to the general problem of the calculation of radiation on tilted surfaces when only the total radiation on a horizontal surface is known. For this, we need the directions from which the beam and diffuse components reach the surface in question.

The angular distribution of diffuse is to some degree a function of the reflectance ρ_g (the albedo) of the ground. A high reflectance (such as that of fresh snow, with $\rho_g \sim 0.7$) results in the reflection of solar radiation back to the sky, which in turn may be scattered to account for horizon brightening.

Consider the case when sunrise (or sunset) occurs at the midpoint of the hour; the cosine of the zenith angle is zero and R_b (Equation A.8) evaluated at the midpoint of the hour is infinite. Under these circumstances, the recorded radiation is not zero, so the estimated beam radiation on the tilted surface can be very large. Arbitrarily limiting R_b to some value may not be the best general approach as large values of R_b do occur even at midday at high-latitude regions during the winter. The best approach is to extend Equation A.8 from an instantaneous equation to one integrated over a time period ω_1 to ω_2.

It is clear that when ω_1 and ω_2 represent two adjacent hours in a day away from sunrise or sunset $R_{b,ave} \approx R_b$. However, when either ω_1 or ω_2 represent sunrise or sunset R_b changes rapidly and integration is needed:

$$R_{b,\,\text{ave}} = \frac{a}{b} \tag{A.15}$$

where

$$\begin{aligned} a =& (\sin\delta \sin\phi \cos\beta - \sin\delta \cos\phi \sin\beta \cos\gamma) \times \frac{1}{180}(\omega_2 - \omega_1)\,\pi \\ &+ (\cos\delta \cos\phi \cos\beta + \cos\delta \sin\phi \sin\beta \cos\gamma) \times (\sin\omega_2 - \sin\omega_1) \\ &- (\cos\delta \sin\beta \sin\gamma) \times (\cos\omega_2 - \cos\omega_1) \end{aligned}$$

and

$$b = (\cos\phi \cos\delta) \times (\sin\omega_2 - \sin\omega_1) + (\sin\phi \sin\delta) \times \frac{1}{180}(\omega_2 - \omega_1)\,\pi.$$

A.3.7.1 Radiation on sloped surfaces: isotropic sky

It can be assumed (as suggested by Hottel and Woertz [329]) that the combination of diffuse and ground-reflected radiation is isotropic. With this assumption, the sum of the diffuse from the sky and the ground-reflected radiation on the tilted surface is the same regardless of orientation, and the total radiation on the tilted surface is the sum of the beam contribution calculated as $I_b R_b$ and the diffuse on a horizontal surface, I_d . This represents an improvement over the assumption that all radiation can be treated as beam, but better methods are available. An improvement on this model, the isotropic diffuse model, was derived by Liu and Jordan [330].

$$I_T = I_b R_b + I_d \left(\frac{1+\cos\beta}{2} \right) + I\rho_g \left(\frac{1-\cos\beta}{2} \right) \tag{A.16}$$

A.3.7.2 Radiation on sloped surfaces: anisotropic sky

The Perez model [331] is based on a more detailed analysis of the three diffuse components. The diffuse on the tilted surface is given by:

$$I_{d,T} = I_d \left[(1-F_1) \left(\frac{1+\cos\beta}{2} \right) + F_1 \frac{a}{b} + F_2 \sin\beta \right] \tag{A.17}$$

where F_1 and F_2 are circumsolar and horizon brightness coefficients and a and b are terms that account for the angles of incidence of the cone of circumsolar radiation (Figure 1-3) on the tilted and horizontal surfaces. The circumsolar radiation is considered to be from a point source at the sun. The terms a and b are given as:

$$a = \max(0, \cos\theta), \quad b = \max(\cos 85, \cos\theta_z) \tag{A.18}$$

With these definitions, a/b becomes R_b for most hours when collectors will have useful outputs.

The brightness coefficients F_1 and F_2 are functions of three parameters that describe the sky conditions, the zenith angle θ_z, a clearness ε, and a brightness Δ, where ε is a function of the hour's diffuse radiation I_d and normal incidence beam radiation $I_{b,n}$. The clearness parameter is given by:

$$\varepsilon = \frac{\frac{I_d + I_{b,n}}{I_d} + 5.535 \times 10^{-6} \theta_z^3}{1 + 5.535 \times 10^{-6} \theta_z^3} \tag{A.19}$$

where θ_z is in degrees and the brightness parameter is:

$$\Delta = m \frac{I_d}{I_{on}} \tag{A.20}$$

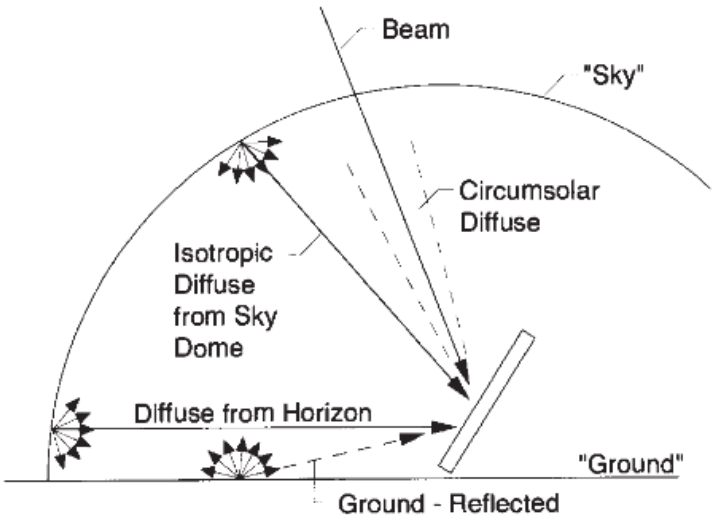


Fig. 1-3. Beam, diffuse, and ground-reflected radiation on a tilted surface.

where m is the air mass ($m = \frac{1}{\cos\theta}$) and I_{on} is the extraterrestrial normal-incidence radiation (Equation A.1), written in terms of I. Thus these parameters are all calculated from data on total and diffuse radiation (i.e., the data that are used in the computation of I_T). The brightness coefficients F_1 and F_2 are functions of statistically derived coefficients for ranges of values of ε; a recommended set of these coefficients is shown in Table 1-2.

Range of ε	f_{11}	f_{12}	f_{13}	f_{21}	f_{22}	f_{23}
1.000-1.065	-0.008	0.588	-0.062	-0.060	0.072	-0.022
1.065-1 - 1.230	0.130	0.683	-0.151	-0.019	0.066	-0.029
1.230-1.500	0.330	0.487	-0.221	0.055	-0.064	-0.026
1.500-1.950	0.568	0.187	-0.295	0.109	-0.152	0.014
1.950-2.800	0.873	-0.392	-0.362	0.226	-0.462	0.001
2.800-4.500	1.132	-1.237	-0.412	0.288	-0.823	0.056
4.500-6.200	1.060	-1.600	-0.359	0.264	-1.127	0.131
6.200-$\propto$	0.678	-0.327	-0.250	0.156	-1.377	0.251

Table 1-2. Brightness Coefficients for Perez Anisotropic Sky **

** From Perez et al. [331].

The equations for calculating F_1 and F_2 are:

$$F_1 = \max\left[0, \left(f_{11} + f_{12}\Delta + \frac{\pi\theta_z}{180} f_{13}\right)\right] \tag{A.21}$$

$$F_2 = \left(f_{21} + f_{22}\Delta + \frac{\pi\theta_z}{180} f_{23}\right) \tag{A.22}$$

This set of equations allows calculation of the three diffuse components on the tilted surface. It remains to add the beam and ground-reflected contributions. The total radiation on the tilted surface includes five terms: the beam, the isotropic diffuse, the circumsolar diffuse, the diffuse from the horizon, and the ground-reflected term:

$$\begin{aligned} I_T =& I_b R_b + I_d (1 - F_1) \left(\frac{1 + \cos\beta}{2} \right) + I_d F_1 \frac{a}{b} \\ &+ I_d F_2 \sin\beta + I \rho_g \left(\frac{1 - \cos\beta}{2} \right) \end{aligned} \tag{A.23}$$

Example 1

Using the isotropic sky model, estimate the total radiation on a surface sloped (β) 90° toward the south at a latitude of 43.83°N (latitude of Nîmes city) for the hour 9 to 10 AM on June 21 ($n^{th} = 172$). Here I (irradiation on horizontal surface) = 3.5 MJ/m^2 and ρ_g = 0.6.

Solution

For this hour, I_o = 4.44 MJ/m^2, so k_T = 3.5/4.44 = 0.78. From the Erbs correlation (Equation A.14), I_d/I = 0.16. Thus

$$\begin{aligned} I_d &= 0.16 \times 3.5 = 0.57 \quad MJ/m^2 \\ I_b &= 0.83 \times 3.5 = 2.92 \quad MJ/m^2 \end{aligned}$$

The hour angle ω for the midpoint of the hour is -7.5°. The declination δ = 23.45°. Then for this south-facing surface

$$\begin{aligned} \cos\theta &= \cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos(\gamma_s - \gamma) = 0.36 \\ \cos\theta_z &= \cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta = 0.93 \end{aligned}$$

Thus

$$R_b = \frac{0.36}{0.93} = 0.39$$

Equation A.16 gives the three radiation streams and the total:

$$\begin{aligned} I_T &= 2.92 \times 0.39 + 0.57 \left(\frac{1 + \cos 90}{2} \right) + 3.5 \times 0.6 \left(\frac{1 - \cos 90}{2} \right) \\ &= 1.14 + 0.28 + 1.05 \\ &= 2.47 \quad MJ/m^2 \end{aligned}$$

Thus the total horizontal radiation of 3.5 MJ/m^2 on the vertical surface for the hour is 2.47 MJ/m^2.

Example 2

Do Example 1 using the Perez method.

Solution

From Example 1, I_o = 4.44 MJ/m^2, I = 3.5 MJ/m^2, I_b = 2.92 MJ/m^2, I_d = 0.57 MJ/m^2, $\cos\theta$ = 0.36, θ = 68.8°, $\cos\theta_z$ = 0.93, θ_z = 21.3°, and R_b = 0.39.

To use Equation A.23, we need a, b, ε, and Δ in addition to the quantities already calculated:

$$a = \max(0, \cos 68.8) = 0.36$$
$$b = \max(\cos 85, \cos 21.3) = 0.93$$
$$\frac{a}{b} = 0.36/0.93 = 0.39 \text{(the same as } R_b \text{ in Example 1)}$$

Next we calculate Δ. The air mass m is

$$m = \frac{1}{\cos 21.3} = 1.07$$

We also need I_{on}. Use Equation A.1 with n = 172,

$$I_{on} = 4.92(1 + 0.033\cos(360 \times 172/365)) = 4.76$$

From the defining equation for Δ (Equation A.20),

$$\Delta = 1.07 \times \frac{0.57}{4.76} = 0.13$$

We next calculate ε from Equation A.19. Thus $I_{b,n} = I_b/\cos\theta_z$ = 3.14, and

$$\varepsilon = \frac{\frac{0.57+3.14}{0.57} + 5.535 \times 10^{-6}(21.3^3)}{1 + 5.535 \times 10^{-6}(21.3^3)} = 6.16$$

With this we can go to the table of coefficients needed in the calculation of F_1 and F_2. These are, for the seventh ε range,

$$f_{11} = 1.060, \quad f_{12} = -1.600, \quad f_{13} = -0.359$$
$$f_{21} = 0.264, \quad f_{22} = -1.127, \quad f_{23} = 0.131$$

So

$$F_1 = \max\left[0, \left(1.060 - 1.600 \times 0.13 + \frac{21.3\pi}{180} \times (-0.359)\right)\right] = 0.72$$
$$F_2 = 0.264 - 1.127 \times 0.13 + \frac{21.3\pi}{180} \times 0.131 = 0.17$$

We now have everything needed to use Equation A.23 to get the total radiation on the sloped surface:

$$\begin{aligned} I_T =& 2.92 \times 0.39 + 0.57\,(1 - 0.72)\left(\frac{1 + \cos 90}{2}\right) + 0.57 \times 0.72 \times 0.39 \\ &+ 0.57 \times 0.17 \sin 90 + 3.5 \times 0.6\left(\frac{1 - \cos 90}{2}\right) \\ &= 1.14 + 0.08 + 0.16 + 0.09 + 1.05 \\ &= 2.52 MJ/m^2 \end{aligned}$$

B. Climate sensors

B.1 Class'Air



Les Atouts

Grâce à ses leds, l'analyseur Class'Air permet en un coup d'oeil de vérifier la qualité de l'air intérieur environnant. Son design épuré cache une sonde CO2 à haute précision (technologie NDIR) qui permet l'affichage avec une résolution à 1 ppm près.

L' allumage des leds permet d'alerter et de sensibiliser à l'aération des pièces en fontion du taux de CO2. Outre la détection du CO2, Class' Air renseigne également sur la température, l'hygrométrie ainsi que la pression, tout en gardant une autonomie de 1 an.

Son option Datalogger, son interface logicielle et son certificat d'étalonnage en font un outil de campagne de mesure de la qualité de l'air indispensable.

Les Applications

Conçu pour un usage pédagogique, Class' Air possède différents supports afin de se fondre dans l'environnement de mesure (école, crèche, bureaux, etc....).

Class' Air permet un paramétrage simple et intuitif des seuils d'alertes, sur le capteur directement ou via son logiciel.



- *qualité d'air mauvaise, il est impératif de ventiler ou aérer la zone.*
- *qualité d'air moyenne, il est conseillé de ventiler la zone.*
- *qualité d'air correcte.*

Les Accessoires



Supports de fixation

- *Crochet pour fixation suspendue.*
- *Base pour fixation murale du capteur ou « posé sur un bureau ».*

Support USB et de recharge



- *Communication entre capteur / logiciel.*
- *Récupération des mesures.*
- *Recharge de la batterie.*

Logiciel Class'Air

- *Communication avec le capteur & paramétrage du capteur (seuils des 3 leds, activation des bips sonores).*
- *Gestion des campagnes (récupération des mesures, calcul de l'indice ICONE de confinement, édition de rapports).*
- *Archivage et traçabilité des données par capteur.*
- *Exportation des données au format tableur (.csv).*



FICHE TECHNIQUE

Conçu et fabriqué en France

Paramètres mesurés

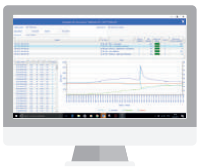
Dioxyde de Carbone CO2	Rapport en Partie Par Million (PPM)	De 0 à 5 000 ppm
	Résolution	1 ppm
	Principe de mesure du CO2	Technologie Infrarouge non dispersive (NDIR)
	Erreur de justesse à 25 °C et 1 013 mbar	≤, ± (50 ppm + 3% de la valeur mesurée)
	Indicateur de seuils	3 leds d'état (verte, orange, rouge)
	Compensation en Pression	Sur activation
Température	Plage de mesure	de -10 à +50 °C
	Résolution	0,1 °C
Hygrométrie	Plage de mesure	de 0 à 100 % RH
	Résolution	1 % RH
Pression	Plage de mesure	de 300 à 1 100 hPa
	Résolution	1 hPa

Option "Datalogger" (enregistrement des mesures)

Période d'acquisition :	Paramétrable (1 point moyenné sur 10 minutes par défaut).
Capacité d'enregistrement :	De plusieurs semaines à plusieurs mois Ex : 7 semaines pour 4 mesures relevées (CO2-T-HR-P) à 10 minutes.
Autonomie (batterie rechargeable) :	De plusieurs mois à plusieurs années suivant le paramétrage (périodes de mesure, activation des leds).



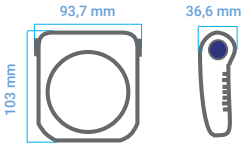
Station d'accueil des analyseurs



L' analyseur Class'Air mesure et enregistre dans sa fonction « Datalogger » le taux de CO2, la température, l'humidité et la pression.

Les 2 boutons intégrés en façade du capteur facilitent le démarrage / arrêt des mesures, complétés par des bips sonores associés.

L' analyseur Class'Air communique via un câble USB avec le logiciel Class'Air pour permettre, en plus de son paramétrage, la récupération et l'exploitation des données enregistrées.



Poids : 175 grammes



KR-WEB-CVP-FR20181120

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B.2 Elsys

Datasheet
Publish Date: 20.08.2019

ERS CO_2

ELSYS.se
LoRaWAN Wireless Sensor

Description



ERS CO_2 is a sensor for measuring the indoor environment. It is enclosed in a room sensor box and is designed to be wall mounted. ERS CO_2 is completely wireless and powered by two 3.6V AA lithium batteries. Inside you will find internal sensors for measuring indoor CO_2 levels, temperature, humidity, light, and motion.

Applications

- Indoor environment measuring
- Smart buildings
- Workplace management
- Room occupancy

Product features

- LoRaWAN Certified CM
- CO_2 sensor
- Temperature sensor
- Humidity sensor
- Light sensor
- Motion detection sensor (PIR)
- NFC for configuration
- Configuration over the air

Device Specifications

Mechanical specifications	
Weight	80 g excluding batteries / 120 g including batteries
Dimensions	86 x 86 x 28 mm
Enclosure	Plastic, PC/ABS

Operating conditions	
Temperature	0 to 40 °C
Humidity	0 to 85% RH (non-condensing)

Device Power Supply	
Battery Type	2 x 3.6V AA Lithium Batteries
Expected Battery Life	<10 years (Depending on configurations and environment)

Device Logging Function	
Sampling Interval	Configurable via NFC and downlink configuration
Data Upload Interval	Configurable via NFC and downlink configuration

Elektroniksystem i Umeå AB Industrivägen 12, 90130 Umeå, Sweden
E-mail: support@elsys.se | Web: www.elsys.se

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Datasheet
Publish Date: 20.08.2019

ELSYS.se
ERS CO_2

Radio / Wireless	
Wireless Technology	LoRaWAN® 1.0.3
Wireless Security	LoRaWAN® End-to-End encryption (AES-CTR), Data Integrity Protection (AES-CMAC)
LoRaWAN Device Type	Class A/C (configurable) End-device
Supported LoRaWAN® features	OTAA, ABP, ADR, Adaptive Channel Setup
Supportet LoRaWAN® regions	US902 – 928, EU863 – 870, AS923, AU915 – 928, KR920 – 923, RU864, IN865
Link Budget	137 dB (SF7) to 151 dB (SF12)
RF Transmit Power	14 dB / 20 dB (Region specific)

Data types			
Type value	*Type*	*Data size*	*Comment*
0x01	Temperature	2	-3276.5 °C → 3276.5 °C (Value of: 100 → 10.0 °C)
0x02	Humidity	1	0 – 100 %
0x04	Light	2	0 – 65535 Lux
0x05	Motion (PIR)	1	0 – 255 (Number of motion counts)
0x06	CO_2	2	0 – 10000 ppm
0x07	VDD (Battery voltage)	2	0 – 65535 mV
0x3D	Debug information	4	Data depends on debug information
0x3E	Sensor settings	n	Sensor setting sent to server at startup (first package). Sent on Port+1.

Sensors

Temperature

Resolution: 0.1 °C

Accuracy: ±0.2 °C (See figure 1)

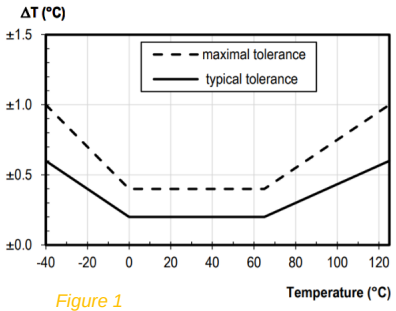

Figure 1

Humidity

Resolution: 0.1 % RH

Accuracy at 25 °C: ± 2 % RH (See figure 2)

Accuracy of humidity over temperature: See figure 3

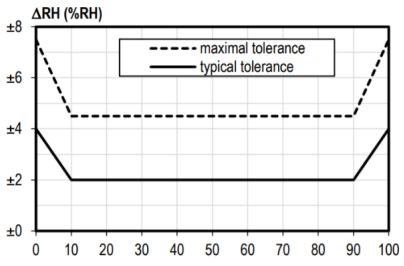

Figure 2

Elektroniksystem i Umeå AB Industrivägen 12, 90130 Umeå, Sweden
E-mail: support@elsys.se | Web: www.elsys.se

Specifications in this document are subject to change without notice.
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Light

Range: 4 – 2000 LUX

Resolution: 1 LUX

Accuracy: ± 10 LUX

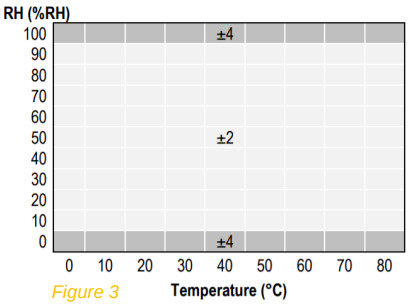
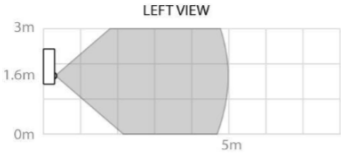
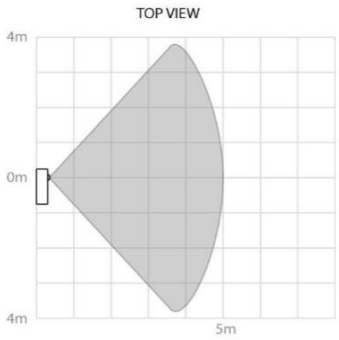


Figure 3

Motion (PIR)





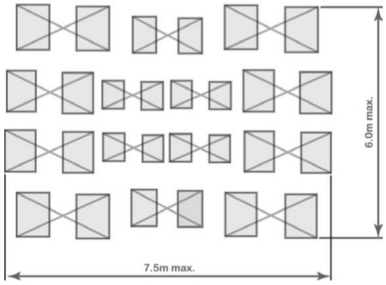


Figure 4 - Detection pattern

Note:
There is a blanking time of 30 seconds of the PIR triggering after each PIR trig and after each transmission. This is to reduce the risk of self-triggering from internal events that could disturb the high sensitivity PIR circuits.

CO_2

Range: 0 – 10000 ppm

Accuracy: ± 50 ppm / ± 3% of reading

Accuracy is met at 10 – 40°C, 0 – 60%RH, after minimum three (3) performed Automatic Baseline. Corrections, preferably spanning eight (8) days in-between, or a successful zero-calibration

Noise: 14 ppm @ 400 ppm / 25 ppm @ 1000 ppm

Note:
The CO2 sensor has an internal automatic calibration routine. This routine calibrates the sensor to set 400 ppm to the lowest value that has been read in the last period of approximately 8 days. This means that in an 8 day period, the sensor must be exposed to fresh (well ventilated) air at least once for the calibration to work. The sensor can also be manually calibrated.

Elektroniksystem i Umeå AB Industrivägen 12, 90130 Umeå, Sweden
E-mail: support@elsys.se | Web: www.elsys.se

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C. Survey questionnaire sheet



+1/1/60+

ENQUÊTE DE CONFORT PERSONNEL **Été 2023**

Bâtiment:	Salle:	Date - Heure (dd/mm/yy - HH:mm):
.....	.....	.....

QUESTIONS SUR LA SALLE DE COURS/TD/TP

Paramètres de confort

Où êtes-vous assis dans la salle? ☐ À côté de la fenêtre ☐ À côté du mur intérieur ☐ Au centre de la pièce

Utilisez-vous un ordinateur ou d autre appareil pour ce cours? ☐ oui ☐ non

La porte est-elle ouverte ? ☐ oui ☐ non

Y a-t-il des fenêtres ouvertes ? ☐ non ☐ partiellement ☐ totalement

Y a-t-il des volets ouverts ? ☐ non ☐ partiellement ☐ totalement

QUESTIONS SUR VOTRE PERCEPTION

Comment appréciez-vous la température de cette salle ?

☐ Très froid ☐ Froid ☐ Neutre ☐ Chaud ☐ Très chaud

Comment appréciez-vous l'humidité?

☐ Très sec ☐ Sec ☐ Neutre ☐ Humide ☐ Très humide

Comment appréciez-vous les mouvements d'air ?

☐ Immobile ☐ Faible ☐ Correct ☐ Fort ☐ Très fort

Comment appréciez-vous l'odeur (désagréable au niveau des gens, des poussières, du mobilier, etc.) ?

☐ Pas d'odeur ☐ Odeur faible ☐ Odeur forte

QUESTIONS SUR VOTRE ACCEPTABILITÉ

Évaluez votre acceptabilité de :

la température	☐ Acceptable	☐ Plutôt Acceptable	☐ Plutôt inacceptable	☐ Inacceptable
l'humidité	☐ Acceptable	☐ Plutôt Acceptable	☐ Plutôt inacceptable	☐ Inacceptable



+1/2/59+

les flux d'air	☐ Acceptable	☐ Plutôt Acceptable	☐ Plutôt inacceptable	☐ Inacceptable
l'odeur	☐ Acceptable	☐ Plutôt Acceptable	☐ Plutôt inacceptable	☐ Inacceptable

QUESTIONS SUR VOTRE PRÉFÉRENCE

Quelle température pour la pièce souhaiteriez-vous ?

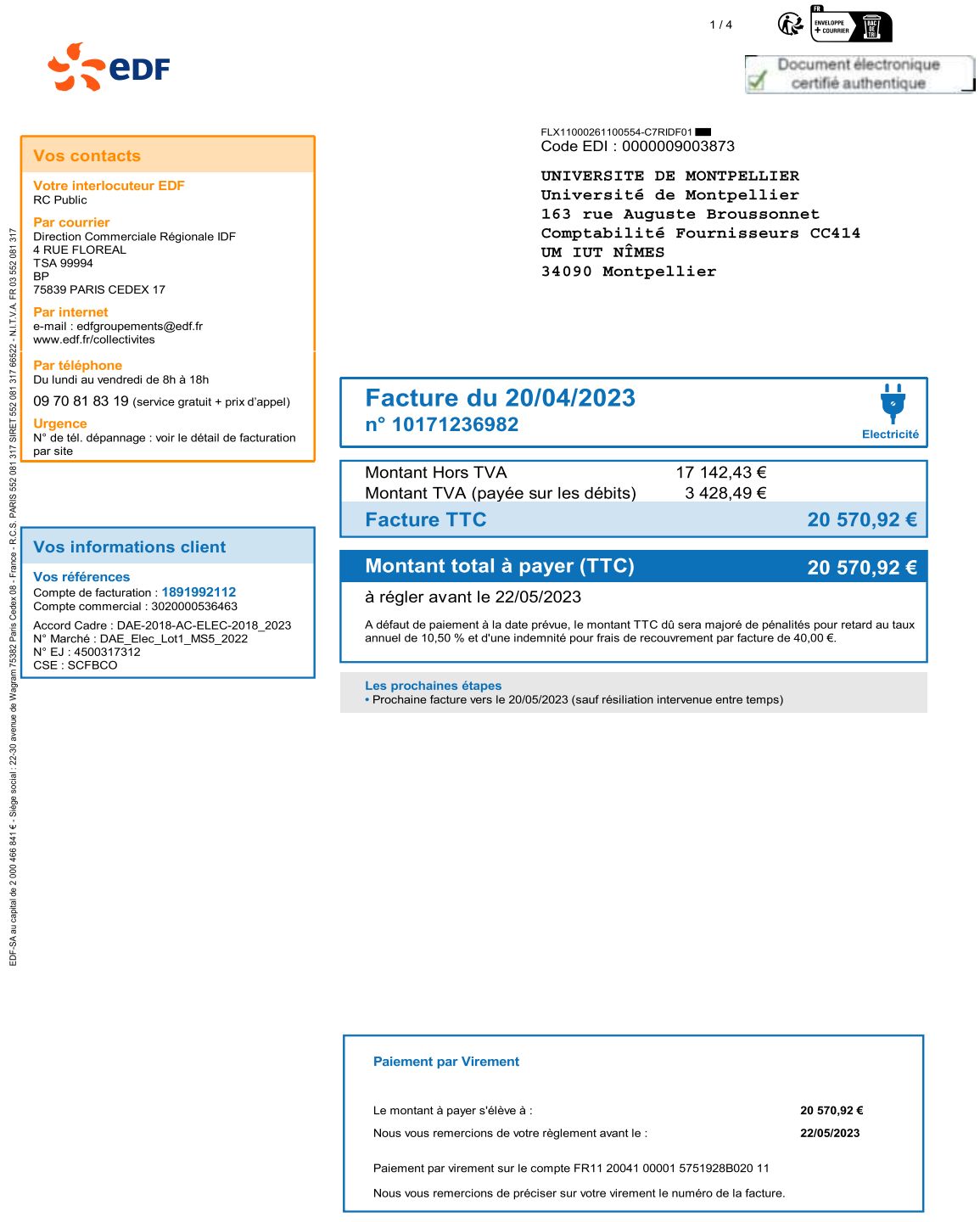
☐ Plus chaud ☐ Pas de changement ☐ Plus froid

Que feriez-vous pour satisfaire votre confort de l'état actuel de la pièce?
(Plusieurs selections possibles)

☐ Ouvrir la/les fenêtre(s)
☐ Fermer la/les fenêtre(s)
☐ Ouvrir la porte
☐ Fermer la porte
☐ Ouvrir le/les volet(s)
☐ Fermer le/les volet(s)
☐ Augmenter la ventilation
☐ Diminuer la ventilation

D. Electric and Heating Energy bills

D.1 Electricity bill



1 / 4

Document électronique certifié authentique

FLX11000261100554-C7RIDF01
Code EDI : 0000009003873

UNIVERSITE DE MONTPELLIER
Université de Montpellier
163 rue Auguste Broussonnet
Comptabilité Fournisseurs CC414
UM IUT NÎMES
34090 Montpellier

Vos contacts

Votre interlocuteur EDF
RC Public

Par courrier
Direction Commerciale Régionale IDF
4 RUE FLOREAL
TSA 99994
BP
75839 PARIS CEDEX 17

Par internet
e-mail : edfgroupements@edf.fr
www.edf.fr/collectivites

Par téléphone
Du lundi au vendredi de 8h à 18h
09 70 81 83 19 (service gratuit + prix d'appel)

Urgence
N° de tél. dépannage : voir le détail de facturation par site

Vos informations client

Vos références
Compte de facturation : 1891992112
Compte commercial : 3020000536463

Accord Cadre : DAE-2018-AC-ELEC-2018_2023
N° Marché : DAE_Elec_Lot1_MS5_2022
N° EJ : 4500317312
CSE : SCFBCO

Facture du 20/04/2023
n° 10171236982
Electricité

Montant Hors TVA	17 142,43 €
Montant TVA (payée sur les débits)	3 428,49 €
Facture TTC	**20 570,92 €**

Montant total à payer (TTC) 20 570,92 €

à régler avant le 22/05/2023

A défaut de paiement à la date prévue, le montant TTC dû sera majoré de pénalités pour retard au taux annuel de 10,50 % et d'une indemnité pour frais de recouvrement par facture de 40,00 €.

Les prochaines étapes
• Prochaine facture vers le 20/05/2023 (sauf résiliation intervenue entre temps)

Paiement par Virement

Le montant à payer s'élève à : **20 570,92 €**
Nous vous remercions de votre règlement avant le : **22/05/2023**

Paiement par virement sur le compte FR11 20041 00001 5751928B020 11

Nous vous remercions de préciser sur votre virement le numéro de la facture.

EDF-SA au capital de 2 000 466 841 € - Siège social : 22-30 avenue de Wagram 75382 Paris Cedex 08 - France - R.C.S. PARIS 552 081 317 SIRET 552 081 317 66522 - N.I.T.V.A. FR 03 552 081 317

Document à conserver 10 ans

Facture du 20/04/2023 n° 10171236982
Récapitulatif de votre facture

Total Electricité (HT)		**16 979,02 €**
Fourniture		19 927,74 €
Mécanisme de capacité		357,71 €
CEE (Certificats d'Economies d'Energie)		346,12 €
Amortisseur Electricité		-5 355,62 €
Acheminement		1 703,07 €
Taxes et contributions Hors TVA (identiques pour l'ensemble des fournisseurs)		**163,41 €**
Contribution Tarifaire d'Acheminement électricité (CTA)		135,85 €
Contribution au Service Public de l'Electricité (CSPE)		27,56 €
Services (HT)		**0,00 €**
Services		0,00 €
Total Hors TVA		**17 142,43 €**
TVA (identique pour l'ensemble des fournisseurs)	Assiette	**3 428,49 €**
TVA à 20,00%	17 142,43	3 428,49 €
Total TTC facturés sur la période		**20 570,92 €**

Nombre de Points de Livraison facturés 1

Prix
Aucun escompte n'est accordé pour paiement anticipé
Retrouver l'ensemble de nos offres, des tarifs et autres informations sur la gestion de votre énergie sur www.edf.fr/collectivites

Réclamations
Vous souhaitez faire une réclamation écrite ? Vous pouvez vous adresser à EDF, qui met à disposition un parcours en trois étapes, pour vous assurer une réponse dans les meilleurs délais. Etape 1 : vous adressez votre réclamation au Service Clients, dont les coordonnées se trouvent en haut à gauche de votre facture dans la rubrique contact.
Etape 2 : la réponse apportée par le Service Clients ne vous satisfait pas, vous pouvez alors envoyer votre réclamation à l'attention du Directeur Commercial Régional dont l'adresse figure en haut à gauche de votre facture. Etape 3 : vous restez en désaccord avec la réponse du Directeur Commercial Régional, vous pouvez dans ce cas solliciter le Médiateur EDF par internet sur https://mediateur.edf.fr ou par écrit au Médiateur EDF – TSA 50026 – 75804 PARIS CEDEX 8. Indépendamment de ce parcours en 3 étapes, si dans un délai de deux mois, votre réclamation écrite auprès d'EDF n'a pas permis de régler le différend, vous pouvez saisir le médiateur national de l'énergie dans le respect de son champ de compétence déterminé par les articles L122-1 et suivants du Code de l'énergie sur www.energie-mediateur.fr ou par écrit au Médiateur national de l'énergie – Libre réponse n°59252 – 75443 PARIS CEDEX 9.

Origine 2021 de l'électricité des offres EDF sans option énergie renouvelable: 82,7% nucléaire, 8,03% renouvelables (dont 2% hydraulique, 3,1% éolien, 1,9% solaire, 1% Biomasse, > 0,1% Géothermie), 7,5% gaz, 0,9% charbon, 0,4% pétrole, 0,4 % autres fossiles.
Origine 2021 de l'électricité des offres EDF certifiées 100% d'origine renouvelable (via le mécanisme des garanties d'origine, sans engagement de provenance/filière) :
94,3% hydraulique : 93,4% France et 0,9% hors France (Norvège, Suède, Allemagne, Finlande),
2,6% éolien : 2% France (dont 1,6% enchères) et 0,6% hors France (Italie, Croatie, Espagne, Suède),
1,6% biomasse : 0,04% France et 1,6% hors France (Danemark, Finlande, Italie, Suède, Croatie, Pays-Bas, Portugal),
1,5% solaire : 1,1% France (dont 1% enchères) et 0,4% hors France (Italie, Espagne, Portugal, République Tchèque).
Origine 2021 de l'électricité des offres EDF certifiées 100% d'origine renouvelable France (via le mécanisme des garanties d'origine France) : 84,2% hydraulique, 15% éolien, 0,5% solaire, 0,3% biomasse.
Si votre option énergie renouvelable (sans engagement de provenance/filière ou France) est inférieure à 100%, le mix de votre offre correspond à la pondération des mix concernés ci-dessus en fonction du pourcentage d'énergie renouvelable retenu (ex : pour une option énergie renouvelable de 20% : le mix « énergie renouvelable 100% » s'applique pour 20% de la consommation et le mix sans option énergie renouvelable pour le reste de la consommation).
Origine 2021 de l'ensemble de l'électricité vendue par EDF à ses clients et indicateurs d'impacts environnemental sur www.edf.fr

UNIVERSITE DE MONTPELLIER

Détail de votre facturation par site du 20/04/2023 n° 10171236982

Données contrat

Contrat Electricité Structuré
Réf. de votre contrat 2010006651442
Prix non réglementés
Souscrit depuis le 01/01/2023
Venant à échéance le 31/12/2023
Groupe de sites : Lot 02 | C2C3C4 | TR | 1P

Données Point de Livraison

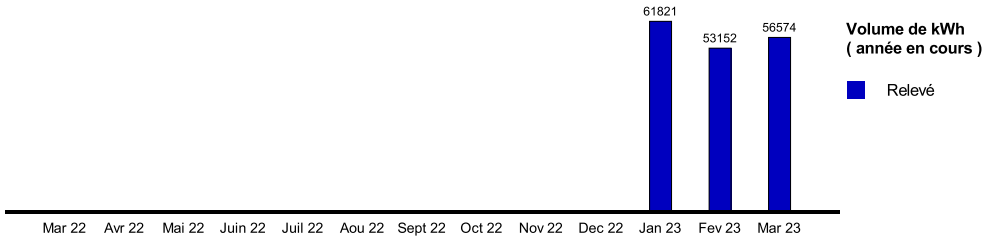
8 Rue Jules Raimu 30000 NIMES
Réf Acheminement Electricité : 30002450052868
Code site : 14_IUT_NIMES

Document à conserver 10 ans

Urgence

Dépannage Electricité Enedis
0 811 010 211 Service 0,05 €/appel + prix appel

Evolution de la consommation facturée en kWh



Total EDF Electricité				15 275,95 €	HT
Consommation (HT)	Période	Conso 55 116 kWh	Prix unitaire HT	15 275,95 €	Taux de TVA
Electricité Période unique	du 01/03/2023 au 31/03/2023	56 574 kWh	36,156 c€/kWh	20 454,90 €	20,00 %
Amortisseur Electricité Période unique	du 01/03/2023 au 31/03/2023	56 574 kWh	-9,717 c€/kWh	-5 497,30 €	20,00 %
Mécanisme de capacité Période unique	du 01/03/2023 au 31/03/2023	56 574 kWh	0,649 c€/kWh	367,17 €	20,00 %
CEE (Certificats d'Economies d'Energie)	du 01/03/2023 au 31/03/2023	56 574 kWh	0,628 c€/kWh	355,28 €	20,00 %
Estimation Electricité Période unique	du 01/04/2023 au 20/04/2023	36 508 kWh	36,156 c€/kWh	13 199,83 €	20,00 %
Estimation Amortisseur Electricité Période unique	du 01/04/2023 au 20/04/2023	36 508 kWh	-9,720 c€/kWh	-3 547,48 €	20,00 %
Estimation Mécanisme de capacité Période unique	du 01/04/2023 au 20/04/2023	36 508 kWh	0,649 c€/kWh	236,94 €	20,00 %
Estimation CEE (Certificats d'Economies d'Energie)	du 01/04/2023 au 20/04/2023	36 508 kWh	0,628 c€/kWh	229,27 €	20,00 %
Annulation estimation facture n°10169112685 Période unique	du 01/03/2023 au 20/03/2023	-37 966 kWh	36,156 c€/kWh	-13 726,99 €	20,00 %
Annulation Estimation Amortisseur Electricité Période unique	du 01/03/2023 au 20/03/2023	-37 966 kWh	-9,720 c€/kWh	3 689,16 €	20,00 %
Annulation Estimation Mécanisme de capacité Période unique	du 01/03/2023 au 20/03/2023	-37 966 kWh	0,649 c€/kWh	-246,40 €	20,00 %
Annulation Estimation CEE (Certificats d'Economies d'Energie)	du 01/03/2023 au 20/03/2023	-37 966 kWh	0,628 c€/kWh	-238,43 €	20,00 %

Utilisation du réseau de distribution et prestations techniques (identique pour l'ensemble des fournisseurs)				1 703,07 €	HT
		Quantité	Prix unitaire HT		Taux de TVA
Composante de gestion - Reprise	du 01/03/2023 au 30/03/2023			-30,97 €	20,00 %
Composante de gestion - Echu	du 01/03/2023 au 31/03/2023	31.000 c.j	103.23 c€/c.j	32,00 €	20,00 %
Composante de gestion - Echoir	du 01/04/2023 au 30/04/2023	30.000 c.j	103.23 c€/c.j	30,97 €	20,00 %
Composante de comptage - Reprise	du 01/03/2023 au 30/03/2023			-26,24 €	20,00 %
Composante de comptage - Echu	du 01/03/2023 au 31/03/2023	31.000 p.j	87.45 c€/p.j	27,11 €	20,00 %
Composante de comptage - Echoir	du 01/04/2023 au 30/04/2023	30.000 p.j	87.45 c€/p.j	26,24 €	20,00 %
Composante de soutirage fixe - Reprise	du 01/03/2023 au 30/03/2023	PS pondérée : 290 kW		-542,27 €	20,00 %
Composante de soutirage fixe - Echu	du 01/03/2023 au 31/03/2023	8990.000 kW	6.23 c€/kW	560,35 €	20,00 %
Composante de soutirage fixe - Echoir	du 01/04/2023 au 30/04/2023	8700.000 kW	6.23 c€/kW	542,27 €	20,00 %
Composante de soutirage Pointe	du 01/03/2023 au 31/03/2023	0.000 kWh	2.78 c€/kWh	0,00 €	20,00 %
Composante de soutirage Heures Pleines Hiver	du 01/03/2023 au 31/03/2023	39893.000 kWh	2.11 c€/kWh	841,74 €	20,00 %
Composante de soutirage Heures Creuses Hiver	du 01/03/2023 au 31/03/2023	16681.000 kWh	1.45 c€/kWh	241,87 €	20,00 %
Composante de soutirage Heures Pleines Eté	du 01/03/2023 au 31/03/2023	0.000 kWh	0.80 c€/kWh	0,00 €	20,00 %
Composante de soutirage Heures Creuses Eté	du 01/03/2023 au 31/03/2023	0.000 kWh	0.67 c€/kWh	0,00 €	20,00 %
Dépassement quadratique Pointe	du 01/03/2023 au 31/03/2023	0.000 kW	2275.00 c€/kW	0,00 €	20,00 %
Dépassement quadratique Heures Pleines Hiver	du 01/03/2023 au 31/03/2023	0.000 kW	2108.00 c€/kW	0,00 €	20,00 %
Dépassement quadratique Heures Creuses Hiver	du 01/03/2023 au 31/03/2023	0.000 kW	1460.00 c€/kW	0,00 €	20,00 %
Dépassement quadratique Heures Pleines Eté	du 01/03/2023 au 31/03/2023	0.000 kW	1083.00 c€/kW	0,00 €	20,00 %
Dépassement quadratique Heures Creuses Eté	du 01/03/2023 au 31/03/2023	0.000 kW	676.00 c€/kW	0,00 €	20,00 %
Tangente Phi : 0.198	du 01/03/2023 au 31/03/2023				
Composante réactive gratuite	du 01/03/2023 au 31/03/2023			0,00 €	
Eléments de calcul, pour information	39893 kWh (6h-22h)	7916kVArh (6h-22h)	7916 kVArh en franchise		

Services			0,00 €	HT
		Assiette		Taux de TVA
E-Services (Espace client, Bilan annuel)			INCLUS	

Taxes et contributions (identiques pour l'ensemble des fournisseurs)				163,41 €	Hors TVA
	Période	Assiette	Prix unitaire HorsTVA		Taux de TVA
Contribution au Service Public de l'Electricité	du 01/03/2023 au 20/04/2023	93 082 kWh	0,05000 c€/kWh	46,54 €	20,00 %
Annulation de CSPE sur consommations estimées	du 01/03/2023 au 20/03/2023	-37 966 kWh	0,05000 c€/kWh	-18,98 €	20,00 %
Contribution Tarifaire d'Acheminement	du 01/03/2023 au 01/04/2023	619,46	21,93 %	135,85 €	20,00 %

UNIVERSITE DE MONTPELLIER

Détail de votre facturation par site du 20/04/2023 n° 10171236982

Données contrat

Contrat Electricité Structuré
Réf. de votre contrat 2010006651442
Prix non réglementés
Souscrit depuis le 01/01/2023
Venant à échéance le 31/12/2023
Groupe de sites : Lot 02 | C2C3C4 | TR | 1P

Données Point de Livraison

8 Rue Jules Raimu 30000 NIMES
Réf Acheminement Electricité : 30002450052868
Code site : 14_IUT_NIMES

Total Hors TVA pour ce site		**17 142,43 €**	**Hors TVA**
TVA (identique pour l'ensemble des fournisseurs)	Assiette	**3 428,48 €**	
TVA à 20,00%	17 142,43 €	3 428,48 €	
Total TTC pour ce site		**20 570,91 €**	**TTC**

Les montants de TVA et le montant TTC par site sont fournis à titre d'information. Seuls les montants figurant sur la première page font foi.

Données de comptage

Identifiant de comptage : 041536048113 **Type de compteur :** PME-PMI
Pertes Fer : 0,930 W **Pertes Joule :** 1,010
Acheminement : Tarif HTA5 à Pointe Fixe Longue Utilisation
Puissance souscrite actuelle (kW ou kVA) : 290

Puissance(s) souscrite(s) (kW ou kVA)

Operateur Heures de pointe	290
Operateur Heures de pointe	290
Opérateur Heures pleines hiver	290
Opérateur Heures pleines hiver	290
Opérateur Heures creuses hiver	290
Opérateur Heures creuses hiver	290
Opérateur Heures pleines été	290
Opérateur Heures pleines été	290
Opérateur Heures creuses été	290
Opérateur Heures creuses été	290

Index (**relevés** / estimés)	index de début	index de fin
Pointe	278283 le 01/03/2023	**278283 le 31/03/2023**
Heures Pleines Hiver	1534264 le 01/03/2023	**1574157 le 31/03/2023**
Heures Creuses Hiver	752550 le 01/03/2023	**769231 le 31/03/2023**
Heures Pleines Eté	1544709 le 01/03/2023	**1544709 le 31/03/2023**
Heures Creuses Eté	691580 le 01/03/2023	**691580 le 31/03/2023**

Puissances atteintes (kW ou kVA)

du 01/03/2023 au 31/03/2023 : **Pointe**	0
du 01/03/2023 au 31/03/2023 : **Heures Pleines Hiver**	203
du 01/03/2023 au 31/03/2023 : **Heures Creuses Hiver**	66
du 01/03/2023 au 31/03/2023 : **Heures Pleines Eté**	0
du 01/03/2023 au 31/03/2023 : **Heures Creuses Eté**	0

D.2 Heating energy bill

nîmergie

Lieu de règlement :
Le Kaly
15A avenue Albert Einstein VILLEURBANNE 69100 France
Courriel : virtbanclyon@dalkia.fr
IBAN : FR76 3000 4008 1900 0119 0336 461
BIC : BNPAFRPPPAC

1. Références

Facture n° 0284 E R17858 du 03/04/2023
Payable pour le 09/05/2023

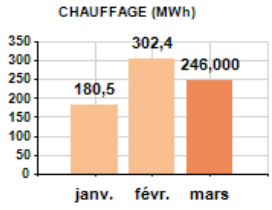
Saison : 2022/2023
Echéance au : 31/03/2023
Période de facturation : 01/03/2023 au 31/03/2023

Une question sur votre facture ?
M. FRANCOIS Philippe – Tél. : philippe.francois@dalkia.fr
Vos références
Police abonnement du 23/10/2013 et avenants
Service exécutant : SCFBCO
Engagement juridique 4500289310
Nos références
Contrat n°3026765K / GL0019532W / 0284 E 30 A 100/14 / PHF

A rappeler lors du paiement :
L00163690K / 0529389L / 0284 E R17858

UNIVERSITE DE MONTPELLIER
BAT 7 CC414 PLACE EUGENE BATAILLON
SCE FACTURIER
34095 MONTPELLIER

2. Récapitulatif de votre facture



C.U. DE NIMES - SST 101 - INSTITUT UNIVERSITAIRE DE TECHNOLOGIE

TERME PROPORTIONNEL R1

CHAUFFAGE	Quantités	Prix	TVA	Montant HT
R1	246,000 MWh	52,57	5,5%	12 932,22 €
Total à facturer				12 932,22 €
Montant TVA (5,5%)				711,27 €
Total TTC à payer				**13 643,49 €**

Voir détail au dos

dalkia GROUPE EDF

Payable à la date mentionnée ci-dessus. Sauf stipulation contraire qui ne peut toutefois fixer un taux inférieur à 3 fois le taux d'intérêt légal, le taux d' intérêt des pénalités de retard exigibles le jour suivant la date de règlement est égal au taux d'intérêt appliqué par la Banque centrale européenne à son op ération de refinancement la plus récente majoré de 10 points de pourcentage. En outre, le montant de l'indemnité pour frais de rec ouvrement est fixé à 40 euros, et porté, le cas échéant, à hauteur du coût des frais réellement exposés.

NIMERGIE - S.A.S. au capital de 500 000 Euros - SIRET 52923958400046 - RCS NIMES - APE 3511Z - Siège social : 150 AVENUE AMEDEE BOLLE - 30900 NIMES - N° Intracommunautaire FR66529239584

nîmergie

C.U. DE NIMES - SST 101 - INSTITUT UNIVERSITAIRE DE TECHNOLOGIE
Facture n°0284 E R17858 du 03/04/2023
A rappeler lors du paiement : L00163690K / 0529389L / 0284 E R17858

3. Détail des redevances hors taxes

CHAUFFAGE	TERME PROPORTIONNEL R1 - R1				
Energie	Coef. Mixité	Libellé	Détail du calcul	Référence	
TERME PROPORTIONNEL R1C	0,13810	Prix révisé	26,91 € x 1,777427	Révision A	47,83 €
TERME PROPORTIONNEL R1G	0,30390	Prix révisé	51,46 € x 1,777427	Révision A	91,47 €
TERME PROPORTIONNEL R1OM	0,55800	Prix révisé	28,69 € x 1,134570	Révision B	32,55 €
				Prix mixte 1 = 0,1381 x 47,83 € + 0,3039 x 91,47 € + 0,558 x 32,55 € =	**52,57 €**

CHAUFFAGE		TERME PROPORTIONNEL R1 R1		R1 - COMBUSTIBLE
Période	Libellé	Détail du calcul	Référence	Résultat HT
	Prix révisé	52,57 €	Mixte 1	
01/03/2023 au 31/03/2023	Montant redevance	52,57 x 246,000 MWh	Conso 1	12 932,22 €
			Total HT	**12 932,22 €**

4. Révision des prix

Révision A – Révision au 31/03/2023

$$0{,}1092 + 0{,}1898 \times \frac{641 \times (TCS + TCR \times 3 + TCL) + PFGRDF + 641 \times PPGRDF + Cst - 0}{641 \times (TCS_0 + TCR_0 \times 3 + TCL_0) + PFGRDF_0 + 641 \times PPGRDF_0} + 0{,}0194 \times \frac{TVT4}{TVT4_0} + 0{,}0201 \times \frac{C \times CTAT \times 641 \times (TCS + TCR \times 3 + TCL) + CTAD \times (PFGRDF + 641 \times PPGRDF)}{CTAT_0 \times 641 \times (TCS_0 + TCR_0 \times 3 + TCL_0) + CTAD_0 \times (PFGRDF_0 + 641 \times PPGRDF_0)} + 0{,}6574 \times \frac{PEG5D}{PEG5D_0} + 0{,}0029 \times (0{,}986 \times \frac{TICGN \times 1}{TICGN_0 \times 0{,}09} + 0{,}014 \times \frac{CSPG}{CSPG_0}) + 0{,}0012 \times \frac{CTSS}{CTSS_0}$$

Ref.	Libellé Variable	Valeur finale		Valeur contrat	
TCS	TCS GRT Gaz	93,25000	/	76,22000	
TCR	TCR GRT Gaz	82,62000	/	54,97000	
TCL	TCL GRT Gaz PITD	48,54000	/	27,48000	
PF GRDF	T4 - GRDF - Abonnement Annuel	15 405,24000	/	13 737,72000	
PP GRDF	T4 - GRDF - Terme de Souscription Annuelle	204,12000	/	178,68000	
Cst	Stockage NIMERGIE	55 485,24000	/		
TV T4	T4 - GRDF - Prix Proportionnel	0,84000	/	0,71000	
C	ASSIETTE CTA TRANS.DISTRIB SVD17	0,84130	/		
CTAT	Taux CTA Transport	0,04710	/	0,05300	
TCS	TCS GRT Gaz	93,25000	/		
TCR	TCR GRT Gaz	82,62000	/		
TCL	TCL GRT Gaz PITD	48,54000	/		
CTAD	Taux CTA Distribution	0,20800	/	0,17700	
PF GRDF	T4 - GRDF - Abonnement Annuel	15 405,24000	/		
PP GRDF	T4 - GRDF - Terme de Souscription Annuelle	204,12000	/		
PEG 5D	PEG Gaz Futures Settlement Price 5 days	47,37900	/	24,07000	
TICGN	TICGN ETS	0,15200	/	0,11900	
CSPG	CSPG	0,00000	/	0,00015	
CTSS	Contribution TSS	0,00000	/	0,00450	
			Coefficient de révision		**1,777427**

nîmergie

C.U. DE NIMES - SST 101 - INSTITUT UNIVERSITAIRE DE TECHNOLOGIE
Facture n°0284 E R17858 du 03/04/2023
A rappeler lors du paiement : L00163690K / 0529389L / 0284 E R17858

Détail des prix et indexations

Prix	Période	Référence	Date d'effet	Jours	Valeur	Moyenne prorata du temps
TCS		TCS GRT Gaz - Terme Capacité Sortie réseau	01/04/2022		93,25000	93,25000
TCR		TCR GRT Gaz - Terme Capacité transport Résea	01/04/2022		82,62000	82,62000
TCL		TCL GRT Gaz PITD - Terme de Capacité de Livraison	01/04/2022		48,54000	48,54000
PF GRDF		T4 - GRDF - Tarifs de Distribution - Abonnement Annuel	01/07/2022		15 405,24000	15 405,24000
PP GRDF		T4 - GRDF - Tarifs de Distribution - Terme de Souscription Annuelle	01/07/2022		204,12000	204,12000
Cst		Stockage NIMERGIE - Gaz divers Med - € HT / An	01/04/2021		55 485,24000	55 485,24000
TV T4		T4 - GRDF - Tarifs de Distribution - Prix Proportionnel	01/07/2022		0,84000	0,84000
C		ASSIETTE CTA TRANS.DISTRIB SVD17 - Tarif SVD17 & PEG	01/07/2022		0,84130	0,84130
CTAT		Taux CTA Transport - Taux CTA Transport	01/05/2013		0,04710	0,04710
TCS		TCS GRT Gaz - Terme Capacité Sortie réseau	01/04/2022		93,25000	93,25000
TCR		TCR GRT Gaz - Terme Capacité transport Résea	01/04/2022		82,62000	82,62000
TCL		TCL GRT Gaz PITD - Terme de Capacité de Livraison	01/04/2022		48,54000	48,54000
CTAD		Taux CTA Distribution - Taux CTA Distribution	01/05/2013		0,20800	0,20800
PF GRDF		T4 - GRDF - Tarifs de Distribution - Abonnement Annuel	01/07/2022		15 405,24000	15 405,24000
PP GRDF		T4 - GRDF - Tarifs de Distribution - Terme de Souscription Annuelle	01/07/2022		204,12000	204,12000
PEG 5D		PEG Gaz Futures Settlement Price 5 days - Tarif SVD17 & PEG	01/03/2023		47,37900	47,37900
TICGN		TICGN ETS - Tarifs divers	01/01/2016		0,15200	0,15200
CSPG		CSPG - Tarifs divers	01/01/2016		0,00000	0,00000
CTSS		Contribution TSS - Tarifs divers	01/01/2016		0,00000	0,00000

Révision B – Révision au 31/03/2023

$\frac{OM}{OM_0}$

Ref.	Libellé Variable	Valeur finale		Valeur contrat	
OM	Prix de Chaleur - UTVE de Nimes	28,75000	/	25,34000	
				Coefficient de révision	**1,134570**

Détail des prix et indexations

Prix	Période	Référence	Date d'effet	Jours	Valeur	Moyenne prorata du temps
OM		Prix de Chaleur - UTVE de Nimes - Chauffage Urbain - €	01/11/2022		28,75000	28,75000

5. Relevés de compteurs

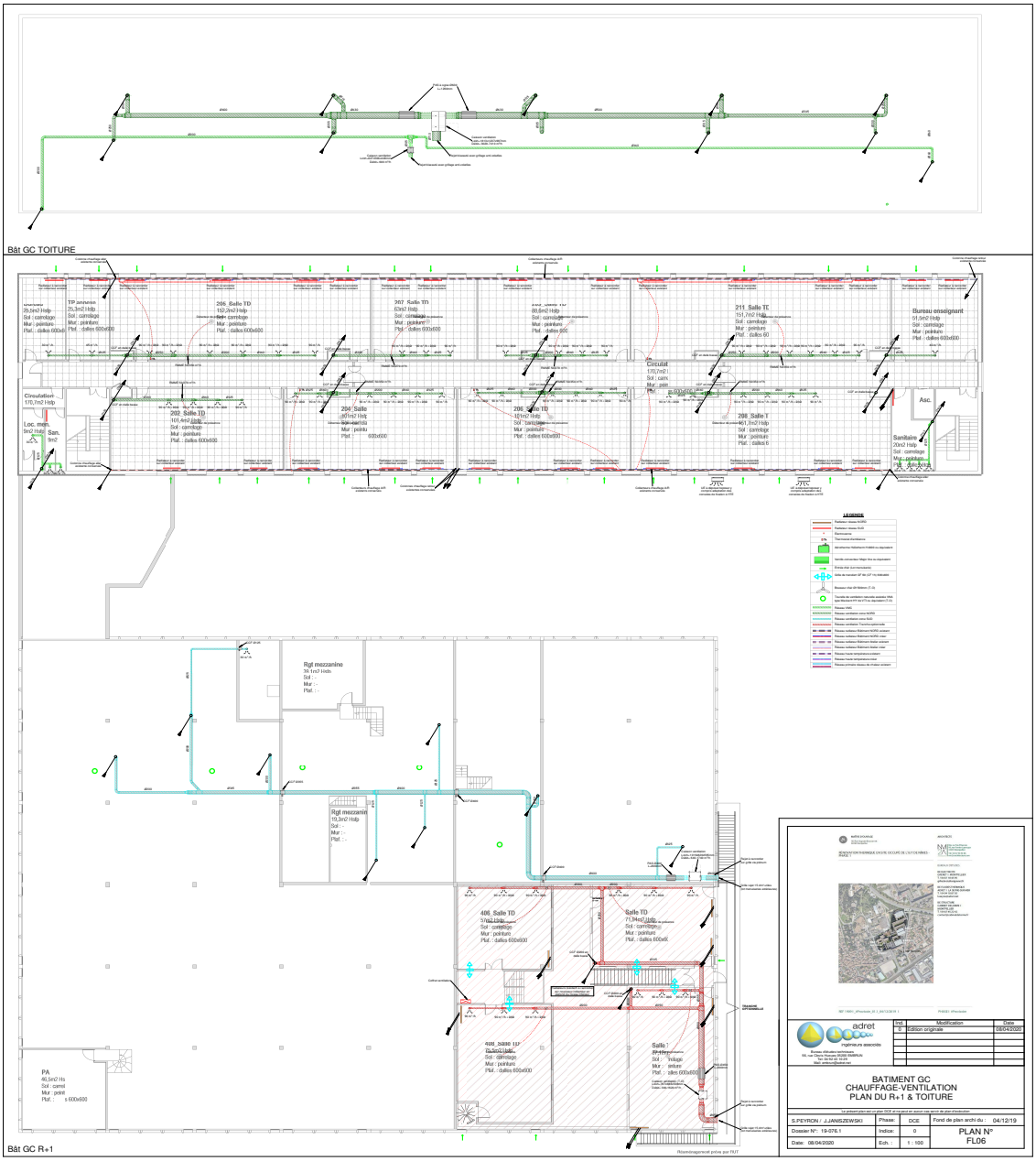
Du 01/03/2023 au 31/03/2023

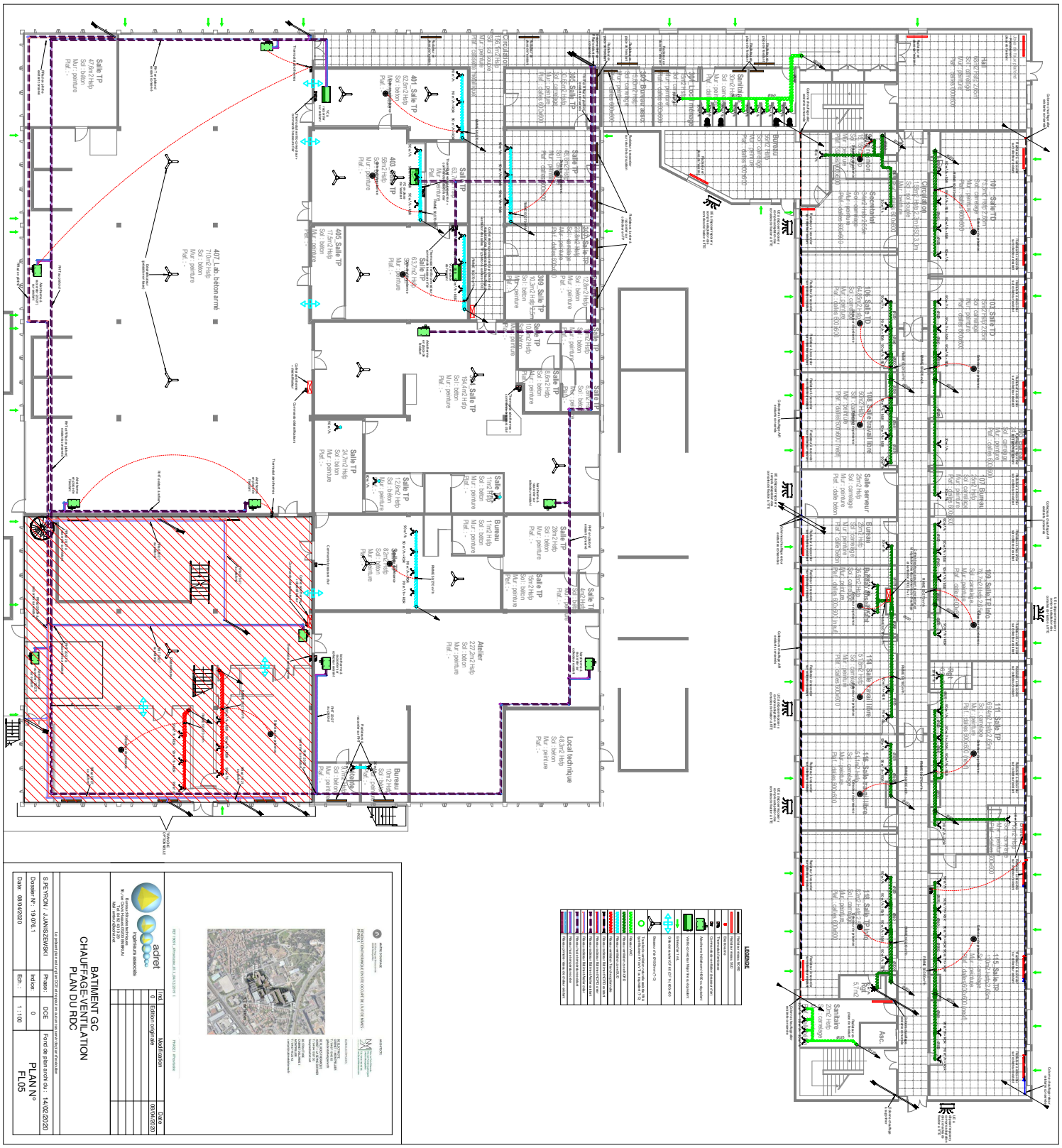
CHAUFFAGE	TERME PROPORTIONNEL R1 - R1					R1 - COMBUSTIBLE
Compteurs	Index fin	Index début	Consommation	Coef. conversion	Résultat	A facturer
SST 101 - IUT	3 589,400	3 343,400	246,000		246,000	
				Consommation 1 à facturer		**246,000 MWh**

Page 3 sur 3

E. Renovation measures

E.1 Mechanical ventilation

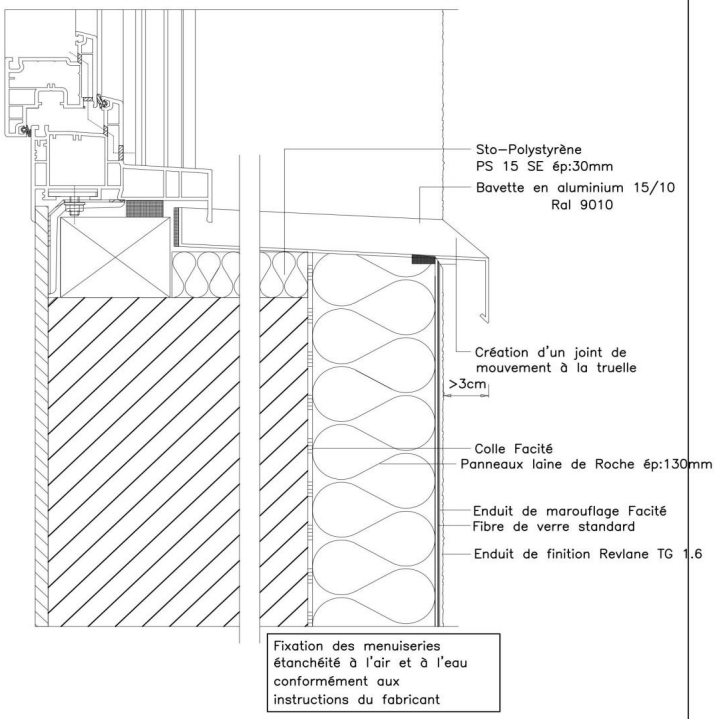



BATIMENT GC
CHAUFFAGE-VENTILATION
PLAN DU RDC
S.PEYRON / J.JANISZEWSKI
Dossier N° : 19-076.1
Date: 08/04/2020
DCE
Fond de plan arrêté du : 14/02/2020
PLAN N°
FL05
Ech. : 1 : 100
Indice: 0
Edition originale
Modification
Ind
Date
08/04/2020
LEGENDE

E.2 External wall insulation

ISPÉ Bât
Isolation Thermique par l'Extérieur

Systèmes d'isolation thermique de façades
Raccord du système sous tablette de menuiserie posée au nu intérieur maçonnerie



ISPÉ Bât
ISPE BAT
219 Chemin de la Jardinière
84 100 ORANGE
T 09 84 03 12 17 - F 09 89 03 12 17
E contact@ispe-bat.fr
www.ispebat.fr

Lot N°3 -ECHAFAUDAGES-FACADE ITE

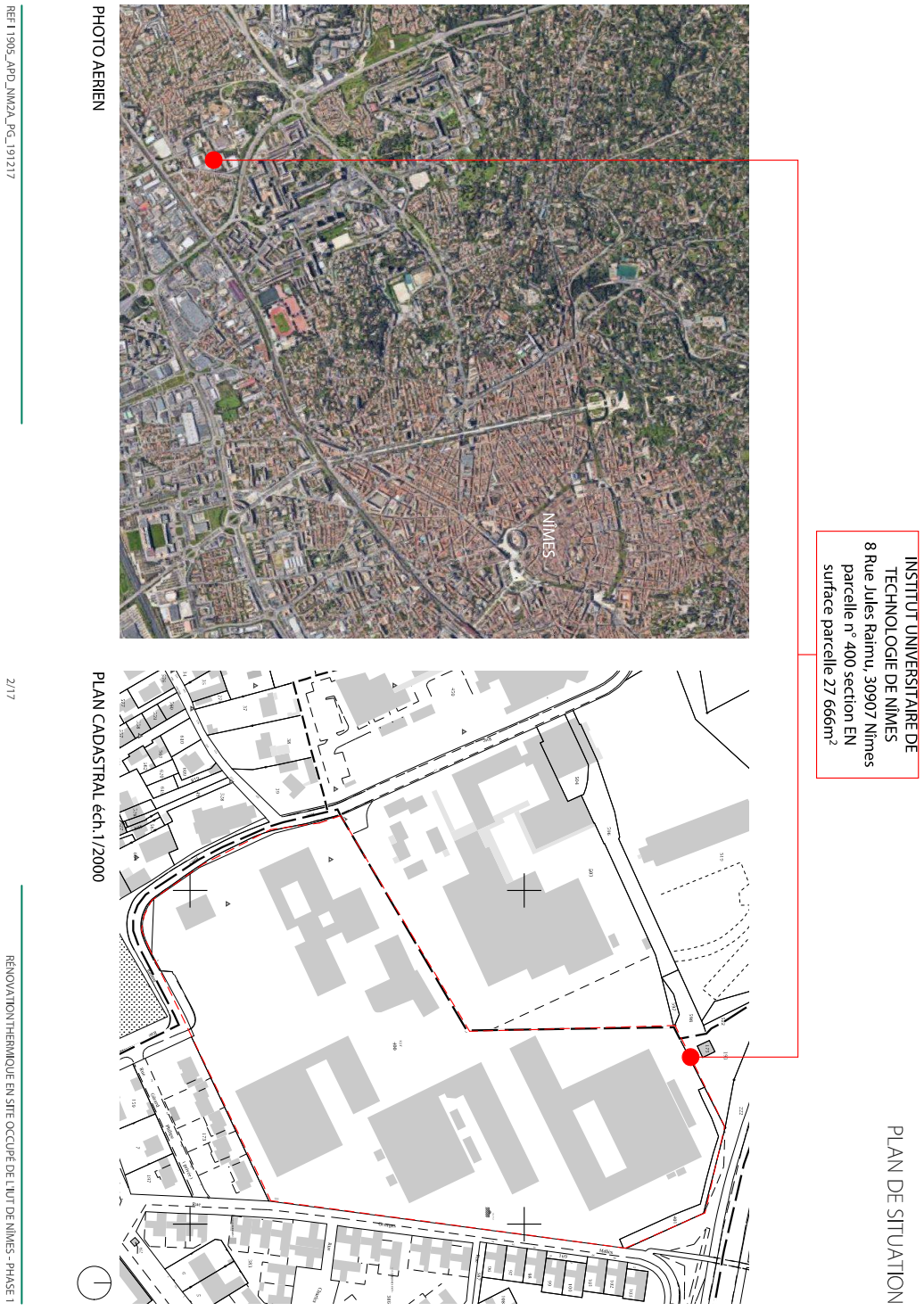
RENOVATION THERMIQUE IUT - NIMES

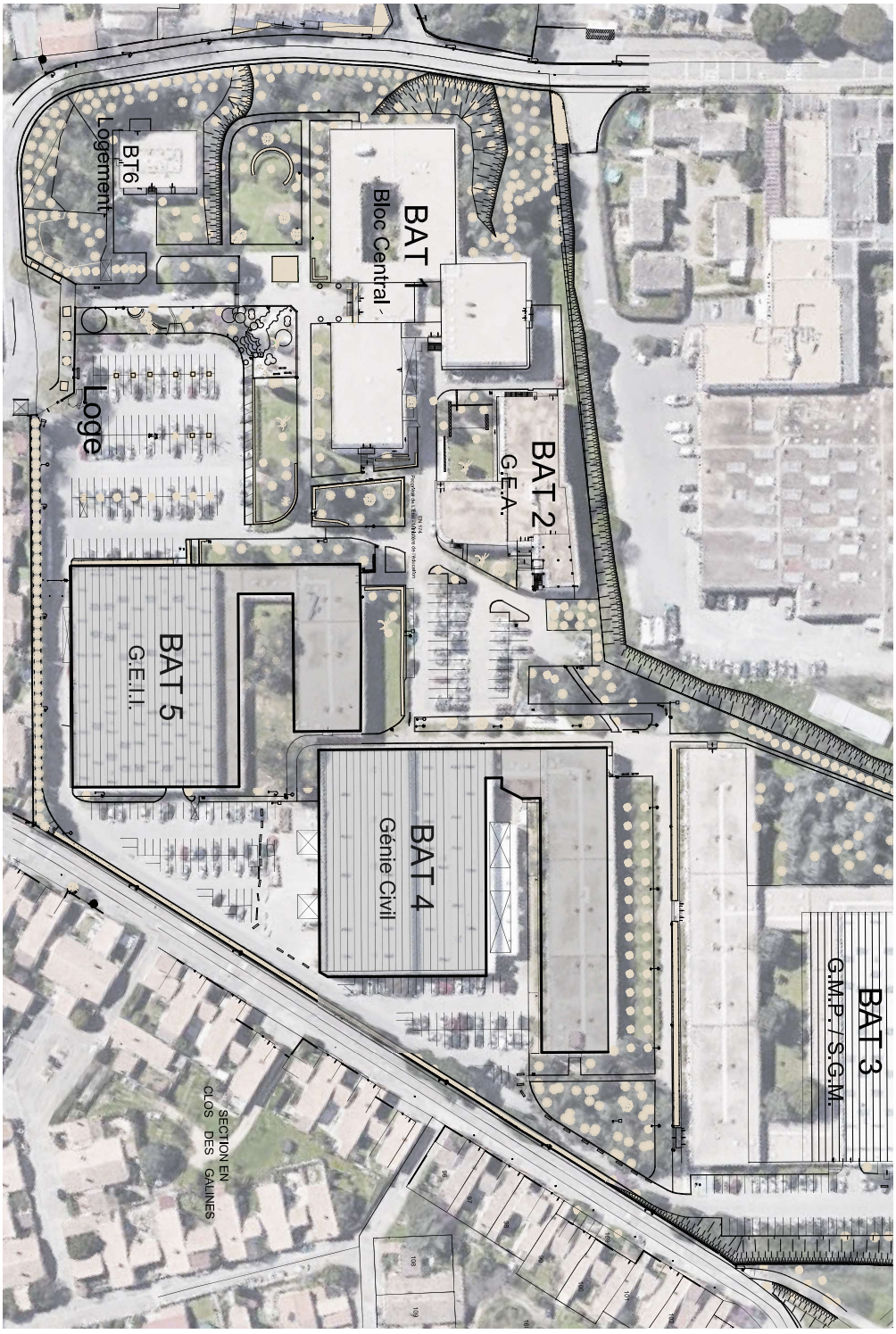
ISPE Bât
219 Chemin de la Jardinière 84100 ORANGE
SIRET : 79779841000024
Tél : 0984031217 - contact@ispe-bat.fr





E.3 Synoptic plans and details of the IUT de Nîmes





PLAN MASSE
Ech. 1/2000



BATIMENT 04 GC - PLAN EXISTANT RDC

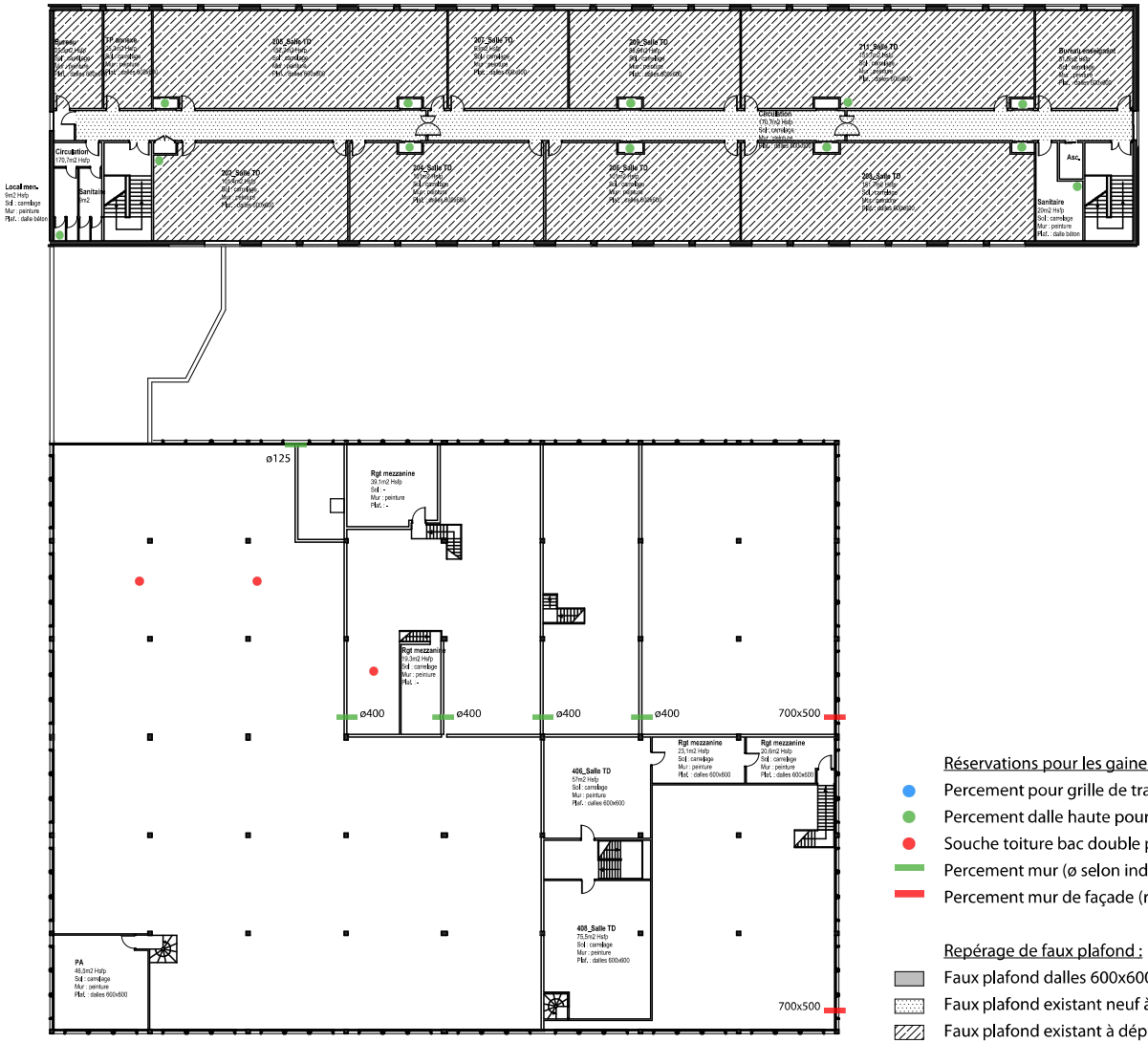
0 5 10 20

Réservations pour les gaines techniques :

- Percement pour grille de transfert 500x300
- Percement dalle haute pour gaine max. ø315
- Souche toiture bac double peau pour tourelle VNA ø 400 (TO)
- Percement mur (ø selon indication)
- Percement mur de façade (rejet ventilation)

Repérage de faux plafond :

- Faux plafond dalles 600x600 existant neuf
- Faux plafond existant neuf à déposer/reposer
- Faux plafond existant à déposer/remplacer
- Faux plafond à créer



BATIMENT 04 GC - PLAN EXISTANT R+1

0 5 10 20

Réservations pour les gaines techniques :

- Percement pour grille de transfert 500x300
- Percement dalle haute pour gaine max. ø315
- Souche toiture bac double peau pour tourelle VNA ø 400 (TO)
- Percement mur (ø selon indication)
- Percement mur de façade (rejet ventilation)

Repérage de faux plafond :

- Faux plafond dalles 600x600 existant neuf
- Faux plafond existant neuf à déposer/reposer
- Faux plafond existant à déposer/remplacer
- Faux plafond à créer

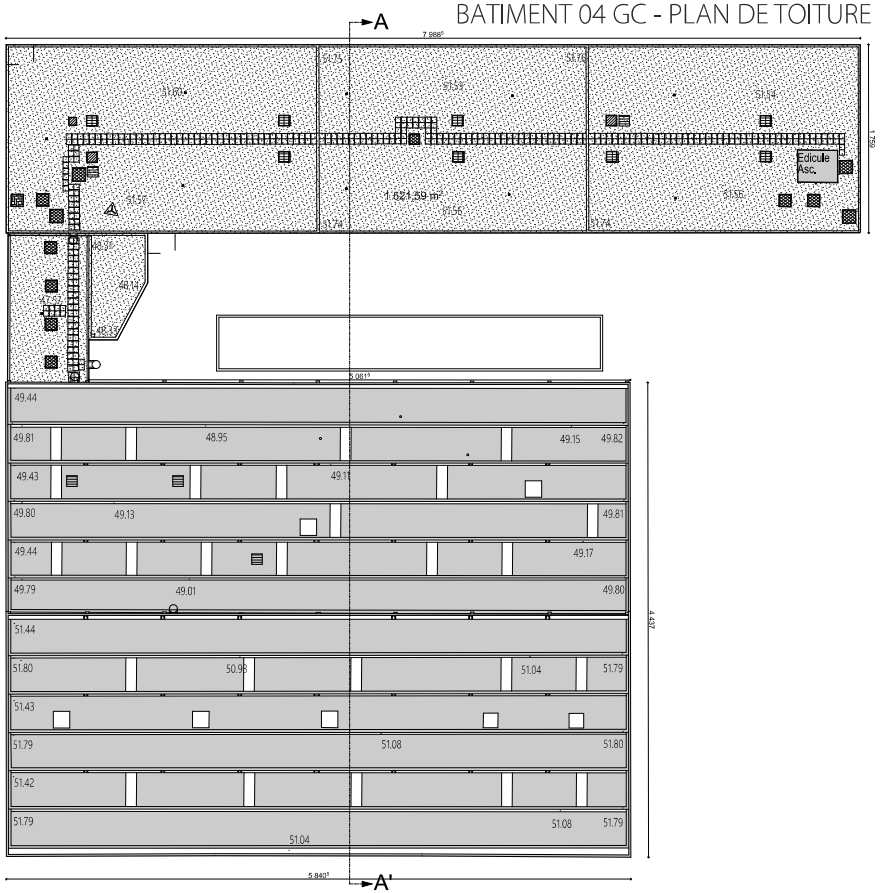
BATIMENT 04 GC - PLAN DE TOITURE

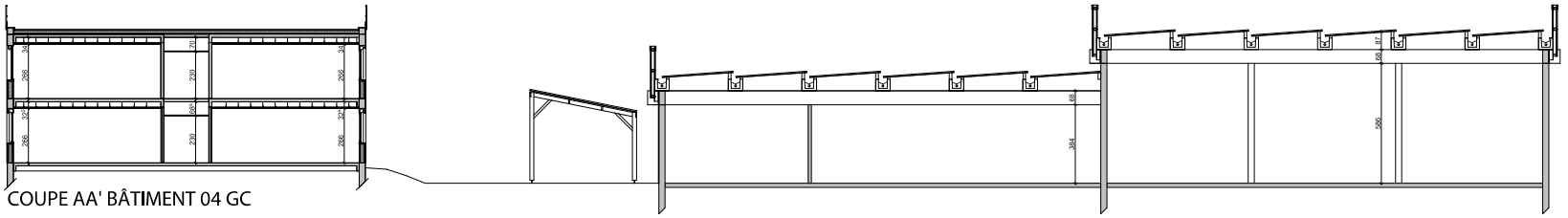
- Dépose isolant/gravillon existant => repose nouveau isolant/étanchéité/gravillon => réhausse d'acrotère + nouvelle couvertine
- Lanterneaux à adapter
- Lanterneaux à déposer/adapter
- Souche à reboucher
- Souche à adapter
- Souche à créer
- Déscente EP
- Echelle à crinoline
- Chemin technique

0 5 10 20





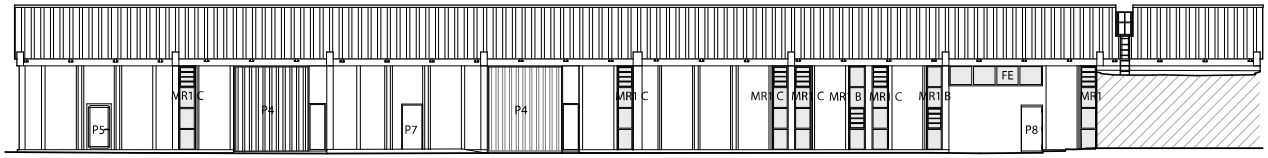




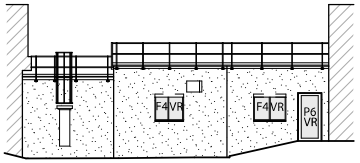
COUPE AA' BÂTIMENT 04 GC

BÂTIMENT 04 GC - FACADE PROJETÉ

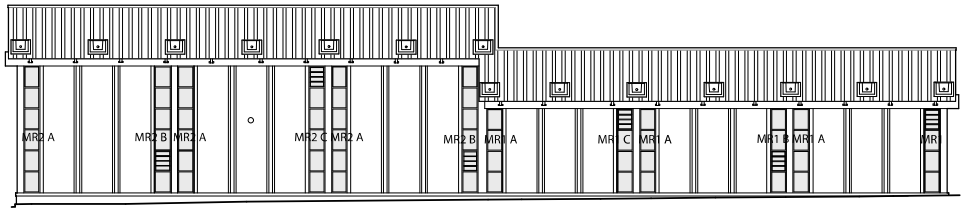
Éch 1/200



FACADE ATELIERS NORD



FACADE JONCTION EST



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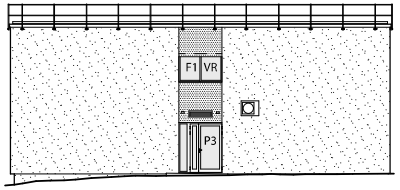
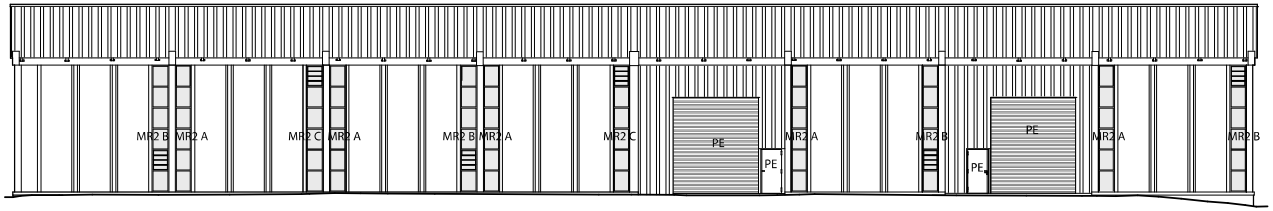


FACADE CLASSES EST



FACADE ATELIERS SUD

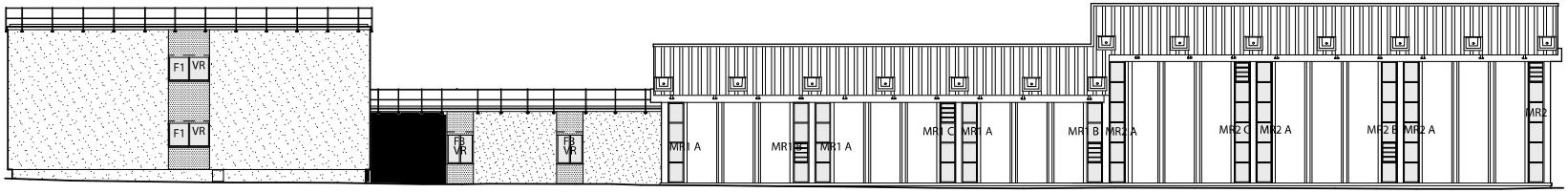
LEGENDE

NB : EN CAS DE POSE D'UNE ITE, LES ELEMENTS DE FACADES DE TYPE : GRILLES ANTI-EFFRACTION, GOULOTTES, GRILLE DE VENTILATION, GAINES, SIGNALETIQUE SERONT DEPOSER ET REPOSER ET/OU REMPLACER

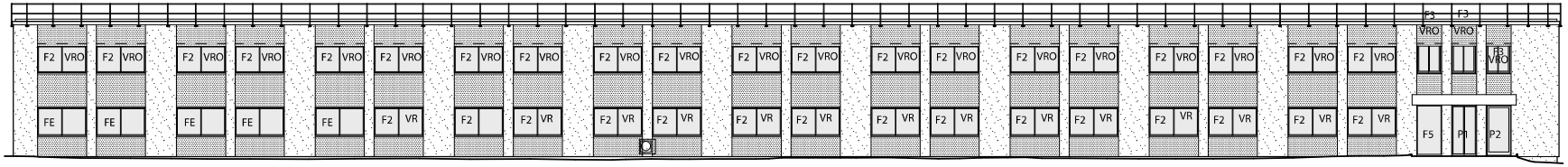
	ITE COULEUR N°1	VR	VOLET ROULANT
	ITE COULEUR N°2	FE	FENETRE EXISTANTE
	GRILLE EXISTANTE A DEPOSER	PE	PORTE EXISTANTE
	GRILLE EXISTANTE A DEPOSER/REPOSER APRES REMISE EN ETAT	BS	BRISE SOLEIL HORIZONTAL EN OPTION
		VRO	VOLET ROULANT EN OPTION

BÂTIMENT 04 GC - FACADE PROJETÉ

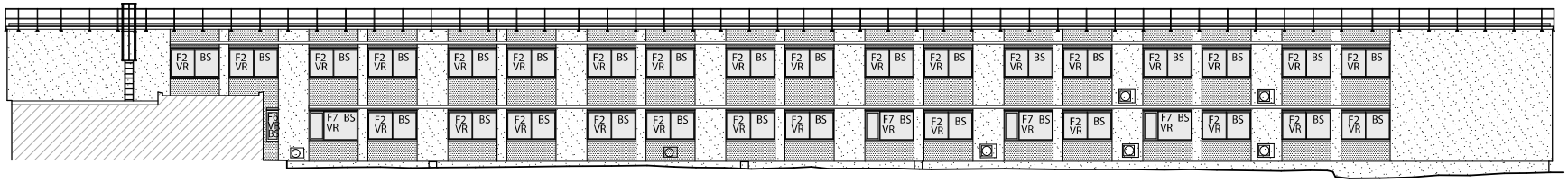
Éch 1/200



FACADE OUEST



FACADE CLASSES NORD



FACADE CLASSES SUD

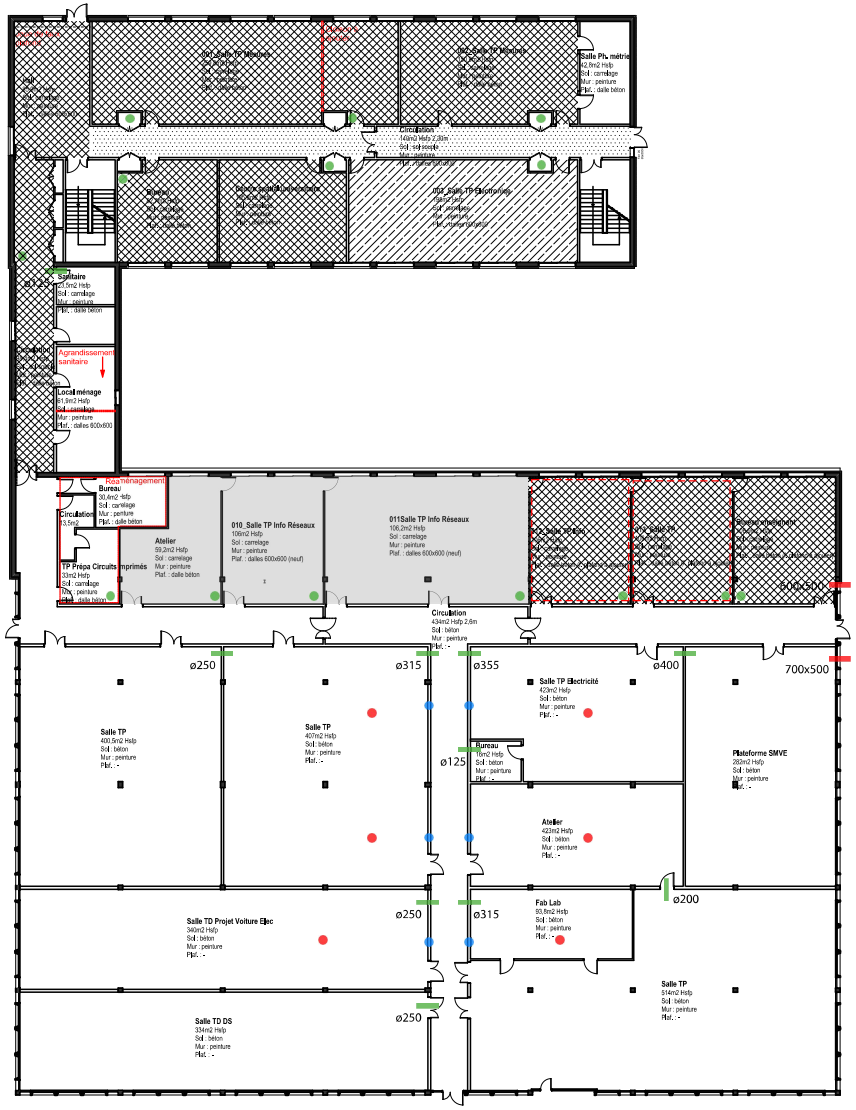
LEGENDE

NB : EN CAS DE POSE D'UNE ITE, LES ELEMENTS DE FACADES DE TYPE : GRILLES ANTI-EFFRACTION, GOULOTTES, GRILLE DE VENTILATION, GAINES, SIGNALETIQUE SERONT DEPOSER ET REPOSER ET/OU REMPLACER

	ITE COULEUR N°1		
	ITE COULEUR N°2	VR	VOLET ROULANT
	GRILLE EXISTANTE A DEPOSER	FE	FENETRE EXISTANTE
	GRILLE EXISTANTE A DEPOSER/REPOSER APRES REMISE EN ETAT	PE	PORTE EXISTANTE
		BS	BRISE SOLEIL HORIZONTAL EN OPTION
		VRO	VOLET ROULANT EN OPTION

BATIMENT 05 GEII - PLAN EXISTANT RDC

0 5 10 20



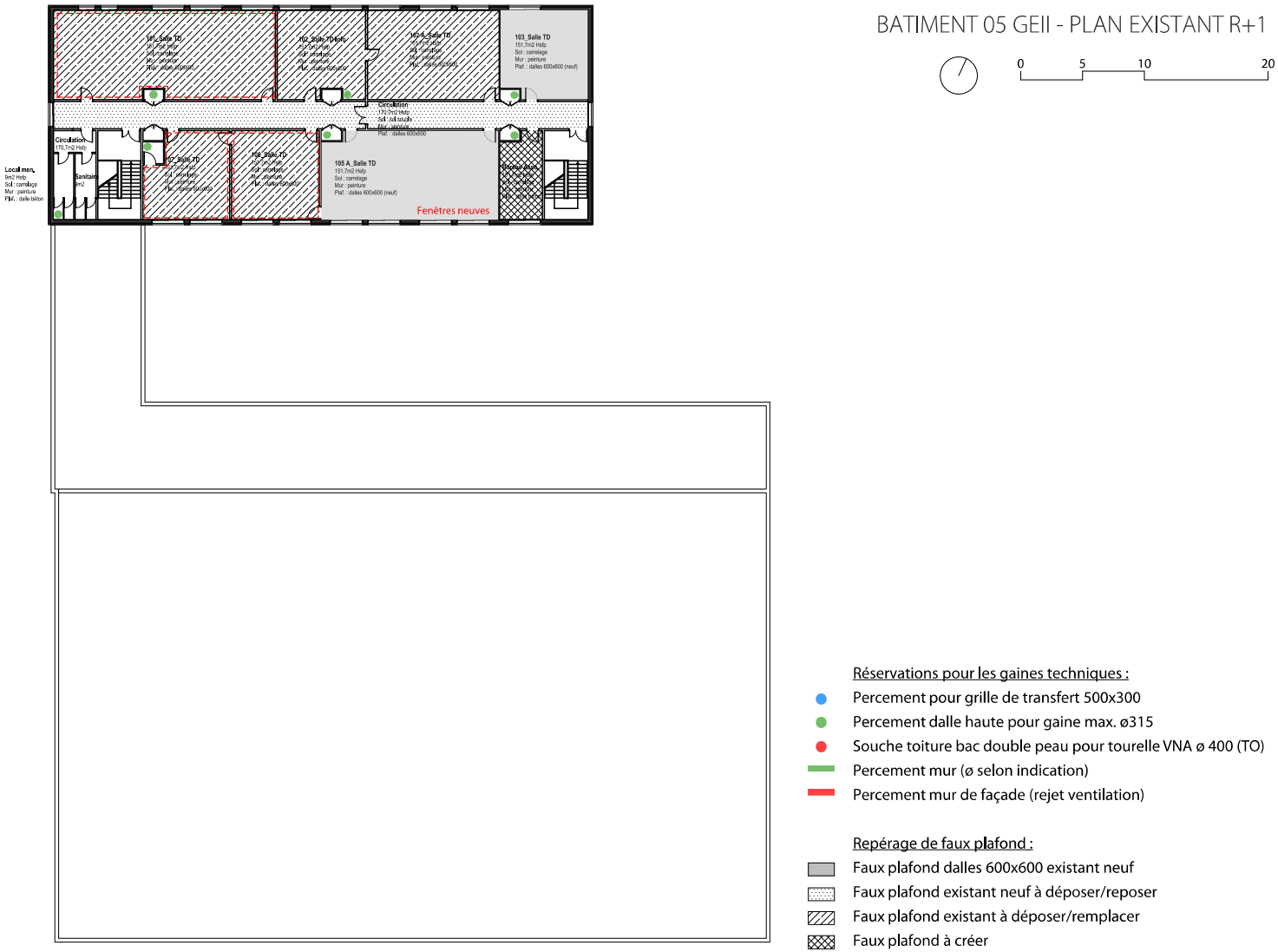
Réservations pour les gaines techniques :

- Percement pour grille de transfert 500x300
- Percement dalle haute pour gaine max. ø315
- Souche toiture bac double peau pour tourelle VNA ø 400 (TO)
- Percement mur (ø selon indication)
- Percement mur de façade (rejet ventilation)

Repérage de faux plafond :

- Faux plafond dalles 600x600 existant neuf
- Faux plafond existant neuf à déposer/reposer
- Faux plafond existant à déposer/remplacer
- Faux plafond à créer
- Prestation à réaliser par l'IUT

BATIMENT 05 GEII - PLAN EXISTANT R+1



Réservations pour les gaines techniques :

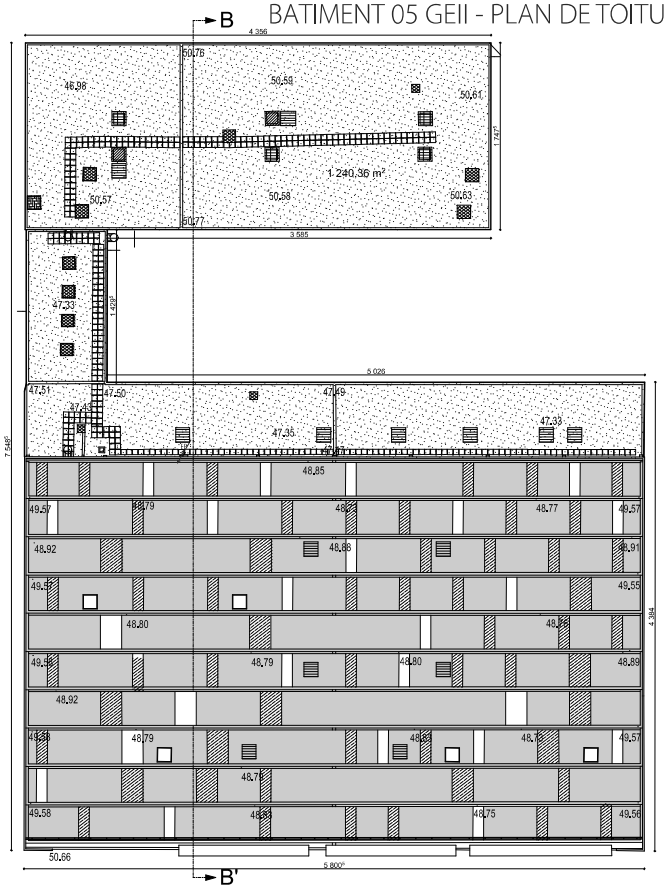
- Percement pour grille de transfert 500x300
- Percement dalle haute pour gaine max. ø315
- Souche toiture bac double peau pour tourelle VNA ø 400 (TO)
- Percement mur (ø selon indication)
- Percement mur de façade (rejet ventilation)

Repérage de faux plafond :

- Faux plafond dalles 600x600 existant neuf
- Faux plafond existant neuf à déposer/reposer
- Faux plafond existant à déposer/remplacer
- Faux plafond à créer
- Prestation à réaliser par l'IUT

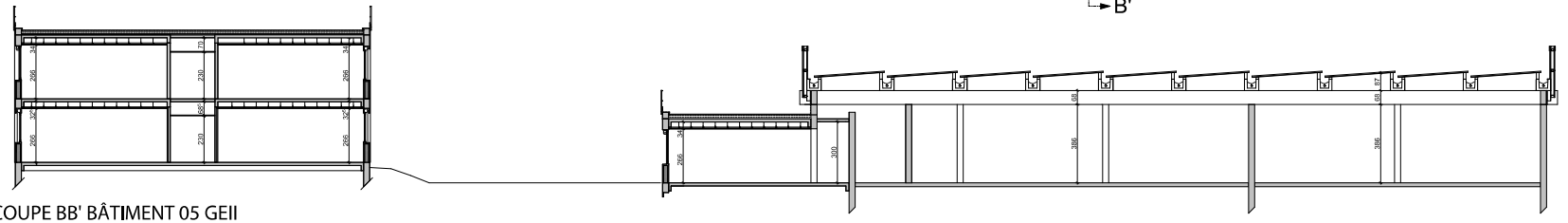
BATIMENT 05 GEII - PLAN DE TOITURE

- Dépose isolant/gravillon existant => repose nouveau isolant/étanchéité/gravillon => réhausse d'acrotère + nouvelle couvertine
- Lanterneaux à adapter
- Lanterneaux à déposer/adapter
- Souche à reboucher
- Souche à adapter
- Souche à créer
- Déscente EP
- Echelle à crinoline
- Chemin technique
- Panneaux polycarbonate translucide type Isoclair remplacé par des panneaux sandwich type Vulcasteel (70%)





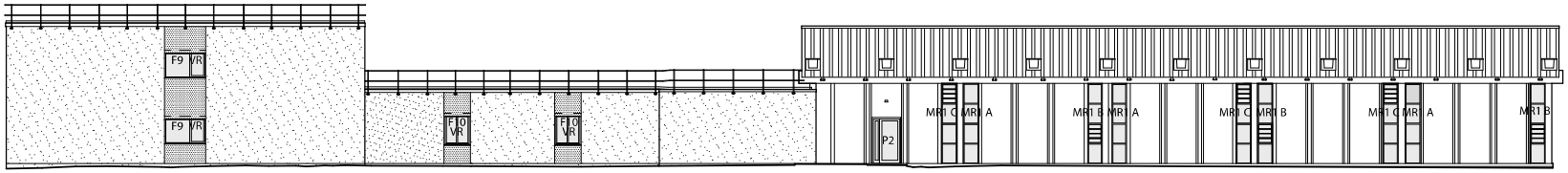




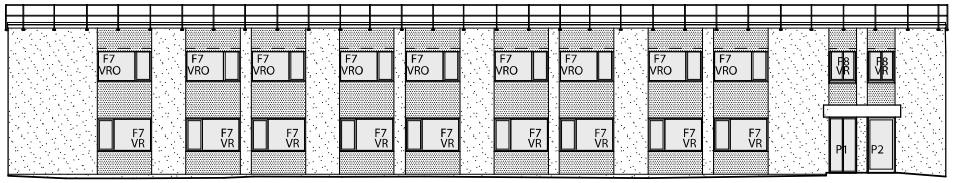
COUPE BB' BÂTIMENT 05 GEII

BÂTIMENT 05 GEII - FACADE PROJETÉ

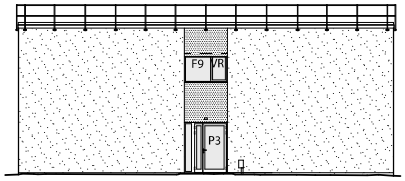
Éch 1/200



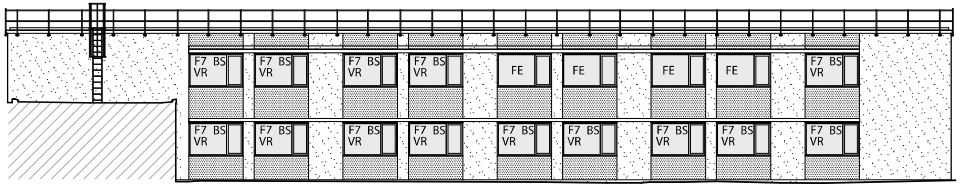
FACADE OUEST



FACADE CLASSES NORD



FACADE CLASSES EST



FACADE CLASSES SUD

LEGENDE

NB : EN CAS DE POSE D'UNE ITE, LES ELEMENTS DE FACADES DE TYPE : GRILLES ANTI-EFFRACTION, GOULOTTES, GRILLE DE VENTILATION, GAINES, SIGNALETIQUE SERONT DEPOSER ET REPOSER ET/OU REMPLACER

- ITE COULEUR N°1
- ITE COULEUR N°2
- GRILLE EXISTANTE A DEPOSER
- GRILLE EXISTANTE A DEPOSER/REPOSER APRES REMISE EN ETAT

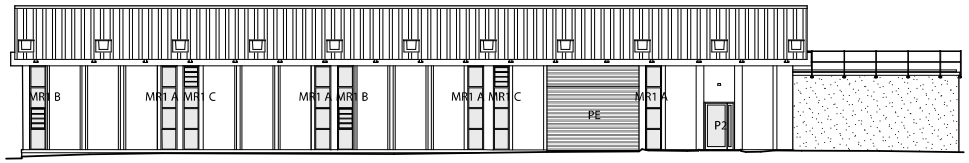
VR	VOLET ROULANT
FE	FENETRE EXISTANTE
PE	PORTE EXISTANTE
BS	BRISE SOLEIL HORIZONTAL EN OPTION
VRO	VOLET ROULANT EN OPTION

BÂTIMENT 05 GEII - FACADE PROJETÉ

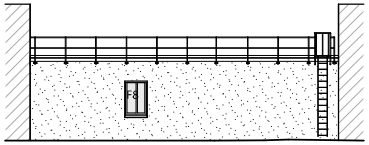
Éch 1/200



FACADE ATELIERS SUD



FACADE ATELIERS EST



FACADE JONCTION EST



FACADE ATELIERS NORD

LEGENDE

NB : EN CAS DE POSE D'UNE ITE, LES ELEMENTS DE FACADES DE TYPE : GRILLES ANTI-EFFRACTION, GOULOTTES, GRILLE DE VENTILATION, GAINES, SIGNALETIQUE SERONT DEPOSER ET REPOSER ET/OU REMPLACER

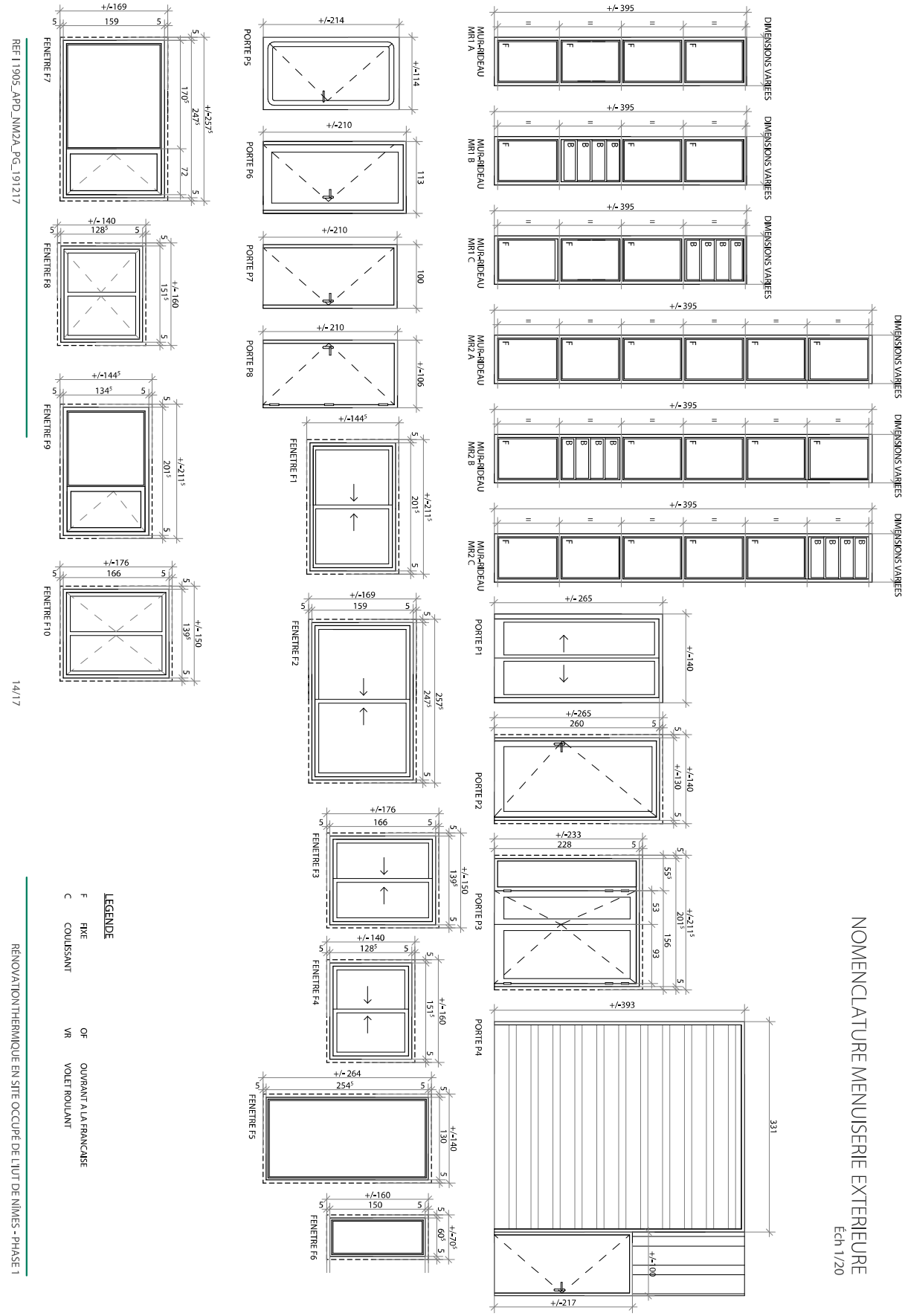
ITE COULEUR N°1

ITE COULEUR N°2

GRILLE EXISTANTE A DEPOSER

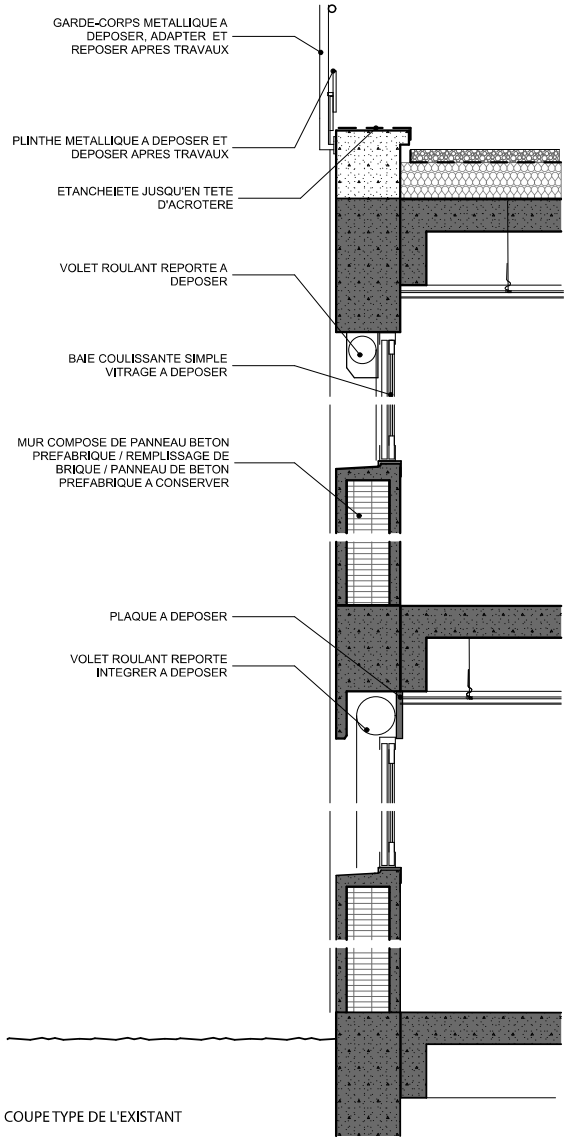
GRILLE EXISTANTE A DEPOSER/REPOSER APRES REMISE EN ETAT

VR	VOLET ROULANT
FE	FENETRE EXISTANTE
PE	PORTE EXISTANTE
BS	BRISE SOLEIL HORIZONTAL EN OPTION
VRO	VOLET ROULANT EN OPTION

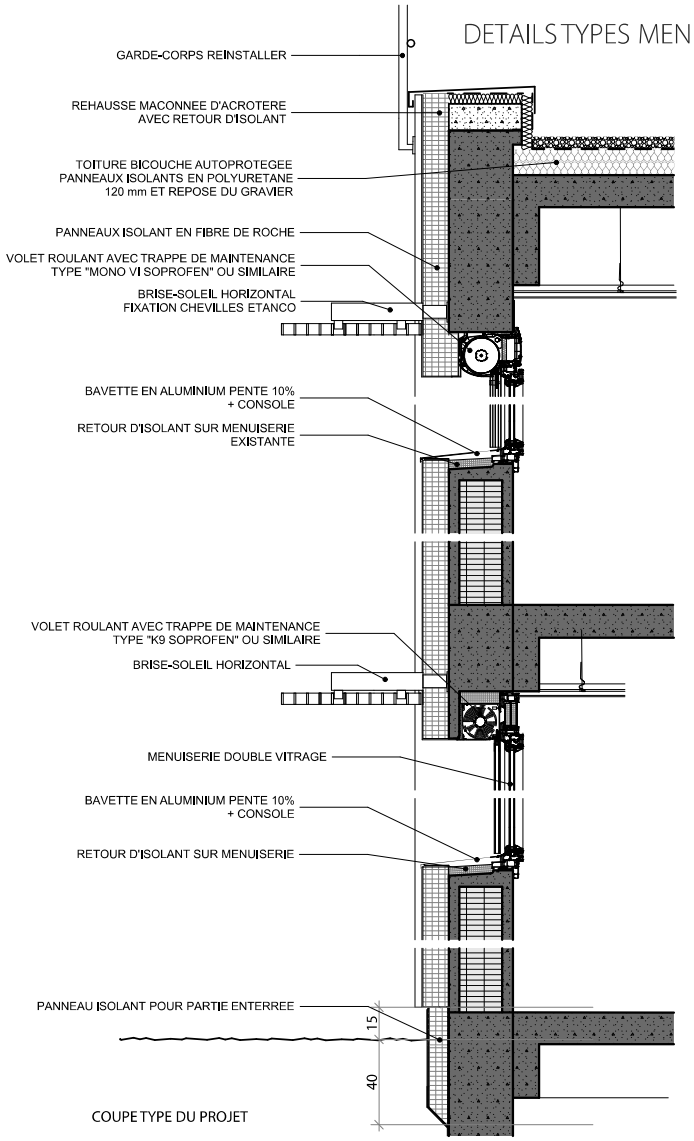

NOMENCLATURE MENUISERIE EXTERIEURE
Éch 1/20
MUR+RIDEAU MR1 A
MUR+RIDEAU MR1 B
MUR+RIDEAU MR1 C
MUR+RIDEAU MR2 A
MUR+RIDEAU MR2 B
MUR+RIDEAU MR2 C
DIMENSIONS VARIEES
PORTE P1
PORTE P2
PORTE P3
PORTE P4
PORTE P5
PORTE P6
PORTE P7
PORTE P8
FENETRE F1
FENETRE F2
FENETRE F3
FENETRE F4
FENETRE F5
FENETRE F6
FENETRE F7
FENETRE F8
FENETRE F9
FENETRE F10
LEGENDE
F FIXE
C COULISSANT
OF OUVRANT A LA FRANCAISE
VR VOLET ROULANT

DETAILS TYPES MENUISERIE SALLE DE CLASSE

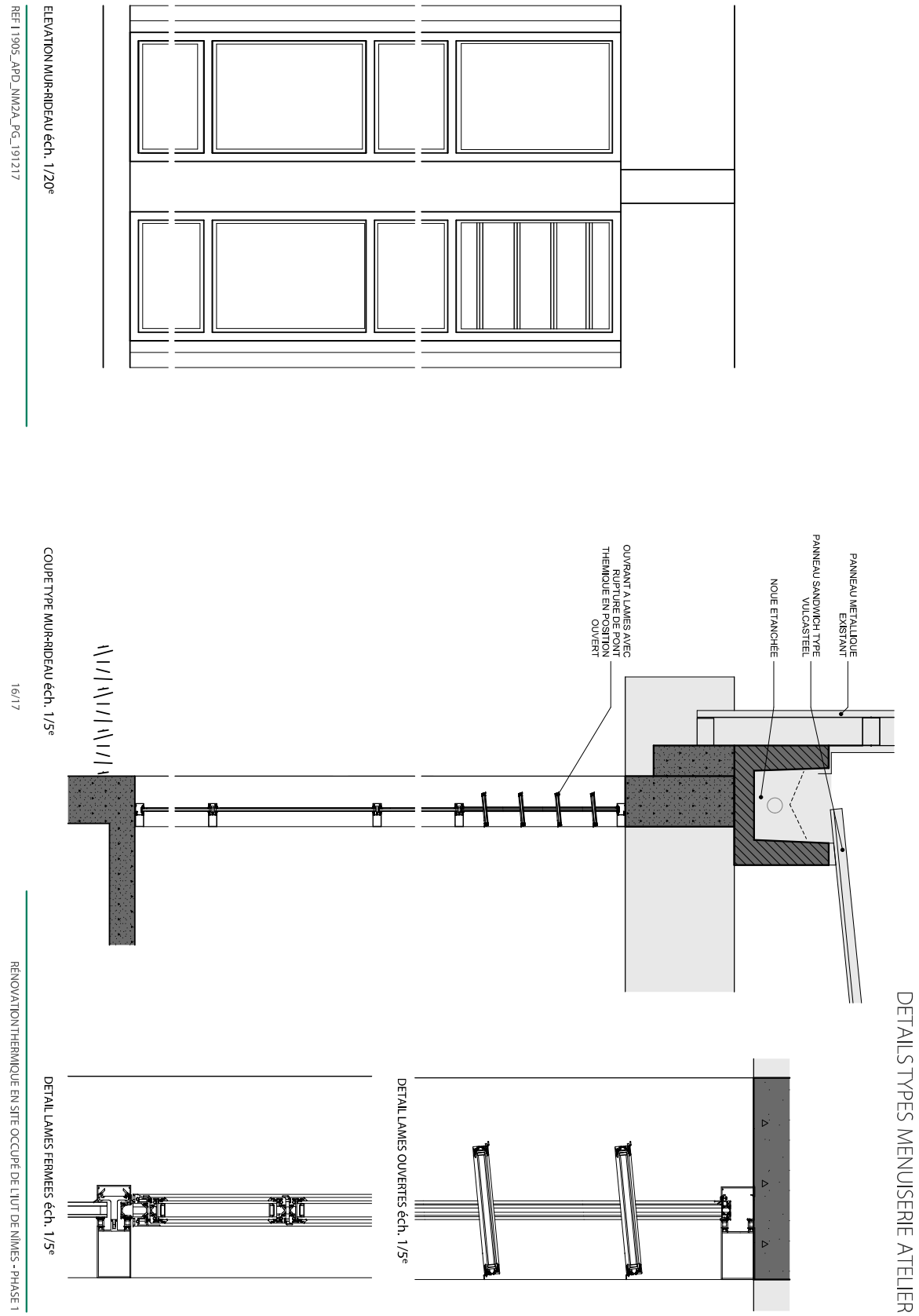
Éch 1/20



COUPE TYPE DE L'EXISTANT



COUPE TYPE DU PROJET


DETAILS TYPES MENUISERIE ATELIER
ELEVATION MUR-RIDEAU éch. 1/20e
COUPE TYPE MUR-RIDEAU éch. 1/5e
PANNEAU METALLIQUE EXISTANT
PANNEAU SANDWICH TYPE VULCASTEEL
NOUE ETANCHÉE
OUVRANT A LAMES AVEC RUPTURE DE PONT THERMIQUE EN POSITION OUVERT
DETAIL LAMES OUVERTES éch. 1/5e
DETAIL LAMES FERMEES éch. 1/5e
REF I 1905_APD_NM2A_PG_191217
16/17
RÉNOVATION THERMIQUE EN SITE OCCUPÉ DE L'IUT DE NÎMES - PHASE 1