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Holistic monitoring approach of occupant behavior analysis in residential buildings

Yousra Laaroussi

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**Développement d'une méthode basée sur l'approche du monitoring
pour l'analyse du comportement d'occupant dans les bâtiments
résidentiels**

**Holistic monitoring approach of occupant behavior analysis in
residential buildings**

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Abstract

Energy efficiency of buildings is a key for energy consumption and CO₂ emissions reduction. The analysis of the factors affecting the energy consumption in buildings are considered as necessary for the assessment and optimization of the energy performance of buildings. Many research showed that the buildings' technical, structural and environmental factors are not sufficient any more for a complete assessment of building energy performance. Indeed, recently, the occupant behavior has been identified as a major factor affecting the energy use in buildings, and the works presented throughout this dissertation demonstrated the necessity of considering the occupant behavior in all the building energy performance analysis. The aim of this PhD research is to analyze and assess the impact of occupant's behavior on buildings energy consumption based on large scale in-situ monitoring and propose a methodology for a monitoring design guided procedure. To do so, three different groups of building (social housing, private building and smart building) has been deeply investigated and monitored. The occupant behavior has been characterized and the affecting drivers has been analyzed taking lighting use, electricity use, heating and set-point regulation of thermostat, and windows openings into account. Finally, and as a valorization of the occupant behavior analysis, a methodology based on a holistic approach was developed and proposed as a guideline for defining the main phases of designing, implementing, analyzing and valorizing the monitoring activity.

This research is a part of a European project entitled "Holistic Energy and Architectural Retrofit Toolkit (HEART)" funded by Horizon 2020 programme.

Keywords: Building Energy Performance, Occupant Behavior, Monitoring Approach, Social Housing, Private Buildings, Smart Buildings, Data Analysis.

Résumé

L'efficacité énergétique des bâtiments est considérée comme levier d'action important pour réduire la consommation d'énergie et les émissions de CO₂. Il est nécessaire d'analyser les facteurs influençant la consommation énergétique des bâtiments afin d'évaluer et d'optimiser leur performance énergétique. A cet égard, la considération des facteurs techniques, structurels et environnementaux ne justifie pas à elle seule les consommations énergétiques constatées. En effet, dernièrement, le comportement des occupants a été identifié comme facteur majeur affectant la consommation d'énergie dans les bâtiments. Le travail de recherche présenté dans ce rapport confirme l'importance d'intégration du comportement des occupants dans toutes les analyses de performance énergétique des bâtiments. Les travaux de cette thèse de doctorat ont pour objectif d'analyser les comportements des occupants et de proposer une méthodologie d'aide à la décision et ce en adoptant une approche expérimentale In-Situ à grande échelle. Ainsi, trois types de bâtiments (logements sociaux, bâtiments privés et ilot à énergie positive) ont été exploités pour caractériser le comportement des occupants et les facteurs influençant. L'approche analytique développée prend en compte l'usage de l'éclairage, l'électricité, le chauffage et le thermostat d'ambiance, ainsi que les ouvertures des fenêtres. En fin, une approche holistique a été développée dans le but de proposer un guide d'accompagnement pour l'établissement des principales phases de conception, de mise en œuvre, d'analyse et de valorisation des activités du monitoring.

Cette recherche s'inscrit dans le cadre d'un projet européen intitulé "Holistic Energy and Architectural Retrofit Toolkit (HEART)".

Mots clés : Performance énergétique des bâtiments, Comportement des occupants, L'approche du monitoring, Logement social, Bâtiment privé, Bâtiment intelligent, Analyse des données.

ملخص

تعتبر النجاعة الطاقية للبنىات وسيلة محورية في مسلسل المساعي الراهنة للتقليل من استعمال الطاقة الاحفورية ومن انبعاثات غاز ثاني أكسيد الكربون على الصعيد العالمي. علاوة على العوامل التقنية والمناخية التي كانت محل الأبحاث العلمية منذ عدة عقود, تضافرت الأبحاث العلمية في الآونة الأخيرة في مجال دراسة سلوكيات السكان ومستعملي ومديري البنىات إذ تم تصنيف هذه من بين اهم العوامل المؤثرة على استهلاك الطاقة، وهو ما يؤكد هذا البحث العلمي الذي بين وبرهن على ضرورة اخذ السلوكيات بعين الاعتبار اثناء دراسة او تحليل الأداء الطاقى للبنىات. يركز العمل المنجز في نطاق هذا البحث العلمي على منهج الرصد التقني نظرا لفعاليتيه في فهم وتحليل دوافع السلوكيات وعلاقتها بالاستهلاك الطاقى. في هذا الصدد، تمت دراسة ثلاثة أنواع من البنىات: الذكية، الخاصة والسكن الاجتماعى حيث تم تطبيق منهج الرصد الميدانى لقياس معطيات الاستهلاك الطاقى ومستويات جودة الهواء الداخلى وعادات فتح النوافذ واستعمال الانارة والتدفئة. هذا البحث العلمي مكن من فهم وتحليل السلوكيات ودوافعها حيث تم تثمين عدد كبير من دراسات الرصد الميدانى على نطاق واسع. أخيرا , وبناء على نتائج الرصد الميدانى والتحليل العلمى المنجز تم ابتكار منهج شامل وتوجيهى جديد يمكن من تحديد المراحل الأساسية لتصميم، تنفيذ، تحليل وتثمين الرصد التقنى والميدانى للبنىات في طور الاستعمال أخذا بعين الاعتبار السلوكيات ونوعية البنىات. مول هذا البحث من طرف المفوضية الأوروبية وساهمت نتائجه هذ انجاز مشروع علمى أوروبى بعنوان " الطاقة الشاملة ومجموعة أدوات التعديل التديثى المعماري.

الكلمات الدالة: كفاءة الطاقة في البنىات , سلوكيات المقيمين في المباني , منهج الرصد , المباني الخاصة , المباني الذكية ,السكن الاجتماعى , تحليل المعطيات.

Contents

Résumé détaillée	13
A. Introduction	14
A.1 Problématiques scientifiques :	15
A.2 Objectifs et démarche scientifique :	15
B. Synthèse d'étude bibliographique	16
C. Description des cas d'études	17
D. Analyse des bases de données	18
D.1 Méthodologie	18
D.2 Synthèse des résultats	18
E. Le guide HOBIM (Holistic approach for Occupant Behavior assessment based on In-situ Monitoring).	20
F. Conclusion et perspectives	20
General Introduction	23
Overview and energy context	23
Scientific issues of the topic	26
Research objectives, scientific approach and dissertation outline	28
Chapter I: State of the art	32
Occupant behavior: A major issue for building energy performance simulation and assessment	32
I.1 Introduction	32
I.2 Occupant Behavior: presence and occupancy profile	33
I.3 Occupants' interactions	34
I.3.1 Occupant Behavior: factors and drivers	35
Drivers of windows interactions: synthesis review	36
III.3.1 Drivers of thermostat use and set-point regulation: synthesis review	38
III.4.1 Drivers of lighting use: synthesis review	39
I.4 Occupant Behavior: analysis approach and modeling	40
I.4.1 Monitoring approach and data analysis	40
I.4.1.1 Related work to data analysis and mining	44
I.4.2 Occupant behavior modeling	45
I.5 Energy feedback approach	46
I.6 Discussion and key findings	47
I.7 Conclusion	48
Chapter II: Case studies	52
Monitoring and assessment of pilot projects	52
II.1 Introduction	52
II.2 Case study 1: HEART project, French case study	53

II.2.1 Generalities	53
II.2.2 Monitored apartments	54
II.2.3 Instrumentation details	55
II.2.4 Buildings and Systems characteristics	57
II.3 Case study 2: PREBAT project	58
II.3.1 “AMPLIA” case study.....	58
II.3.2 “LES GENTIANES” case study	62
II.4 Case study 3: HIKARI project.....	64
II.4.1 Generalities	64
II.4.2 Monitored apartments	64
II.4.3 Instrumentation details	65
II.4.4 Buildings and Systems characteristics	66
II.5 Conclusion & discussion	67
Chapter III: Data-driven analysis	72
Occupant behavior: A comprehensive analysis of the drivers affecting the occupant’s interactions in smart residential building.....	72
III.1 Introduction.....	72
III.2 Occupant behavior analysis: windows opening.....	73
III.2.2 Methodology of analyzing windows opening in HIKARI case study	74
III.2.3 Analysis of windows opening drivers in winter season	75
III.2.4 Analysis of windows opening in summer season	78
III.2.5 Results & discussion	84
III.3 Occupant behavior analysis: thermostat use.....	85
III.3.2 Methodology of analyzing thermostat use in HIKARI case study	85
III.3.3 Analysis of thermostat modification in heating period: overview and drivers	85
III.3.4 Results & discussion	88
III.4 Occupant behavior analysis: lighting use	89
III.4.2 Methodology of analyzing lighting-on	89
III.4.3 Analysis of lighting use drivers in winter season	90
III.4.4 Analysis of lighting use drivers in summer season	93
III.4.5 Results & discussion	97
III.5 General assessment of the monitoring activity of this case study	98
III.6 Conclusion	100
Chapter IV: Data-driven analysis.....	104
Comparative analysis of occupant’s energy use in private and social residential building	104
IV.1 Introduction	104
IV.2 Occupant’s energy use: lighting use	105
IV.2.1. Methodology of analyzing lighting use in LES GENTIANES case study	105

IV.2.2 Analysis of lighting use in winter season	106
IV.2.3 Analysis of lighting use in summer season	110
IV.2.4 Results & discussion.....	113
IV.3 Occupant’s heating behavior	113
IV.3.1 Methodology of analyzing heating use in AMPLIA case study	114
IV.3.2 Clustering analysis of heating consumption	114
IV.3.3 Comparison analysis of heating consumption.....	115
IV.3.4 Results & discussion.....	117
IV.4 Occupant’s energy use: electricity consumption	117
IV.4.1 Methodology of analyzing the electricity consumption in AMPLIA case study	118
IV.4.2 Electricity use in winter season	118
IV.4.3 Electricity use in summer season	121
IV.4.4 Results and discussion	122
IV.5 Occupant behavior in COVID19 confinement.....	123
IV.5.1 Methodology of analyzing the energy behavior in HEART case study	124
IV.5.2 Energy use analysis: HEART case study	125
IV.5.3 Results & discussion.....	129
IV.6 Conclusion.....	130
Chapter V.....	134
HOBIM: Holistic approach for Occupant Behavior assessment based on In-situ Monitoring.....	134
V.1 Introduction	134
V.2 Definition of HOBIM tool	134
V.3 Phase 1: Monitoring decision-making	135
V.3.1 Definition of the objectives	135
V.3.2 Selection of the parameters to monitor	136
V.3.3 Implementation of monitoring activity and collecting data.....	144
V.4 Phase 2: Data analysis.....	146
V.5 Phase 3: valorization	149
V.6 Conclusion.....	150
General Conclusion	152
Outlook and perspectives.....	154
Bibliography.....	156
Appendix A	164
Appendix B.....	169

List of Figures

Figure 1: Démarche scientifique exploitée dans ce travail de thèse.....	16
Figure 2: Synthèse de la méthodologie d'analyse des données développée dans cette recherche.	18
Figure 3: Energy consumption in residential construction in 2010 and 2030, by type of use (France, ADEME [9]).	24
Figure 4: Scientific approach employed during this dissertation.....	30
Figure 5: Evolution of the number of published research on the occupant behavior topic (Scopus).	33
Figure 6: Examples of occupant interactions with their environment.....	35
Figure 7: Layout of drivers, needs and occupant behavior actions.....	36
Figure 8: Synthesis of windows opening drivers in literature.....	37
Figure 9: Distribution of time interval in the reviewed monitoring activities [17].	43
Figure 10: Monitoring duration review [17].	43
Figure 11: The principal phases for data analysis process.	45
Figure 12: Technical framework on building energy performance, occupant behavior, drivers and aspects.	49
Figure 13: Site localization Source-Google Earth.....	53
Figure 14: The plan of the building and the selection of the dwellings for instrumentation.	54
Figure 15: Specification of the interior condition's sensor [98].	55
Figure 16: Exterior sensors installed on the façade of the building.	55
Figure 17: Connectors sensors of energy consumption.	56
Figure 18: Energy consumption of DHW sensors.	56
Figure 19: Specification of the communication system [99].	57
Figure 20: Overview of HIKARI buildings (OLIVIER GUERRIN,2015).	64
Figure 21: Cogeneration system: COGENGreen.....	66
Figure 22: Absorption chiller System from YAZAKI.	67
Figure 23: A comparative synthesis of the collected data (1).....	69
Figure 24: A comparative synthesis of the collected data (2).	70
Figure 25: Synthesis of the monitored parameters in HIKARI case study.....	73
Figure 26: Methodology framework of the HIKARI database analysis.....	73
Figure 27: Methodology framework of windows opening analysis.....	75
Figure 28: Frequency of windows opening in winter according to time day for each space in the apartment.	76
Figure 29: Evolution of the outdoor temperature according to windows opening in bedroom 1 and 2 (from 01/01 to 01/10).	77
Figure 30: Evolution of CO2 concentration function of the windows opening in bedroom 1 and 2 in the period of January 10 to 19.	78
Figure 31: Windows opening frequency in summer according to time for kitchen and living room.	79
Figure 32: Windows opening frequency in summer according to time for the three bedrooms.	80
Figure 33: analysis of the windows opening in summer according to each month for kitchen and bedrooms.	81


Figure 34: Evolution of outdoor temperature compared to windows opening in bedroom 1 and kitchen from 07/05 to 07/25.....	82
Figure 35: Methodology framework of thermostat-use analysis.	86
Figure 36: Synthesis of the artificial lighting use in the bedrooms according to each time slot (winter).	91
Figure 37: Artificial lighting use in the Kitchen according to each timeslot during winter season. ..	92
Figure 38: Correlation analysis of artificial lighting use and exterior illuminance in the period of 11/01 to 11/10 in the various spaces of the apartment (winter).....	94
Figure 39: Artificial lighting use in the bedrooms according to each time slot (summer).....	95
Figure 40: Artificial lighting use in the Kitchen according to each timeslot for summer.	96
Figure 41: Correlation analysis of artificial lighting use and exterior illuminance in the period of 06/05 to 06/14 in the various spaces of the apartment (summer).	97
Figure 42: Synthesis of the occupant behavior analysis in smart residential buildings.	102
Figure 43: Methodology framework of Chapter IV analysis.	105
Figure 44: Technical framework of lighting use analysis in 'LES GENTIANES' case study.	106
Figure 45: Lighting consumption in winter season for the LES GENTIANES case study.	108
Figure 46: Peaks frequency of lighting use in winter according to time day for apartment 1 and 2 for the "LES GENTIANES" case study.	109
Figure 47: Lighting consumption in summer season for the "LES GENTIANES" case study.	111
Figure 48: Number of peaks in apartment 1 during summer season, according to the time of day.	112
Figure 49: Number of peaks in apartment 2 during summer season, according to the time of day.	112
Figure 50: Methodology framework of occupant's heating behavior analysis.	114
Figure 51: Results of clustering of heating consumption for the monitored apartments.	116
Figure 52: Technical framework of electricity use (AMPLIA case study).	118
Figure 53: Clustering of electricity consumption according to exterior solar irradiance.....	119
Figure 54: Peak's frequency of lighting use in winter according to time of day for apartment (A) and (B) (AMPLIA case study).	120
Figure 55: Peak's frequency (superior than 1 kWh) in apartment (A) and (B) during Winter season.	121
Figure 56: Peak's frequency (superior to 0.35 kWh) in apartment (A) and (B) during Summer season.	122
Figure 57: Evolution of electricity consumption in 2020 (France, Germany, Italy, Spain, Great Britain and India) [120].	124
Figure 58: Technical framework of energy use analysis during and before the lockdown (HEART case study).	125
Figure 59: Evolution of the lighting use according to the global illuminance in March 2020.	126
Figure 60: Comparison of the lighting consumption during and before the lockdown (March 2020).	127
Figure 61: Hourly peak's frequency of electricity before and during the lockdown (March 2020).	128
Figure 62: Heating use according to outdoor temperature during the months of February and March.	129

Figure 63: Synthesis of the occupant's energy use in private and social housing.	132
Figure 64: List of final objectives of monitoring approach applied to occupant behavior analysis (stage 1 of phase 1).....	136
Figure 65: Flowchart of monitoring decision-making of lighting use (stage 1 and 2 of phase 1). ..	139
Figure 66: Flowchart of monitoring decision-making of heating/cooling use (stage 1 and 2 of phase 1).	140
Figure 67: Flowchart of monitoring decision-making of windows opening (stage 1 and 2 of phase 1).	141
Figure 68: Flowchart of monitoring decision-making of thermostat use (stage 1 and 2 of phase 1).	142
Figure 69: Flowchart of monitoring decision-making of electricity use (stage 1 and 2 of phase 1).	143
Figure 70: Synthesis of the monitoring activity implementation (stage 3 of phase 1).....	145
Figure 71: Synthesis of data analysis methodology developed in this research (phase 2).....	148
Figure 72: Evolution of the outdoor temperature according to windows opening in Kitchen and Stay (from 01/01 to 10/01).....	164
Figure 73: Evolution of CO2 concentration according to windows opening in bedroom 1 & 2 in the period of 01/01 to 10/01.....	164
Figure 74: Evolution of outdoor temperature according to windows opening in bedroom 2,3 and living room from 05/07 to 25/07.	165
Figure 75: Evolution of outdoor temperature from January to March.....	165
Figure 76: Evolution of outdoor temperature from September to December.	166
Figure 77: Artificial lighting use in the living-room according to each time slot for winter.	166
Figure 78: Lighting use in the living-room according to each timeslot for summer.	167
Figure 79: Evolution of indoor temperature, windows opening and set-point regulation for bedroom 1 & 2 in the period from October to December.	167
Figure 80: comparison of the lighting power and light on data on January.	168
Figure 81: Analysis of peak's frequency of lighting use in winter according to the weekdays and weekend for apartment 1 and 2 (LES GENTIANES case study).	169
Figure 82: Analysis of peak's frequency of lighting use in summer according to the weekdays and weekend for apartment 1 and 2 (LES GENTIANES case study).	169

List of tables

Table 1: Review on drivers affecting the use of thermostats tools.	38
Table 2: Synthesis of the monitoring approach for occupant behavior.....	42
Table 3: Identity record of HEART case study	53
Table 4: General information about the apartments instrumented in HEART project (French case Study).	54
Table 5: Identity record of AMPLIA case study [101].....	59
Table 6: General information about the apartments instrumented of “AMPLIA” case study.....	59
Table 7: synthesis of the parameters monitored in AMPLIA case study.....	60
Table 8: Identity record of LES GENTIANES case study [102].	62
Table 9: General information about apartments instrumented of “LES GENTIANES” case study. ...	63
Table 10: Identity record of HIKARI case study.....	65
Table 11: synthesis of the parameters monitored in HIKARI project.....	66
Table 12: Average of interior and outdoor temperature during the night ventilation for bedrooms.	83
Table 13: Overview of setpoint regulation in the bedrooms.	88
Table 14: Overview of setpoint regulation in living room.....	88
Table 15: Frequency of daily light use, according to each month in winter and summer season.....	91
Table 16: Average of exterior solar irradiance per time slot in winter season.....	110
Table 17: Results of the heating consumption clustering according to interior and exterior conditions.	170

Résumé détaillée



Développement d'une méthode basée sur l'approche du monitoring pour l'analyse du comportement d'occupant dans les bâtiments résidentiels.

A. Introduction

Le secteur résidentiel consomme 25,17 % de l'énergie finale en Europe, 29% en France et 25% au Maroc [1][2][3]. Il est donc considéré parmi les secteurs les plus prédominants de la consommation d'énergie finale. Dans ce contexte, l'efficacité énergétique des bâtiments représente un levier d'action important pour réduire la consommation d'énergie et les émissions de CO₂. A l'échelle **Européenne**, le cadre réglementaire (EPBD, 2010/31/EU, EED, 2012/27/EU, EPBD*recast*) encourage les membres de l'union européenne à adopter des longues stratégies pour améliorer l'énergie dans les bâtiments. Après la stratégie de 2020 pour l'augmentation de l'efficacité énergétique, l'intégration des énergies renouvelables, et la minimisation des émissions de gaz à effet de serre, le prochain objectif est d'atteindre le cadre climatique et énergétique 2030 qui vise :

- i) À augmenter l'efficacité énergétique de 32,5%,
- ii) À intégrer les renouvelables à 32 % dans le mix énergétique,
- iii) À diminuer les émissions de gaz à effet de serre de 40 % par rapport au niveau de 1990 [5].

Pour la **France**, les objectifs développés se basent principalement sur : a) l'augmentation de l'efficacité énergétique des bâtiments neufs, b) la réduction de 50% de la consommation d'énergie par le plan de rénovation nationale, c) l'implémentation et le développement de technologies et d'équipements plus économes en énergie et d) le développement des réglementations pour une meilleure gestion d'énergie et l'incitation des différents stakeholders à construire et rénover efficacement et à sensibiliser les citoyens pour améliorer l'exploitation de l'énergie [4].

En ce qui concerne le **Maroc**, le secteur d'énergie nationale se développe avec une croissance importante depuis 2009, afin de soutenir le développement économique et social du pays [10]. Le Règlement Thermique de Construction au Maroc (RTCM) représente un des aspects développés, et a été adopté par le parlement marocain en 2014. Le Règlement consiste principalement à améliorer la performance thermique du bâtiment tout en réduisant les besoins de chauffage et climatisation et à améliorer le confort des bâtiments non climatisés [11].

La grande consommation énergétique du secteur résidentiel incite les différents stakeholders à développer des stratégies et solutions pour augmenter leur efficacité énergétique. En plus, une analyse profonde des facteurs affectant la performance énergétique des bâtiments permet la bonne évaluation et optimisation de cette performance. D'après plusieurs recherches

[12][13][14], les facteurs techniques, structurels et environnementaux ne justifient pas à elle seules les consommations énergétiques constatées. Ainsi, le comportement des occupants a été identifié comme facteur majeur affectant la consommation d'énergie dans les bâtiments.

A.1 Problématiques scientifiques :

Le sujet du comportement des occupants devient un aspect important dans le domaine de l'énergie du bâtiment. Dans le contexte de ce projet de thèse, le comportement des occupants dans le secteur résidentiel a été analysé en développant et exploitant l'approche du monitoring. Cette recherche contribue à répondre aux enjeux suivants :

- Quelles sont les phases principales pour développer et implémenter l'approche du monitoring dans les bâtiments résidentiels ?
- Quels sont les facteurs affectant le comportement des occupants dans les bâtiments résidentiels ?
- Comment exploiter les données collectées de l'approche de monitoring pour analyser le comportement des occupants ?
- Comment les différents types de bâtiment résidentiel affectent le comportement des occupants ?

A.2 Objectifs et démarche scientifique :

L'objectif principal de ce travail est de développer une méthodologie pour le développement, l'implémentation et l'analyse des résultats issus de l'approche du monitoring. Par suite, trois sous-objectifs ont été fixés pour cette thèse :

- Développement d'une méthodologie d'analyse du comportement des occupants dans différents types de bâtiment résidentiel,
- L'identification des principaux facteurs influençant le comportement des occupants dans les bâtiments résidentiels étudiés,
- Développement d'un guide qui contribue à guider l'application de l'approche du monitoring dans le secteur résidentiel.

L'élaboration de ce travail a été divisé en trois phases :

Planification de la recherche : en se basant sur l'étude bibliographique menée dans le cadre de cette recherche et présentée dans le chapitre 1, les axes principaux du travail ont été fixés. Ensuite, une description détaillée des cas d'études exploités dans cette étude a été présentée dans le chapitre 2. Trois types de bâtiments (logements sociaux, bâtiments privés et ilot à énergie positive) ont été exploités pour caractériser le comportement des occupants et les facteurs influents ce comportement.

Phase d'étude et analyse : L'analyse des données collectés des cas d'études a été détaillé dans le chapitre 3 et 4. L'objectif est de développer une méthodologie originale pour l'analyse du comportement des occupants et les facteurs influents ce comportement. Le chapitre 3 se focalise sur l'étude de l'ilot à énergie positive dont trois interactions ont été analysées :

utilisation de l'éclairage, utilisation du thermostat d'ambiance et les ouvertures des fenêtres. En plus une évaluation et recommandations des données a été développée. Pour le chapitre 4, les données des bâtiments privés et des logement sociaux ont été utilisés pour analyser l'utilisation de l'éclairage, le chauffage et l'électricité.

Développement et valorisation : le dernier chapitre propose un guide intitulé HOBIM (Holistic approach for Occupant Behavior assessment based on In-situ Monitoring) qui permet l'organisation de l'approche du monitoring en développant toutes les phases nécessaires pour la réussir.

La figure 1 représente une synthèse de la démarche scientifique exploitée.

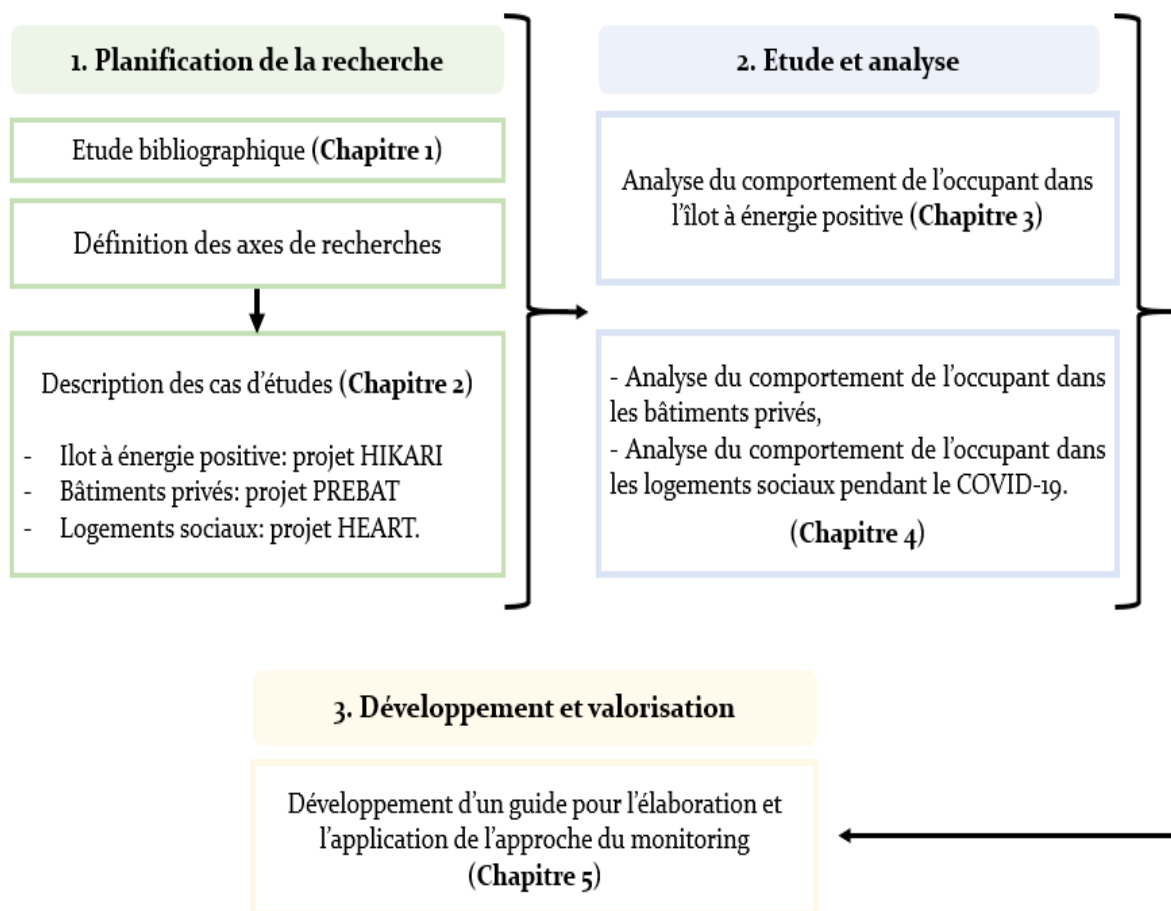


Figure 1: Démarche scientifique exploitée dans ce travail de thèse.

B. Synthèse d'étude bibliographique

En se basant sur l'étude bibliographique menée dans cette recherche, le comportement de l'occupant est défini par deux aspects : 1) sa présence et 2) ses interactions avec son environnement. La présence de l'occupant à l'intérieur d'un bâtiment reflète sa génération de chaleur, CO₂ et humidité. Ensuite à cette présence, l'interaction de l'occupant avec : les fenêtres, le chauffage, l'éclairage, thermostat, l'eau chaude sanitaire et son utilisation d'énergie caractérise le comportement de l'occupant et son influence sur la performance énergétique des bâtiments.

Les approches identifiées pour l'analyse du comportement des occupants sont divisées en trois catégories : l'approche du monitoring, modélisation et l'approche du feedback. L'approche du monitoring se caractérise par une précision importante mais aussi par des contraintes de confidentialités et d'éthique. La modélisation du comportement de l'occupant et en particulier les méthodes stochastiques donnent au comportement plus d'exactitude. Enfin, les programmes du feedback d'énergie ont également été identifiés dans cette recherche comme une méthode essentielle. Ces programmes reflètent le besoin d'intégrer les occupants dans le processus et leur donner la possibilité de contribuer aux stratégies d'économies d'énergie.

La complexité de ce sujet de recherche ne réside pas seulement dans la nature stochastique du comportement de l'occupant, mais aussi dans les multiples facteurs à prendre en considération lors de l'analyse. Ces facteurs peuvent être des facteurs liés à l'occupant comme les facteurs : psychologiques, physiologiques, culturels, économiques et individuels, ou des facteurs non liés à l'occupant comme les caractéristiques techniques du bâtiment et le climat.

Malgré les nombreuses recherches développées afin d'améliorer la performance énergétique des bâtiments, la non-intégration du comportement de l'occupant dans la phase de conception du bâtiment et des technologies intégrés au bâtiment reste un obstacle majeur pour assurer l'efficacité des stratégies appliquées. Pour cette raison, il est nécessaire de considérer les occupants dans les études en tant qu'utilisateur final du bâtiment et des technologies et qui représente une grande source d'influence sur la performance énergétique des bâtiments.

C. Description des cas d'études

Pour développer et réaliser ce projet de recherche, trois cas d'études ont été exploités. Le premier concerne **le projet HEART** dont ce projet de thèse fait partie. Cette expérimentation in-situ a été conçu et développé et implémenté dans le cadre de ce travail. Les paramètres mesurés et analysés dans ce cas d'études sont : les conditions intérieures (température, humidité et CO₂), la température extérieure, la consommation de chauffage, la consommation d'éclairage, la consommation d'électricité général, et la consommation d'eau chaude sanitaire. Le deuxième cas d'étude concerne **le projet PREBAT**, deux bâtiments différents ont été analysés. Les paramètres mesurés sont : les conditions intérieures (température, humidité et CO₂), la consommation de chauffage, la consommation d'éclairage, la consommation d'électricité général, les conditions extérieures (température extérieure et ensoleillement). Les mesures de ces deux premiers cas d'études sont considérées comme des mesures indirectes où il faut analyser la consommation d'énergie pour identifier des modèles de comportement de l'occupant ou d'utilisation de l'énergie.

Le troisième cas d'études est un îlot à énergie positive avec des mesures directes du comportement de l'occupant comme : l'ouverture des fenêtres, la modification de la température du thermostat et l'allumage de l'éclairage.

D. Analyse des bases de données

D.1 Méthodologie

Après le développement et la collection des bases de données à étudier, deux techniques ont été exploitées dans la phase d'analyse afin de proposer une méthodologie générale pour l'analyse du comportement de l'occupant, l'étude des facteurs influençant ce comportement et l'évaluation des mesures. Le KDD (Knowledge Discovery in Databases) et le Data Mining (clustering) sont les deux techniques sélectionnées pour cette étude, et la figure suivante représente une synthèse de la méthodologie développée.

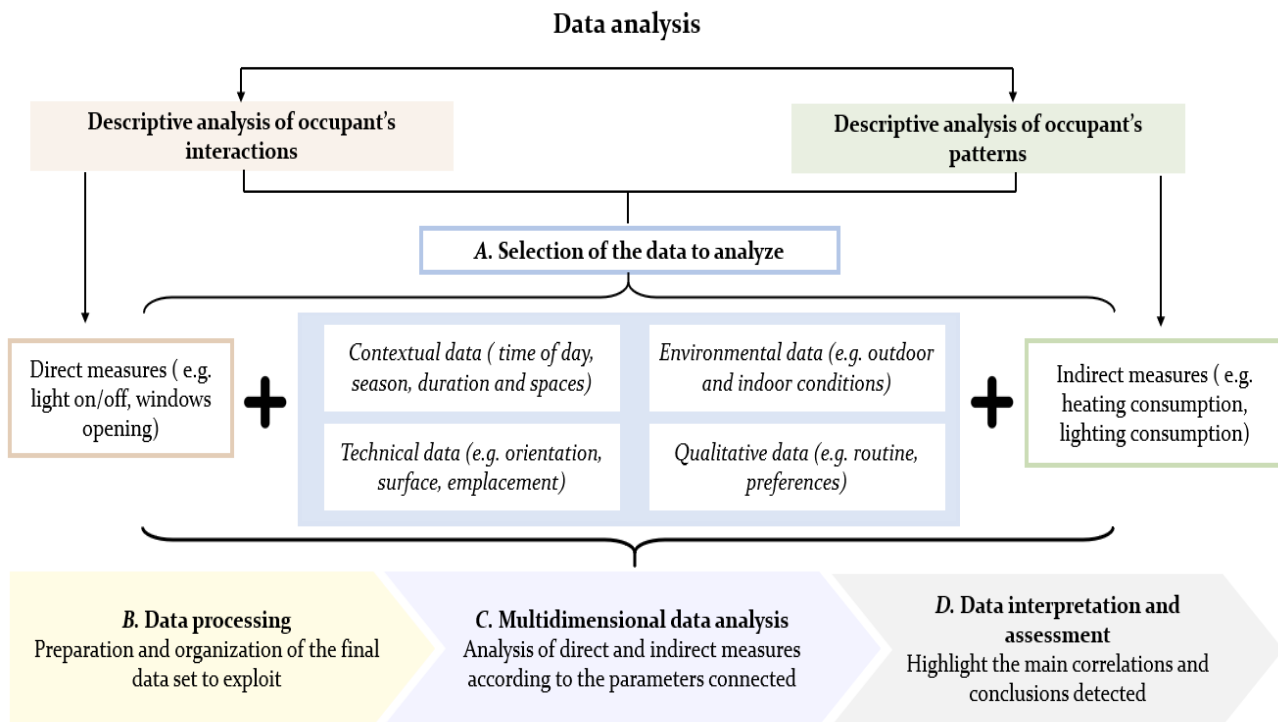


Figure 2: Synthèse de la méthodologie d'analyse des données développée dans cette recherche.

D.2 Synthèse des résultats

En ce qui concerne *l'ilot à énergie positive*, les mesures nous ont permis d'identifier directement le comportement des occupants par des mesures directes implémentés dans les différents espaces de l'appartement (chambres, séjour et cuisine). Les mesures analysées sont : 1) l'ouverture des fenêtres, la modification de la température du thermostat et 3) l'utilisation de l'éclairage. L'analyse a été menée durant la saison d'hiver et d'été. **L'ouverture des fenêtres** en hiver a été affectée par le type d'espace (chambre, séjour, cuisine), par l'heure de la journée (heure de réveil, heure d'arrivée à la maison) ou par les préférences personnelles des occupants. Ces facteurs sont aussi identifiés comme facteur affectant l'ouverture de fenêtres en été, mais en plus, les températures intérieures et extérieures représentent un facteur crucial durant cette saison. La **modification de la température du thermostat** a été influencée principalement par le type d'espace et la durée de la présence dans les espaces (plus la durée de présence est longue plus l'occupant ressent le besoin d'assurer le confort

thermique). Il a été déduit aussi que les températures les plus élevées ont été régulées au début de la saison hivernale. Cette régulation est affectée par la saison qui précède ou l'occupant s'est habitué à des températures élevées et a besoin de garder la même sensation. En conséquence, on peut conclure aussi que la température extérieure joue un rôle important dans la modification de la température du thermostat. En ce qui concerne *l'utilisation de l'éclairage*, les facteurs ne changent pas entre les deux saisons. L'heure d'arrivée à la maison, l'heure de départ de la maison, l'ensoleillement extérieur et le type de l'espace sont identifiés comme facteurs influençant l'utilisation de l'éclairage par les occupants.

Les mesures analysées des *bâtiments privés* sont considérées comme des mesures indirectes à partir desquelles il faut identifier des modèles du comportement de l'occupant. Trois types de mesures ont été exploitées dans cette partie de recherche : 1) la consommation du chauffage, 2) la consommation de l'éclairage et 3) la consommation de l'électricité générale. Ces consommations ont été analysées pour la saison d'hiver et d'été.

L'analyse de plus d'un appartement dans cette partie nous a permis de révéler différents modèles du comportement de l'occupant. Pour l'étude des consommations, les facteurs suivants ont été déduits comme facteurs influençant l'utilisation d'énergie par les occupants :

- **Consommation d'éclairage** : Scenario de présence et absence, ensoleillement, saison, durée de présence et absence (weekend, vacances), besoins et préférences personnelles.
- **Consommation de chauffage** : Surface de l'appartement, orientation et emplacement, température extérieure, ensoleillement, ouverture des fenêtres, durée de présence et absence, facteurs culturels, précarité énergétique, besoins et préférences personnelles.
- **Consommation d'électricité générale** : Scenario de présence et absence, profil des occupants, équipements électriques additionnelles (système de climatisation), besoins et préférences personnelles.

Pour les *logements sociaux*, en plus de l'identification du comportement de l'occupant une analyse d'impact du premier confinement (COVID-19) sur l'utilisation d'énergie dans les logements sociaux a été développée. Les résultats montrent une augmentation significative dans la consommation d'électricité à cause des longues périodes de présence à la maison et du changement d'habitudes des occupants. En ce qui concerne l'utilisation de l'éclairage, le mode d'utilisation reste le même mais avec des pics plus importants.

En outre, l'évaluation des mesures exploitées dans ce travail a affirmé la nécessité de développer une analyse connectée pour tirer le maximum d'informations. C'est pourquoi il est important de développer une base de données complètes qui contient non seulement les interactions de l'occupant avec son environnement, mais aussi le détail technique du bâtiment étudié. Une évaluation du pas de temps de chaque mesure a été développée et l'importance des données qualitatives pour la confirmation de certaines suppositions a été soulevée.

E. Le guide HOBIM (Holistic approach for Occupant Behavior assessment based on In-situ Monitoring).

Le guide HOBIM représente le résultat final de cette recherche. L'objectif principal de ce guide est de fournir une méthodologie qui aide à adopter l'approche du monitoring pour l'étude du comportement de l'occupant dans les bâtiments résidentiels. La méthodologie est divisée en trois phases principales :

1. Phase de design : la première phase permet l'identification des objectifs finaux de l'approche du monitoring, la sélection des paramètres à mesurer, et la planification de l'implémentation du monitoring

2. Analyse des données : la deuxième phase concerne l'analyse des mesures afin de comprendre les interactions/modèles de l'occupant dans le bâtiment résidentiel (identification, évaluation et interprétation du comportement de l'occupant)

3. Valorisation : la dernière phase propose l'exploitation des résultats de l'analyse des données. Cette valorisation va permettre de contribuer à l'évaluation et la prédiction de la performance énergétique des bâtiments résidentiels.

F. Conclusion et perspectives

Les études de la performance énergétique des bâtiments sont considérées complètes seulement si les facteurs techniques et humains sont pris en compte. Le comportement de l'occupant a été négligé pendant une grande période dans les études de l'énergie des bâtiments et son intégration devient une nécessité dans les études de nos jours.

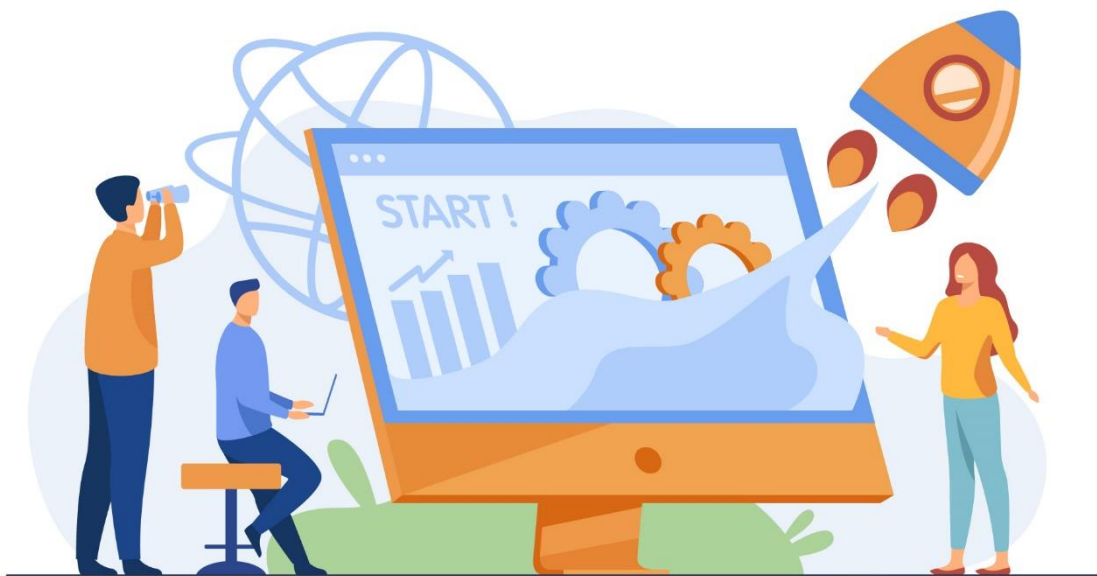
Ce travail de thèse se focalise sur l'étude du comportement de l'occupant par l'approche du monitoring. L'objectif était de développer un guide de planification et d'implémentation de cette approche. En plus, développer une méthode d'analyse des données qui permet de comprendre le comportement de l'occupant et d'identifier les facteurs influents ce comportement.

Les résultats représentés dans cette recherche ont permis : i) l'identification de certains facteurs influençant le comportement de l'occupant dans trois types des bâtiments résidentiels. Ce dernier est également considéré un facteur important de l'utilisation d'énergie par les occupants, ii) l'évaluation des mesures étudiés qui va permettre une meilleure organisation des choix des paramètres à mesurer en fonction de l'objectif final mais aussi de types de l'interaction à étudier, iii) l'élaboration d'un guide complet qui traite les différentes phases de l'approche du monitoring.

Comme suite à cette étude, une instrumentation a été développé dans une maison individuelle au Maroc. L'objectif c'est d'analyser un autre type de bâtiment résidentiel mais dans un contexte climatique et culturel différent. D'autres recherches pourront faire l'objet d'une suite

à ce travail, comme l'investigation d'utilisation des stores et d'eau chaude sanitaire. L'analyse d'autres saisons de l'année est aussi considérable pour voir l'impact des températures modérées sur le comportement de l'occupant. En revanche, l'exploitation des résultats de cette recherche pour analyser l'impact du comportement d'occupant sur la performance énergétique des bâtiments est aussi un aspect très important à explorer.

General Introduction



General Introduction

Overview and energy context

The residential building sector is one of the major sectors in Europe in terms of energy consumption and CO₂ emissions [5]. In 2016, 25.71 % of the final energy consumption was identified in the residential sector, which makes the building energy performance one of the main issues nowadays [1]. At European level, directives related to energy such as the energy performance of building directive (EPBD, 2010/31/EU) and the Energy Efficiency Directive (EED, 2012/27/EU) represent the legislative framework that supports the improvement of building energy by obliging the member states to implement long term strategies. Additionally, it encourages the increase of building energy efficiency by providing support for a complete interactivity between technologies, occupants and environment [6]. At the national level, the EPBD recast introduces specific requirements for each country depending on various factors. The member states should deliver a national plan which contains the principal policy measures and the energy efficiency obligation scheme. In this context, the national energy efficiency action (NEEA) was designed with the objective to report the progress achieved by the EU individual countries. The plans are delivered each three years and an annual report is required.

It has been reported by ODYSSEE-MURE project that an improvement of 28% has been identified in household energy efficiency at European level since 2000 [7]. After the Europe 2020 strategy for increasing energy efficiency, renewables integration and the minimization of greenhouse gas emission, the next goal is to achieve 2030 climate & energy framework. The targeted framework aims to [8]:

- Increase the energy efficiency by 32.5%,
- Integrate the renewables by 32% in the energy mix,
- Decrease the greenhouse gas emission by 40% compared to the level of 1990.

In France, the building sector consumes around 44% of the final energy consumption and emits more than 123 million tons of CO₂ each year [4]. In this respect, the building sector represents a key field for energy transition and key to reduce the global warming. By 2030, France has developed ambitious objectives which consist of:

- **New buildings:** An average of 350,000 dwellings are built per year. The integration of solutions to the increasement of building efficiency in new constructions is made mandatory. This increasement considers the improvement of the well-being of the occupants while minimizing the buildings energy consumption [9][4].
- **Renovation plan:** By 2030, 500 000 of housing will be renovated per year, and more than 50 % of energy consumption reduction is targeted. In addition, the renewable energies will represent 35 % of the energy mix, and the renovation of the social housing

stock built before 2005 is required. Concerning the single-family houses, 70 % of them are built before 1975 and 5 million of the houses will be renovated[6].

- **Equipment and facilities:** The reduction of energy use in buildings needs the implementation of more energy-efficient technologies and equipment. A specific focus will be dedicated to the development of heat pumps for space heating, and electric water heaters for domestic hot water [9]. **Figure 3** represents the ambition by 2030 in residential sector by type of use.
- **Plan management:** France energy policy is based on: **i)** developing regulation for a better control of energy consumption in buildings, **ii)** raising awareness in order to promote eco-citizen behavior, and **iii)** encouraging the different stakeholders to build and renovate more efficiently the buildings [4].

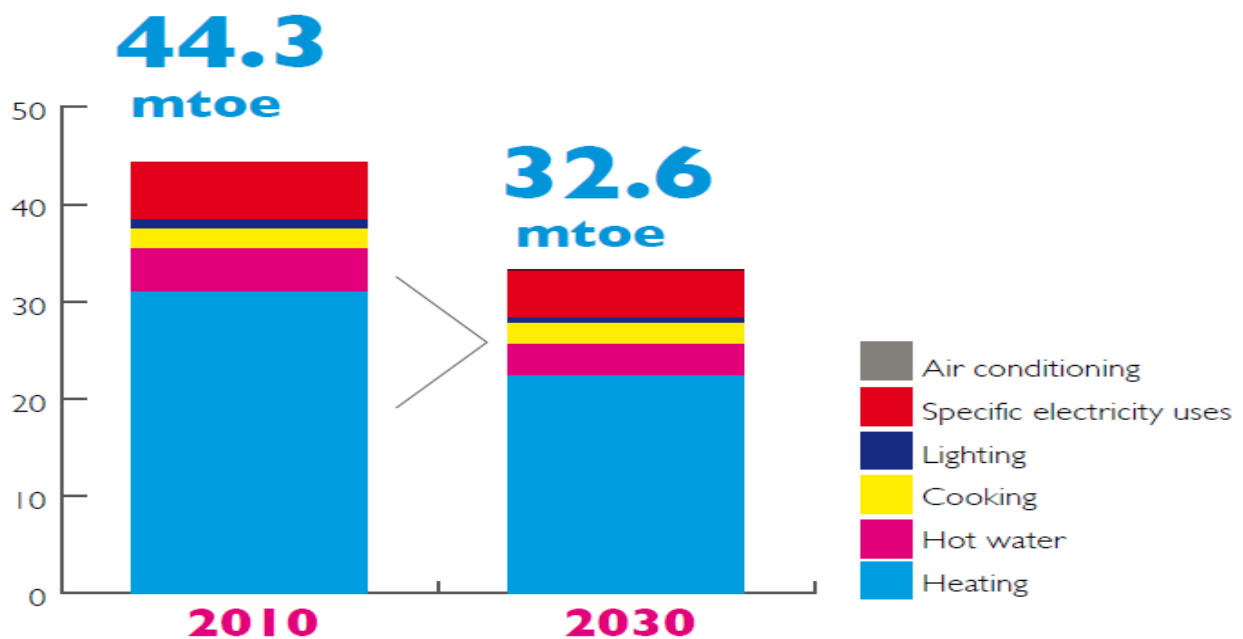


Figure 3: Energy consumption in residential construction in 2010 and 2030, by type of use (France, ADEME [9]).

In Morocco the residential sector consumes around 25% of the total energy of the country [3]. In the same sector the energy consumption has known an increase by 26% between 2007-2017 [3]. The building sector in Morocco is growing rapidly, and it was stated that 50% of the investments are consecrated to this sector in order to meet the needs [10]. In residential buildings, the butane gas is mostly employed for cooking use and water heating. Electricity is used for household appliances, lighting, heating and cooling [10].

The national energy sector has known an important grow since 2009, which aims to support the economic and social development of the country [11]. One of the aspects developed in this respect is the Thermal Regulation Construction Code (RTCM) adopted by the Moroccan parliament in 2014. The RTCM consists mainly on the increasement of the building thermal performance by [12]:

- Improving the comfort of non-air-conditioned buildings

- Reducing the heating and air conditioning needs of buildings
- Encouraging architects, engineers and project managers to adopt efficient thermal approaches for buildings' envelope, and support them for developing energy diagnostics of existing buildings
- Proposing to contracting authorities, public decision-makers and donors funds, a tool to improve the productivity of their investments.

As stated above, the energy consumed by building sector in Europe, France and Morocco implies the development of various strategies for increasing the building energy efficiency. In this respect, we believe in this research that an in-depth control of energy efficiency requires a holistic approach in order to understand what really affects the energy consumption in buildings. According to the international energy agency research developed by Annex 53, 66 and 79, the occupant behavior influences strongly the building energy performance [13][14][15]. The buildings are designed to be occupied and exploited by occupants in comfortable and secure conditions. For this reason, the necessity to integrate occupant behavior in the building conception is important to achieve the building energy performance predicted and to increase its evaluation.

The occupant's energy use is reflected by several interactions such as: windows opening, thermostat use or light-on. The desire to achieve a satisfaction is one of the primary drivers of occupant behavior [14]. In addition to the important impact of technical factors, the occupants' interactions are what made the energy consumption vary differently in dwellings with the same technical characteristics. Thus, this research supports studies of the energy performance of buildings by analyzing the behavior of occupants in residential buildings. The occupant behavior is a complex interaction that varies according to various factors, which makes the understanding of these factors important.

This thesis is a part of the European "HEART" project which consists in the development of a holistic approach to the rehabilitation of residential buildings. The project offers a new and innovative concept of rehabilitation, either in terms of envelope composition or in terms of energy production and management systems. HEART project will develop a toolkit that incorporates different components and technologies, which cooperate to transform an existing building into a smart building. The toolkit had been demonstrated in two case studies. In the French case study, a monitoring approach was developed to analyze the occupant's energy use in a social housing as one of the important types of residential buildings investigated in our research (<https://heartproject.eu/>).

HEART project represents four main objectives:

- Improve European building renovation process by simplifying it,
- Reduce total energy consumption, integrate renewable energy and rationalizes energy flow between buildings and smart grids,

- Involve stakeholders, support energy financing as well as the utilization of renewable energies,
- Possibly extend the concept to new residential buildings, in addition to existing buildings.

Scientific issues of the topic

The topic of occupant behavior becomes a focus in the domain of building energy and almost mandatory to evaluate and predict the building energy performance. In this context, several scientific issues were identified through the literature review:

- What is the most effective method for identifying occupant behavior?
- What are the main factors influencing occupant behavior?
- What is the level of impact of human factors on building energy performance gap?
- How can the accuracy of occupant behavior in thermodynamic simulation tools be improved?
- How can research contribute to the improvement of occupant behavior?
- What is the importance of the social logic in the analysis of this topic?

The points mentioned above are identified by the specialists of building energy performance and considered as a principal step to initiate the topic and to encourage the researchers to further investigations. If the issues are well understood, the strategies and the directions to find solutions will be clearer. The major difficulty of the subject lies in the integration of occupant behavior which is considered to have a stochastic aspect, with the deterministic aspects of building energy. Consequently, it's important to identify the source of the stochastic aspect of occupant behavior and the principal factors affecting the occupant behavior in the buildings. In addition, it should be noted that there is a lack of:

- Understanding of energy-related occupant behavior,
- Characterizing the factors influencing the interaction of the occupants in their environment and identifying the behavioral patterns.

This lack limits the total prediction of energy use in buildings and the complete assessment/evaluation of the energy saving policies and techniques [15].

The two main approaches integrated for the occupant behavior assessment are: the occupant behavior modeling and the monitoring approach. The occupant behavior modeling aims to develop models that could predict the occupant behavior while considering its drivers. However, the stochastic nature of occupant behavior and the various affecting it gives to the approach several aspects to consider. In addition, the integration of this models in the studies is also an important issue that was mentioned by researchers [16]. The monitoring approach consists on the installation of sensors in buildings for occupant behavior observations. It

provides a description of the real occupants' interactions. Nevertheless, the implementation of the approach could not be easy for all the buildings, and the privacy issues is one of the aspects that should be considered [14][17].

The non-consideration of the occupant behavior in the Building Program Simulation (BPS) generates a disagreement between the real energy consumption and the simulated results. Usually, the aspect of human behavior is simplified by a conventional scenario (deterministic or static schedules)[18], ignoring the variety of the occupant behavior (stochastic and dynamics schedules) [19][20][21][22]. The purpose is to eliminate the classic method for presenting the occupant behavior in the BPS and to introduce innovative tools and methods that could consider the stochastic nature of occupants in the simulations. Within this vision several research were developed and insist on the importance of increasing the accuracy of occupant behavior in the BPS [23][24][25][26].

Furthermore, the energy practices tend to focus mainly on the technological and physical logic more than the human and social logic, forgetting that this technology is designed to be used and exploited by humans. If the designers and the owners of buildings choose to eliminate the human aspect, which includes the social, cultural, economic aspect, the condition of appropriation and conviviality in the context of utilization, then the results predicted won't reflect the reality [27]. This issue, lead us to reconsider the communication factor to explore different sides of the occupants' lives nature. The majority of residents have a lack of knowledge and information about the energy use in buildings, and more specifically how they impact the building energy performance. In this context, it's interesting to reconsider the importance of implementing communication strategies for a long-term management of the different building parameters and a control of the factors influencing the energy performance.

In the context of this research, the development, implementation and analysis of the results based on the monitoring approach were our main issue and the residential building sector was our target for the occupant behavior analysis. This research contributes to answer the following issues:

- What are the main steps for developing a monitoring approach in residential buildings?
- What are the main factors affecting the occupant behavior in residential buildings?
- How could the data collected from monitoring approach be analyzed for occupant behavior assessment?
- How can the different types of residential buildings affect the occupant behavior?

Research objectives, scientific approach and dissertation outline

This research defends the importance of including occupant behavior on the assessment of building energy performance. It aims to develop a comprehensive approach for the development, implementation and analysis of the results of monitoring approach. In this respect, three sub-objectives were defined:

- Development of a methodology for occupant behavior assessment in three different types of residential buildings,
- Identification of the main drivers affecting the occupant behavior in residential buildings,
- Development of a guideline to support the application of monitoring approach in residential buildings.

The realization of this research was carried out based on three main stages:

1. Research design

Based on a deep literature review about the occupant behavior analysis and assessment in residential buildings, and about the monitoring approach used for this analysis, the main axes of this dissertation were defined. The results of the literature review are presented in the first Chapter of this thesis.

In Chapter 2, the case studies developed and exploited in this research will be presented in detail. The case studies concern smart, private and social buildings. These three types of building outline the next stages of the analysis.

2. Process analysis

After the collection of the monitored data set, a comprehensive data analysis was performed in order to describe the occupants' interactions and patterns in the targeted case studies. An original methodology was proposed for the data analysis process in Chapter 3 and Chapter 4. Chapter 3 focuses on the analysis of occupant behavior in a smart building. Three interactions were investigated: windows opening, artificial lighting and thermostat use. In addition, an evaluation of the dataset is provided with recommendations.

In Chapter 4, the analysis of occupant behavior concerns the uses of heating, artificial lighting and electricity. The first part of this Chapter represents the occupants' patterns in private building. The second part analyzes the occupants' patterns and the impact of the first lockdown in France of COVID-19 on the energy use.

3. Development and valorization

The last Chapter represents an innovative guideline that supports the stakeholders during the in-situ monitoring process. The guideline proposes the main phases to adopt while developing

a monitoring activity. Furthermore, a detailed definition and recommendation were developed for the several phases in order to provide a comprehensive tool with the principal elements for a successful monitoring approach.

Figure 4 presents the detailed scientific approach employed for this dissertation.

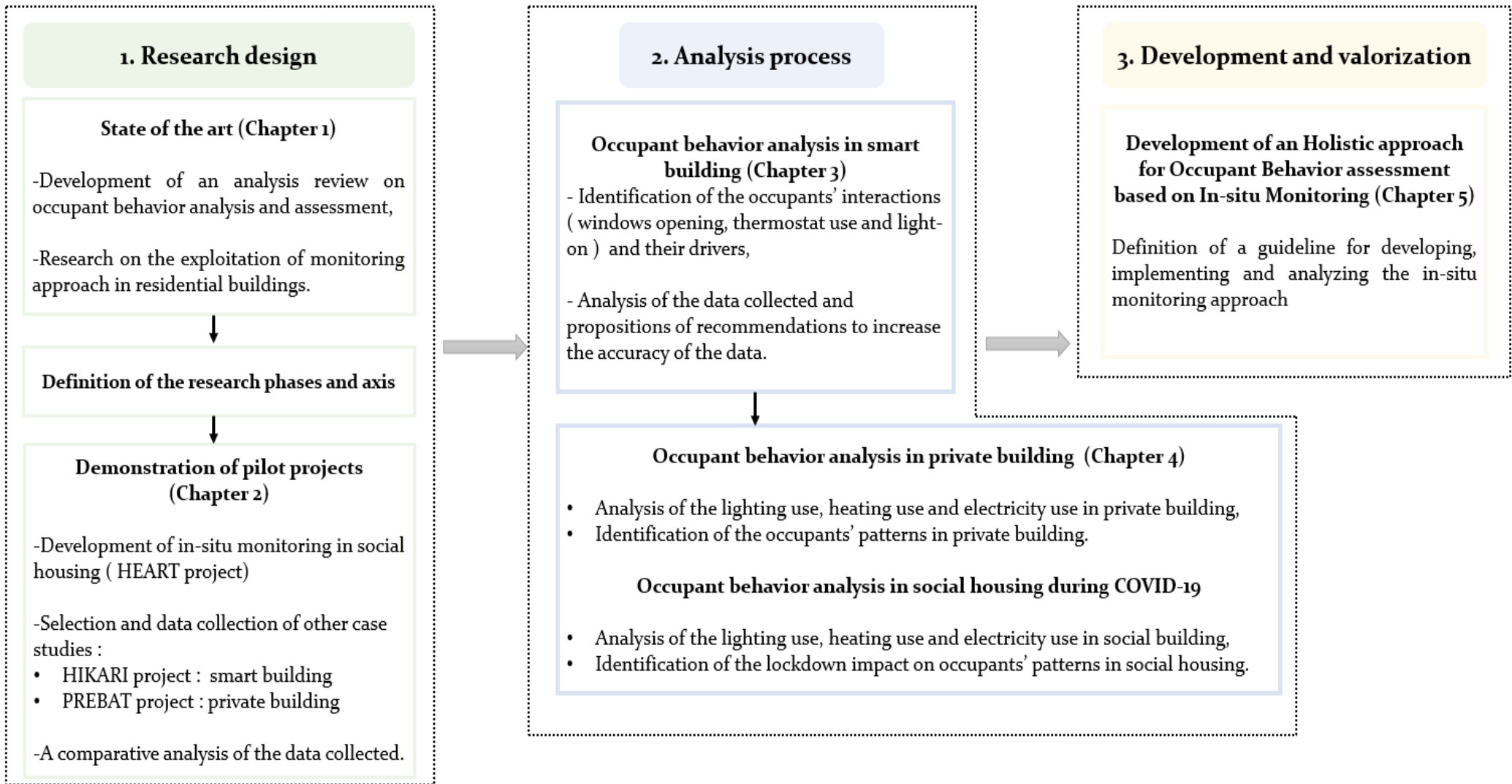


Figure 4: Scientific approach employed during this dissertation.

CHAPTER I

State of the art

Occupant behavior: A major issue for building energy performance simulation and assessment



Chapter I: State of the art

Occupant behavior: A major issue for building energy performance simulation and assessment

I.1 Introduction

The occupant behavior grows into an important approach to integrate in the field of engineering and data mining science, in order to enhance the accuracy of the results and to develop a complete vision of the deterministic studies. According to the International Energy Agency IEA [15], the building energy performance is affected by (1) technical and physical factors as: Climate, building envelope and equipment and, (2) human factors as : Operation and maintenance, and occupant behavior. This latter has been highlighted by many studies as a crucial element to understand the energy use in the buildings prior to analyze their energy performance.

The occupant behavior is defined by the presence of the occupants, and their actions and interactions regarding their interior environment. The aim of this chapter is to provide a general review of the topic of occupant behavior, in order to address the complexity of the subject in a simple way and to highlight its important aspects. In the following sections, three main aspects were detailed:

- Definition of the occupant presence, occupants' interactions,
- Analysis of the drivers affecting the occupant behavior,
- Presentation of the main research approaches presented in the literature.

The interest in the behavior of the occupants began in 1978 [28] with a first study of Princeton Socolow [18] which addressed the influence of the behavior of residents on the energy consumption for space heating. Since 2005, many studies on this topic have been developed and have resulted in several scientific literatures with a publication activity growth of 20% per year and more significant results. The interest in the occupant behavior has evolved in a very impressive way the last 10 years. **Figure 5** shows the evolution of the published research on the topic of occupant behavior. The elaboration of this analyze was carried out by using Scopus database for the period from 1995s up to December 2020. Keywords used for this research are “occupant or human”, “behavior” and “building”. Thereafter, a verification that all the results are in the domain of building energy performance such as: energy consumption, thermal comfort, indoor air quality, energy renovation, energy modeling and design, lighting comfort and occupant's satisfaction was necessary. In addition, we have checked that the occupant behavior is an aspect considered in the research and cited as author/indexed keywords for the research published. More than 650 publications were identified in the period targeted and the

year of 2019 represents the year where the most published research was identified (**Figure 5**). Even if the review and the book Chapter are considered, the majority of the bulk of the production is articles and conference paper. Also, this analysis aims to enrich and to update the investigation conducted by Zhang et al. and Balvedi et al. who have presented the data base of Scopus and Web of Science TM Core Collection – Citation Indexes (SCI-EXPANDED & SSCI)[28][29].

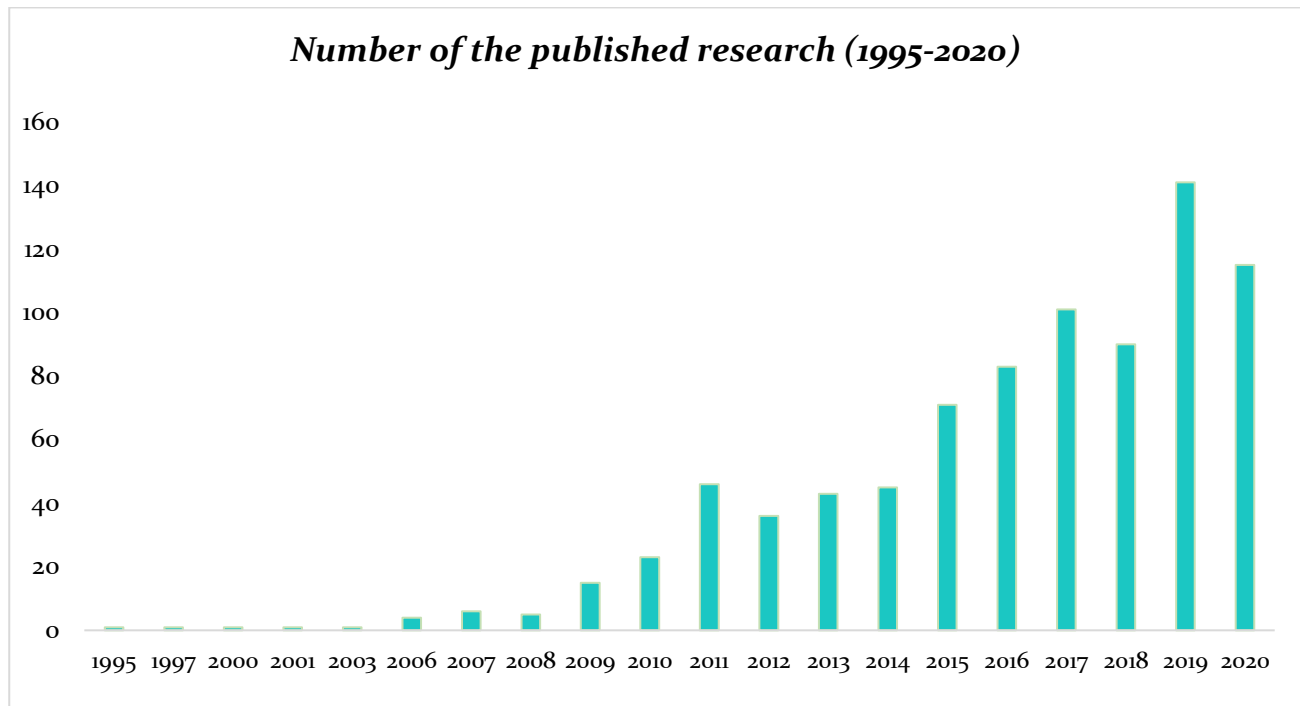


Figure 5: Evolution of the number of published research on the occupant behavior topic (Scopus).

I.2 Occupant Behavior: presence and occupancy profile

The first aspect defining the occupant behavior is the presence of occupants in their households. This presence is described in the research by two main parameters and indicators:

- a) The scenario of presence that reflects the numbers of hours related to the absence and presence of the occupants inside the households and, the nature of the activity.
- b) Occupants profiles that indicates the number of occupants and in some studies the gender and age are important details to consider for higher accuracy.

The occupants are considered as a main source of CO₂, moisture and heat generation in room /apartment. For this reason, the CO₂ parameter is considered in the literature the most significant parameter for the identification of the presence/absence of the occupants and profile estimation [30].

According to Persily et al.[31], the CO₂ generation depends mainly on (1) gender, (2) age and (3) type of activity. In his research, new methodology based on the human metabolism and

exercise physiology is presented to estimate the CO₂ generation. The results confirm the necessity of increasing the level of accuracy of this value instead of the standard values that generalize the same rate of CO₂ generation for all the occupants. Considering that the presence has a direct impact on the quality of indoor air, occupants' needs and interactions, it is crucial to understand this aspect to better assimilate the scientific issues and the occupants' interactions.

Studies have shown that the negligence of occupant behavior in the deterministic approach influences obviously the certitude of the results and hides the power of occupant's reactions on affecting several parameters and improving multiple situations [22][32]. One of the most important issues impacting the evaluation of building energy performance is the accuracy of presence scenario instead of the conventional/ static scenario utilized in the frequent studies [26][33]. For this reason, it was crucial to propose methods, models and tools that allow the identification of occupant presence and estimate the occupancy number. Several studies were developed in this context; and they can be classified into two categories:

- (1) physical models/white box,
- (2) machine learning/statistical/black-box models.

A large work has been developed in this field, for example: the Feature Scaled Extreme Learning Machine FS-ELM has been cited by Jiang et al. [34], as discrete-time dynamic model that allows an estimation of occupant presence based on the function that links the CO₂ data, the venting level and the past occupancy level. In another study presented by Han et al. [35], dynamic neural network model were presented in the context of an experiment measurement in a single room. In this context, other methods are important to be discussed and developed such as the proxy methodology [36], estimators with different level of complexity and filtering [37], and the Gsforest model presented and developed by Zhou et al.[38]. A grey box model was developed recently combining the physical and statistical models for increasing the accuracy of room occupancy [39]. Besides the modeling, the occupant measurements are also available, but with a limited use especially in households for privacy issues. Accordingly, the majority of the research were developed for offices and laboratories where the collaborators can work and contribute comfortably to the measurements. In this respect, several studies were adopting data driven technics to identify and predict the presence and occupancy schedules[40][41][42].

I.3 Occupants' interactions

The term of behavior is simplified by Chen et al. [43] in his study where he defines it as a visible action/ reaction to adapt to the ambient environmental conditions. The definition of the occupants' interactions depends mainly on the context of the study, on the objective from the research, and could be defined by different levels of complexity [43]. However, the definition of the parameters related to the actions and reactions of the occupants differs from case to another because for each case study the environmental conditions are different. Even

when the conditions are the same, the reactions of the occupants are variable and depend on different drivers.

Figure 6 illustrates some examples of the occupant interactions with their environment, and Figure 7 presents the process of occupants' interactions from drivers to actions.

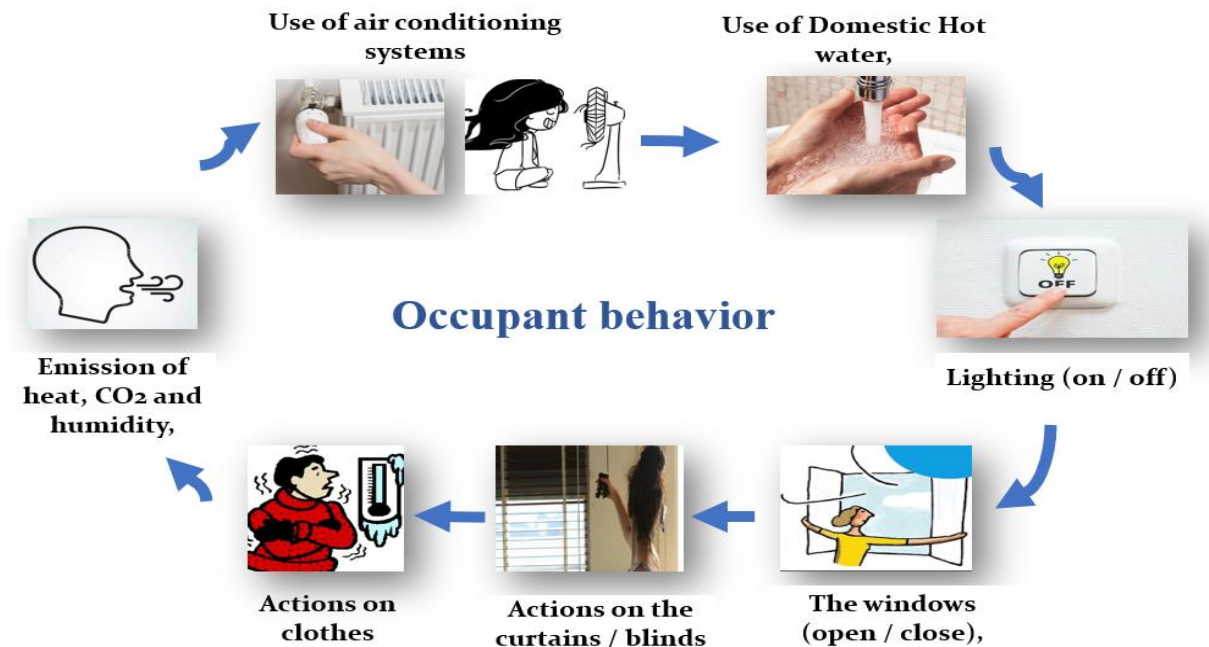


Figure 6: Examples of occupant interactions with their environment.

1.3.1 Occupant Behavior: factors and drivers

A comprehensive analysis of the subject requires the necessity of the identification of several factors/drivers affecting the energy occupant behavior. This identification is the purpose for different approach research, because it allows a better apprehension of behavior patterns and an improvement of building energy performance analysis. But also, to identify the energy behavior gaps and consider it for future strategies and solutions to minimize energy consumption in buildings.

As stated above, the building's energy consumption is also affected by the occupant behavior. The occupant's energy use could be affected by various factors classified in three principal categories: environmental, contextual and other different factors. The environmental factors concern all the technical drivers related to the interior and exterior climatic conditions, building characteristics and building equipment. Moreover, the season, the day time and the type of space are also considered as main drivers affecting the occupant presence and interactions [32] [24]. The impact rate of those drivers on energy occupant behavior is correlated and rely as well on other drivers such as: social, cultural, economic, physiological, psychological drivers that reflect the preferences and needs of each occupant [39]. The drivers are considered to be the source of occupant motivation and need creation. When the

factors/drivers are present, the occupants need to achieve a thermal comfort, air indoor quality, lighting and acoustic comfort and other various needs and preferences and lead the occupants to interact and react with their environment to satisfy their needs.

The various types of drivers are not all attached to all the interactions, and not similar for all interactions. In this context, the interest in analyzing each interaction autonomously was significantly increased in the scientific community. In the following paragraphs, a synthesis review about the drivers affecting the windows, thermostat and lighting interactions have been analyzed separately.

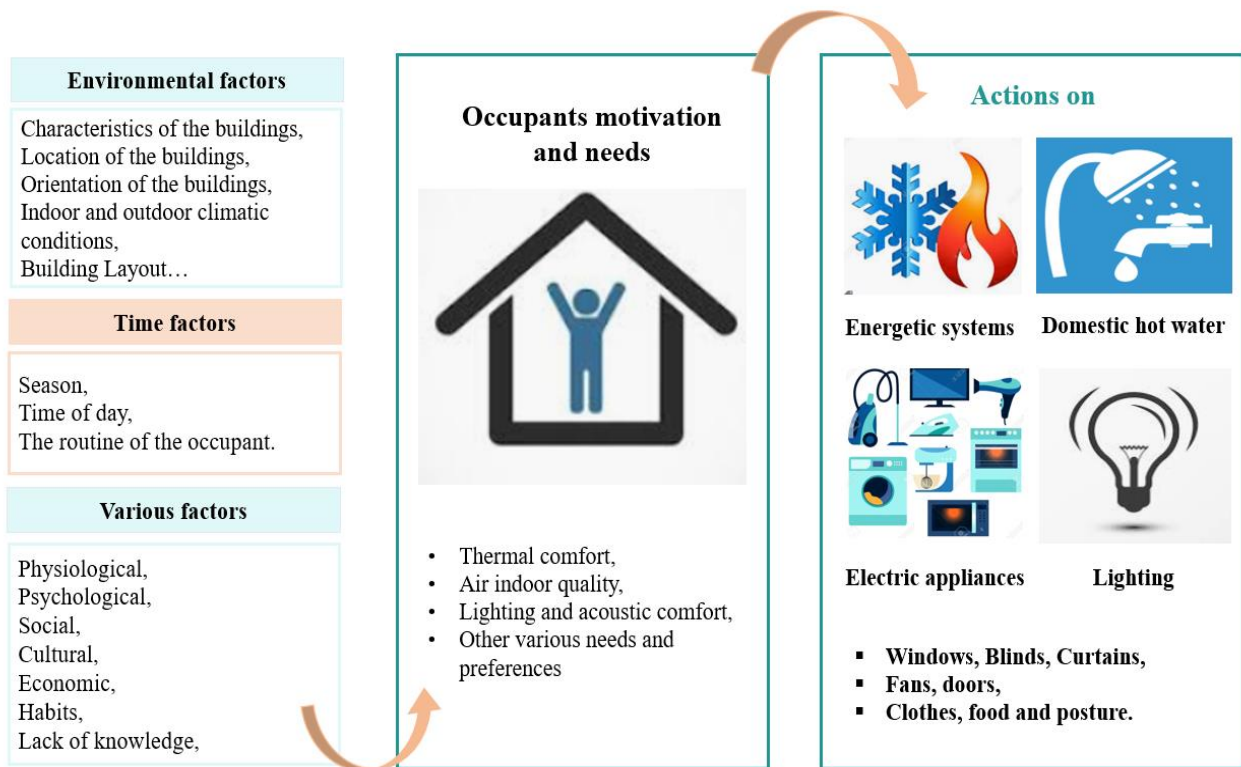


Figure 7: Layout of drivers, needs and occupant behavior actions.

Drivers of windows interactions: synthesis review

The need of ensuring thermal comfort and a good level of air quality is important for the occupants. In this context, the windows opening is one of the main occupant’s interactions that should be considered in the building energy performance assessment. According to the literature review presented by Fabi et al. [44] which was mainly based on the findings of the IEA ECBCS Annex 8 [45], the driving factors for windows operation in residential buildings are divided into five sections :

- (1) *Contextual factors* that include the dwelling and room type, orientation of the space ventilated, season & time of day and system’s type;
- (2) *Physical factors* as exterior and interior conditions;

- (3) *Psychological factors* that vary in accordance with the perception of thermal and lighting comfort;
- (4) *Physiological factors* as age and gender and;
- (5) *Social drivers* that present the schedule of occupant's presence and their habits such as smoking.

Correspondingly, Stazi et al. [46] specify in their literature review that the exterior temperature was considered the first driver correlated with windows opening. The second driver is the indoor temperature and then the CO₂ concentration. The analysis of Stazi et al. was based on the number of research paper identified. In **Figure 8**, the principal outcomes of windows opening drivers are presented.

The outdoor temperature presents linear correlation with the opening of windows and affects the frequency of opening. This correlation is clearly identified between -10°C and 25°C [44]. If the exterior temperature is lower than 15°C, the windows opening is not frequent. The frequency of windows opening increases with the increase of the exterior temperature (between 15°C and 30°C). When the exterior temperature exceeds 30°C, the windows opening is in the maximum of frequency [46]. The indoor temperature doesn't present the same correlation, especially in summer when the temperature exterior is high, the occupants close the windows to avoid heat gains.

The wind was also detected as a factor for opening windows, when its speed exceeds 8m/s, the decrease of windows opening becomes necessary. In addition to these conclusions, the maximum windows opening was identified in the morning and in the bedrooms, especially if it is oriented to the south, and the opening period is much longer. Contrary to the living room and bath room where very few openings and shorter periods were detected.

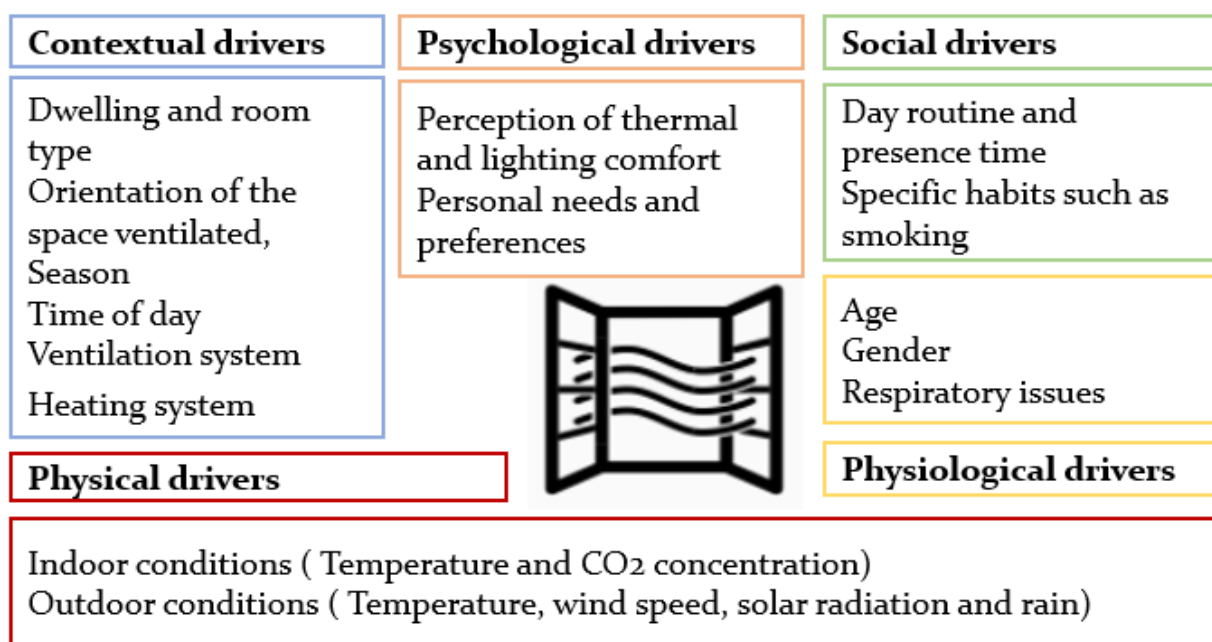


Figure 8: Synthesis of windows opening drivers in literature.

III.3.1 Drivers of thermostat use and set-point regulation: synthesis review

Human behavior toward the energy use in houses becomes a necessity to understand, especially when the energy consumed is very different from that predicted. Recently, a huge progress was observed in the sector of thermostat technologies by proposing several types and utilities. For this reason, and in order to ensure that the tool can achieve the main goal of creating it, it is indispensable to understand how the occupants will exploit it and what factors influencing the thermostat use.

The drivers affecting the thermostat use are classified into several categories presented in **Table 1** below. First, the technical drivers that include the characteristics of heating system: central system or individual system. The central system ensures a full time-full space and can supply more heat than the need of occupants[47], instead of individual heating which is managed only according to the need and the preference of the occupants (part time/part space). Also, the building energy efficiency and the emplacement of the building/house affect directly the thermal environment. In addition, one of the technical issues that can increase the energy consumption is the usability of the thermostat proposed in buildings. In this respect, more effort must be deployed in order to ensure the effectiveness of the thermostats tools [46].

Table 1: Review on drivers affecting the use of thermostats tools.

Technical drivers	<ul style="list-style-type: none"> 1.Type of heating system 2. Building energy efficiency and emplacement 3. Usability of the thermostat
Socio & demographic drivers	<ul style="list-style-type: none"> i. Income of occupants ii. Tenure type (owner of tenants) iii. Presence of child
Preferences and thermal experience effects	<ul style="list-style-type: none"> 1.The last experience with heating systems affects the thermal comfort sensation and requirements. 2. Cultural back ground 3. Activity level and clothing insulation 4. Habits and routine 5. Time of day
Environmental drivers	exterior and interior conditions

The socio-demographic factors as the income of the occupants and tenure type (owner/tenants) affects the use of heating systems and thermostat in general[47]. These two factors modify the behavior according to the needs and constraints of occupants. In this respect, the occupants with high income can prefer to improve thermal comfort by increasing the set-point temperature. Contrary to the occupants with an individual heating and low income, they prefer to use the heating only when it is necessary and reduce the set-point temperature to reduce the energy consumption bill [48][49]. Moreover, the family's composition impacts the thermostat interactions, for example the presence of a children under 12 years old research Noticeably, the research show that some main drivers affect clearly the physiological and psychological needs of occupants. These factors include the last experience with heating and the conditions where the occupants were used to be, the cultural background, routine and time of day and also the activity level and clothing insulation[47][50][46][51]. Eventually, the interior and the exterior conditions have a crucial in defining the optimum comfort temperature for occupants [50][52].

The use of heating is as well a fundamental research focus of this topic. Indeed, European statistics of 2017 indicate that space heating represents 64% of final energy consumption in households in Europe and the same percentage is indicated for France [41] [42]. Rinaldi et al. [53] show in their research that the use of heating depends on the age of the buildings. Thus, for the oldest buildings the use of heating systems is activated for longer period, contrary to the new buildings where the occupants prioritize at first actions on clothes and windows. Ensuring thermal comfort is a goal for the majority of the occupants, and it is subjective and depends on several drivers such as: characteristics of the buildings, cultural, physiological and psychological factors. These latter affect differently not only the use of the heating systems, but also the lighting and ventilation. Nevertheless, habits and the lack of knowledge and awareness about the systems, are considered a strong barrier to adopt effective measures and affect the proper use of heating systems [43] [44] [39].

III.4.1 Drivers of lighting use: synthesis review

The observational studies of occupants' interactions in the residential sector still present a lack in the scientific research on this topic[46][54][55]. In order to perform a complete model of the user's behavior, it is important to understand first the way occupants interact in their environment and the drivers influencing the several interactions. The lighting use in the households could be influenced by the occupant's arrival and departure time (return home and leaving home time), by building architectural features that affect the illuminance level, and by type of lighting systems. Furthermore, the type of space, season, the type of lighting controls & interface design were also categorized as important drivers of daily lighting use[56]. According to Heydarian et al. [57] the occupant habits are considered stronger than their intention in predicting the behavior. Also the number of people sharing the space, the activity of households residents and social-cognitive factors affect the frequency and the duration of lighting use [57][58].

The natural daylight is considered as a driver, and a key to better use the artificial lighting as well. The occupants in general prefer the natural light, but not all the building's architecture gives the best level of natural light. This lack of natural daylight drives the occupants to use highly the artificial lighting use to satisfy their lighting needs [58] [46]. The results in this respect show that if the exterior & interior illuminance are $100 < \text{lux} < 380$ the light is frequently on, but if it is lower than 50 lux the frequency of lighting use increases even more [46]. Recently, various technologies were developed in order to provide more control on lighting systems, and one of the options provided in these lighting on-off systems is the default settings. The lighting choices could be influenced by the default settings while a lot of people prefer to optimize the amount of day lighting in their choices [59]. In this respect, it is important to connect the conception of lighting on-off controls with day light illuminance [59].

Concerning the actions on lighting, blinds and shading, the visual stimuli are the main parameter affecting these interactions. A significant correlation was identified between illuminance, glare and solar radiation and lighting switching, blinds and shading use. In some studies, the thermal parameter is able to present a further need and driver [60][61][57]. The exploration about the windows, lighting, air conditioning systems actions has more researcher's attention than others actions, as fans, doors and thermostats use. The reason for this is the different impact of each action on building energy consumption.

Finally, and in the respect of all the information discussed above, an interdisciplinary approach is directly recommended between drivers, needs and actions. Specifically, between the drivers, which the majority have a clear correlation and create a direct effect on needs and on actions.

I.4 Occupant Behavior: analysis approach and modeling

According to many studies in literature [28][29][23][24][17], the study of the occupant behavior and its impact on the building energy performance was performed according to several axes. Therefore, three main research approaches can be identified: (a) Data collection and analysis; (b) Occupant behavior modeling; (c) Energy feedback approach. These aspects are detailed in the following sections with highlighting the several methods considered in the different studies.

I.4.1 Monitoring approach and data analysis

The monitoring approach is an efficient way for the analysis of occupant behavior. It could represent a separate approach, and it may also be an important contribution for occupant behavior modeling or for developing energy saving strategies. The principle of the data collection is to assimilate the behavior based on the sensors and communications technologies. To respond to the monitoring approach, it is crucial to understand how and what to measure. In the literature, the definition and classification of the data collection differ between authors in vision and in nomenclature. According to the Annex 66 (IEA)[23], one of

the most important research on the topic of occupant behavior, the data collection is conceived in four parts: occupant sensing and data acquisition methods, occupant measurement, validation of the measurement and ethics issues. In another study, Yan et al.[26] classified the monitoring approaches into three main categories: Observational studies, survey and interviews, and laboratory studies. Otherwise, Guerra-Santin et al. [62] divided the monitoring approaches into two main groups: physical monitoring and occupant investigation. Based on the various classification proposed by researchers, a synthesis of the monitoring approach, measurements methods and tools are presented in Table 2. Thus, it is important to adopt the following consideration so that the data collection and analysis approach can be successful:

- On one hand, the type of the approach is adapted to each research context and objective. It should be pointed out that the residential buildings are characterized by: (1) the variance of occupancy hours and activities, (2) the interaction in residential buildings with occupants and equipment occur in several spaces (contrary to the office buildings where the interaction occurs in single space), and (3) the complexity is more important between the case of occupant present and active, and occupant present and inactive. On the other hand, the specification of the parameters to be monitored and the quantity of the information depend also on the context and on the objective of the study. Generally, three main purposes are identified: (1) Reduce the energy consumption by using energy with more efficiency, (2) ensure the satisfaction of the occupants in their interior environment by increasing their thermal comfort, and (3) identification of the impact of the thermal discomfort on the health (mainly for hospitals).
- Ethics issues: monitoring occupants must use solutions to preserve the identity of the occupants and secure sensitive information. Especially in the residential buildings, the privacy issues are present, and need a serious work and involvement of human subjects (e.g., take an interest to the position of the sensors, because the visible equipment may affect the occupant behavior).
- Validation of measurements: this aspect concerns mainly the sensors and survey data where is important to develop methodologies or guidelines about the validation of measurements[23].

The process of data collection allows a detection of various information about the energy use and occupant behavior in their environment. Based on this data, and on different technics of data analysis, it is possible to transform data to pertinent information in view of understanding accurately the behaviors patterns. Thereafter, the global objective is to exploit information in the multiple methodologies for assessing the building energy performance, but also to develop other methodologies related to the improvement of occupant behavior identification and contribution to increase occupant awareness regarding the energy use in buildings.

Table 2: Synthesis of the monitoring approach for occupant behavior.

(a) Quantitative approach or the physical monitoring (In-situ / laboratory studies)		
Types	Parameters	Sensors
Energy consumption & energy use	Gas, electricity, DHW, cold and heat	Gas meter, electricity meter, heat and cooling energy mete etc.
Indoor environmental quality	Temperature, relative humidity and CO ₂	Ambient sensors, thermocouple and hygrometer etc.
Outdoor environmental	Temperature, relative humidity, solar radiation and wind speed and direction	Weather station
Occupant behavior	Presence of the occupants, thermostats adjustments, light switching, shutter/blind management, window and door opening and plug load	Image based, Passive Infrared Contact sensor, smart thermostat, rocker switch, lux meter, plug meter etc.
(b) Qualitative approach		
Parameters	Methods	
Occupant behavior	Questionnaires, interviews, focus group, surveys, diaries, perception and observation, opinions.	
Energy use		
Occupant preferences and needs		
Social, psychological and physiological factors etc.		

Du et.al [17] presented in his research a systematic review that summarizes the applied in-situ monitoring approach in residential buildings in order to analyze the occupant behavior. The monitoring activities are identified in more than 25 countries around the world with different monitored interactions. In this research, the selection of the samples to monitor, the definition of the monitoring duration and time interval, the choice of the data loggers and the consideration of the microclimate in the monitoring activity are considered as main aspects that could limit the outcomes of the monitoring approach.

Regarding the definition of the time interval, Du et.al [17] specified that the selection of the time interval depends on the exploitation of the results and the duration time of the monitoring. In the literature, 5 min is suggested for the energy modeling, and 15 min for the

energy consumption measurements. In the following figures, a summary of the reviewed monitoring activities in this research is presented.

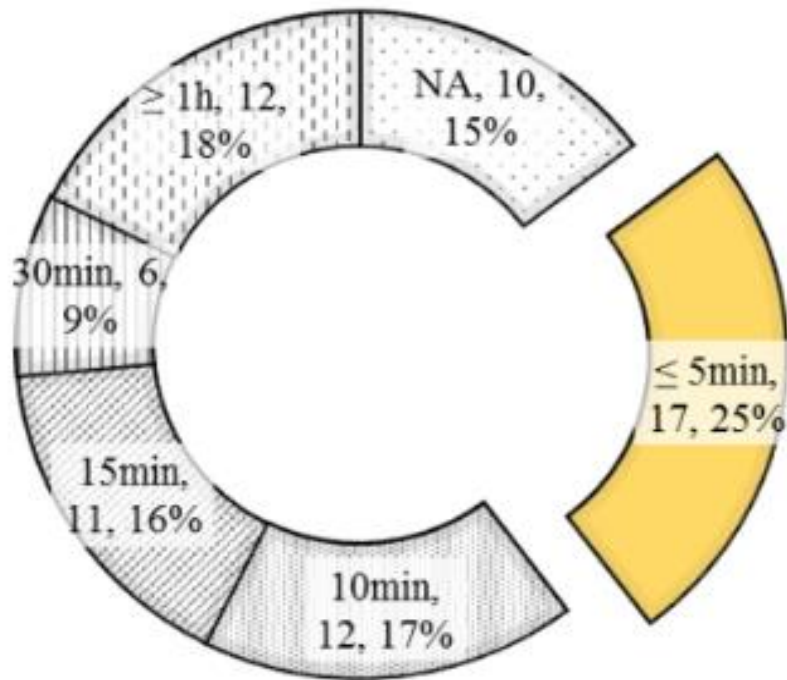


Figure 9: Distribution of time interval in the reviewed monitoring activities [17].

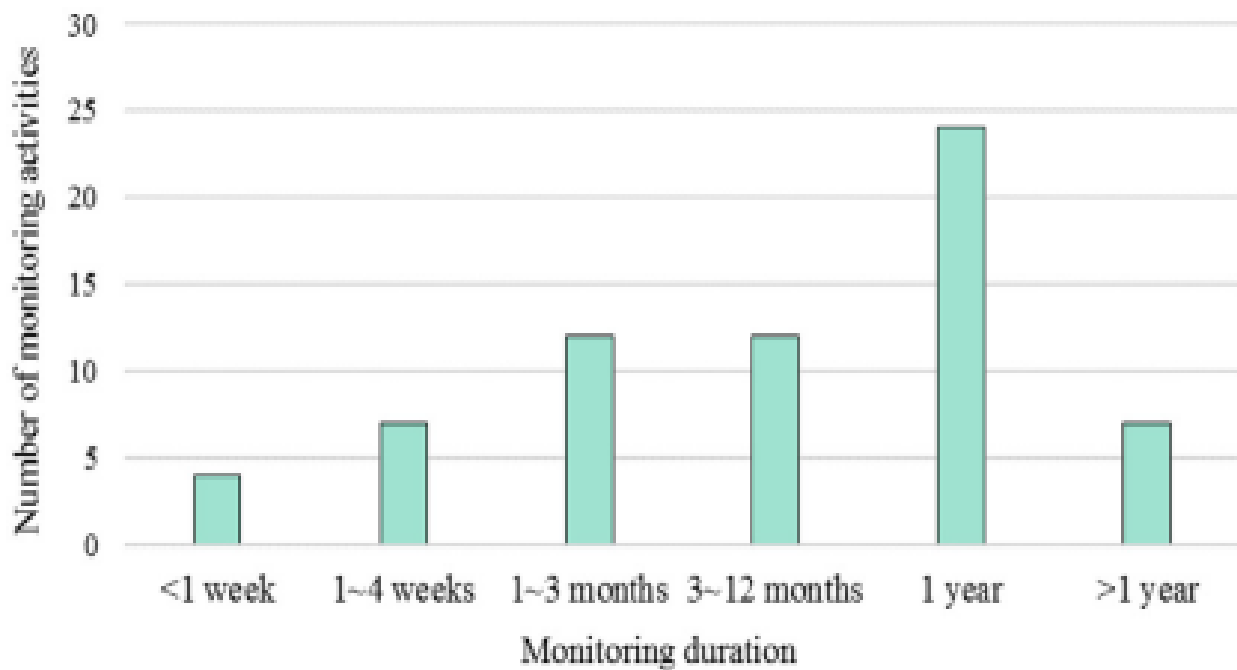


Figure 10: Monitoring duration review [17].

1.4.1.1 Related work to data analysis and mining

The second step after the data collection phase is the operation of data analysis technics [63]. The data analysis process can be performed into 4 main steps after the data collection phase. Firstly, it is recommended to clean data to prepare a data base well organized and structured. Afterwards, the identification of data analysis methods to analyze data, and finally conclude knowledge and pertinent information and identify the exploitation context of results (**Figure 11**).

One of the actual efficient tools is the data mining method which considered a very advanced technology and divided into two main groups:

- Supervised/predictive analysis that consists on a predefinition of the knowledge targeted,
- Unsupervised/descriptive analysis based on exploration and discovering unknown information and knowledge of data collected [64][65].

The unsupervised analysis is more adopted in the monitoring approach which objective is to identify the behavior patterns through the measurements and the data collected. Contrary to the supervised analysis that aims to develop models and functions of occupant behavior [66].

The main technics of data mining identified in the literature are the clustering, association rule mining, sequence and motif discovery and anomalies detection. The regression and classification models are the most used technics for the predictive analysis[67][68][69].

Multiple research investigations were developed in order to analyze the connection between occupant behavior and energy consumption in buildings. The objectives from this investigation are various and crucial regarding the development of the building energy performance. The potential of energy waste patterns was identified by Li et al.[70], and considerable findings about energy savings are performed especially regarding the lighting and appliance usage. The same objective is developed in another study by using clustering, association rule mining and prediction model. In this study, a potential of saving almost 21% of total energy consumption can be achieved by only the modification of occupants' energy use habits[71][72]. Furthermore, data mining technic is employed for the identification of drivers affecting the behavior patterns concerning the opening and closing of windows [73] [74], mechanical ventilation systems[75][76] and the HVAC systems [77][78]. The multivariate regression analysis is identified as an efficient method to process qualitative data and identify the preferences and needs of occupants regarding the use of HVAC systems [53]. Besides, a systemic procedure based on data collection and analysis was developed by Yu et al.[79] in order to evaluate the impact of occupant behavior on energy building consumption.

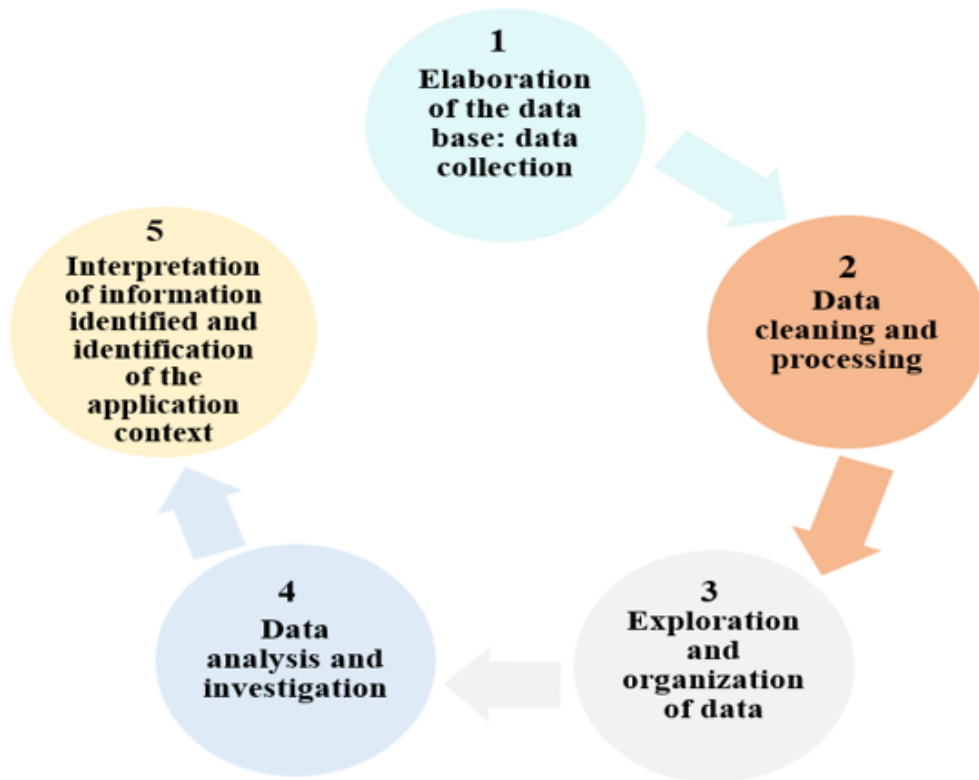


Figure 11: The principal phases for data analysis process.

1.4.2 Occupant behavior modeling

The purpose of modeling approach is to represent a description and prediction of physical phenomenon, and the effect of changes to the systems [80]. The simplification and accuracy are the two important criteria for a successful model [80]. The reality of occupant behavior is diverse and complex. On one hand, the behavior has a stochastic nature which needs an estimation of different probability simulations and distributions. On the other hand, the behavior depends on several factors that affect the behavior, and represented as drivers (section 1.3.1) in the literature [81][82][83][84].

The principle of occupant behavior modeling is the comprehension of the correlation between drivers and occupants' interactions. Thereafter, elaborate a predictive model that take in consideration the behaviors and drivers over time [85].

Many studies have presented several classifications and definitions of the occupant behavior modeling. According to the Annex 66 (IEA)[23], the occupant behavior can be classified under three types: (1) adaptive behavior models, (2)non-adaptive behavior models and (3)occupancy models. Zhang et al. [28] defined the types of quantitative models of occupant behavior in four categories: stochastic/probability, statistical methods, agent based-modeling and data mining approaches [86] [87] [88]. Additionally, the occupant behavior models can be defined by their complexity and classified into different approaches : fixed schedules, data-based models (non- probabilistic), stochastic models (probabilistic) and agent-based models [29] [24]. If this approach is selected in the research, it is important at first to define the purpose

of the study, learn more about the different types of models and then select the accurate model for the research.

Fixed schedules were the most representative form of occupant's schedule used as direct input in building programs simulation. Based on the building type and on statistical analysis, or on long-term patterns an estimation of daily profile is fixed and used on the program for reflecting the presence and absence of occupants[85]. The data-based models are based on data analysis and learn observation, in order to transform data to new information and they are considered as non-probabilistic models[89]. However, the probabilistic/ stochastic models are based on probabilities functions of various outcomes using random parameters. It represents the possibility of modeling the behavior with taking in consideration the several influencing factors. The most complex models are those agent-based for their capacity to model complex phenomena. These types of models aim to simulate and predict the several actions/interactions of individuals and take into consideration their influence on building energy performance. Moreover, the resolution of the models depends on stochastic modeling which give it a large size and high complexity [24].

The elaboration of the model is very important, but it is also necessary to establish a methodology for the model's integration in the simulation programs, and highlight the perspectives of its application. In the literature, the focus is mainly on the implementation of the behavior's models in the building programs simulations. As we mentioned, one of the main issues is the lack of the accuracy in occupant behavior in the Building Program Simulation (BPS), which provides an incomplete prediction for the building energy performance. In this context, the implementation of models that predicts the behaviors with more precision is an effective solution to overcome this inconsideration of the occupant behaviors. Several tools (obXML, obFMU, occupancy simulator) were developed to realize the implementation of the quantitative models on the BPS in order to increase the analysis and evaluation of the impact of occupant behavior on building energy performance [23][19][25][29][28][85].

1.5 Energy feedback approach

As discussed in the previous sections, several approaches have been developed to analyze and predict with better accuracy the occupant behavior and its impact on the energy performance of the building. In addition to those aspects, the involvement of the occupant to be part of the solution is considered one of the most important strategies. The purposes from the energy feedback approach are (1) to increase the awareness of occupants about energy consumption, (2) integrate the residents to contribute to the energy efficiency strategies, and (3) the creation of a tool of communication with the residents which can help them to learn how to control and preserve energy [90]. In this respect, Delmas et al.[91] highlighted in their study that the adoption of efficient behavioral practices reduce the energy use by 7.4% on the average.

According to the meta-analysis conducted by Khosrowpour et al.[90], four approaches have been defined and discussed to be a key for the development of an energy feedback approach: surveys, analytics, simulation and experiments. The results of these approaches provide valuable knowledge about the occupant characteristics (occupant behavior, needs and preference of the occupants, life style and habits, etc.) to the energy feedback programmer's in order to define a design of the feedback approach/program including the main key parameters that depend on the context of utilization. In addition, the experiments are considered also an important approach to evaluate various factors and components of energy feedback programs and, assess the potential for saving energy [92][93][94].In the most cases, the intersection between two approaches is present in the research, which allows identifying different opportunities to study in this field.

In the literature, feedback systems are essential to highlight the specific recommendations about energy savings opportunities to occupants [95][96][97]. The cellphone based, web-based and in-home display are considered the new technologically advanced feedback methods cited by Khosrowpour et al. [90].

I.6 Discussion and key findings

Based on the several research carried out in this topic, the following outcomes are obtained:

- The occupant behavior is characterized by two aspects: (1) the presence of occupants inside the buildings which reflects their CO₂ generation, moisture and heat. This first aspect was the only point considered in the building performance simulation for the assessment of building energy performance and was known by the conventional scenario and fixed schedules. The presence of occupants leads to (2) the occupants' interaction with their interior environment. The use of the various systems in buildings (HVAC, windows, stores, lighting and domestic hot water) affects the energy consumption and creates a partial consumption related to the occupants' needs and preferences.
- The approaches adopted for the analysis of occupant behavior factor are various and divided in this research into three categories: (1) monitoring approach, (2) occupancy modeling and (3) energy feedback programs. Firstly, the monitoring approach was evaluated as the most accurate technique to identify occupant behavior but at the same time it is the most complicated to realize regarding ethics and privacy issues. Secondly, the occupancy modeling was conceived as an important key for simulating the behavior, especially the stochastic methods that give the phenomena more precision and exactitude. Finally, the energy feedback programs were identified also in this research as an essential method to consider for the essential need of integrating occupants in the process and give them the possibility to contribute to the energy savings potential.

- The complexity of the subject doesn't reside only in the stochastic nature of behavior, but also in the interdisciplinary framework that should be developed to achieve a complete assessment of the topic. The psychological, physiological, societal, cultural, economic and individual motivational drivers give to the topic multiple dimensions and impact reliability of the analysis while it doesn't take into consideration all the factors influencing the behavior.
- Occupant behavior in residential and tertiary buildings are affected by the same motivational drivers, the differences are the schedules of presence / absence, type of the systems and the access given to the occupants for their manipulation.
- The important characteristic in this approach is the possibility to complement an approach by the other one. The monitoring approach can be a very important input for occupancy modeling and energy feedback programs.
- Despite the several research developed in this topic and in the solutions identified in the improvement of building energy performance, the lack of analyzing the occupant behavior before designing the solutions and the technologies is considered as a major barrier to ensure the efficiency of the applied strategies. For this reason, the integration of the occupants in the studies and in the process must become a priority approach exactly as the other approaches.

I.7 Conclusion

This study proposes an overall perspective of the topic of the occupant behavior with the identification of the important aspects in this field. The occupant behavior as explained is not a supplement axis to study for the evaluation of the energy building performance, but a main and critical factor that should not be neglected.

For our study, three main approaches were identified for the treatment of the subject of occupant behavior. At first, the monitoring approach is essential for the modeling and the identification of different aspects of occupant behavior. The data collection is developing more and more by the development of sensors and communication technologies, and provide a huge and delicate data to analyze.

However, the main question after the collection part is how we should analyze the database in order to extract the information needed from the research. Secondly, modeling the behavior of occupants who are characterized by a stochastic nature.

Despite this, some studies indicate that the suitable model should be deterministic models with the best selection of the scenario of application[23]. There are several aspects to analyze and many techniques for the development of the occupant behavior models and its implementation. It is important to underline that the data collection provide a fundamental support to the elaboration of these models, and the adoption of the interdisciplinary approach open opportunities for several studies in the future. Thirdly, the energy feedback approach

was identified as an efficient method for addressing this critical subject. In this respect, we should believe that the occupant can influence negatively and/or positively the energy consumption and thus the energy performance of building. The idea is the creation of a link to communicate with the occupants and to give them the chance to understand more his energy consumption and then the possibility to improve his behavior.

The intersection between different approaches is defined as a challenging strategy to progress in this field and need a background of different domains. **Figure 12** represents a synthesis of the aspects and approaches analyzed in this research.

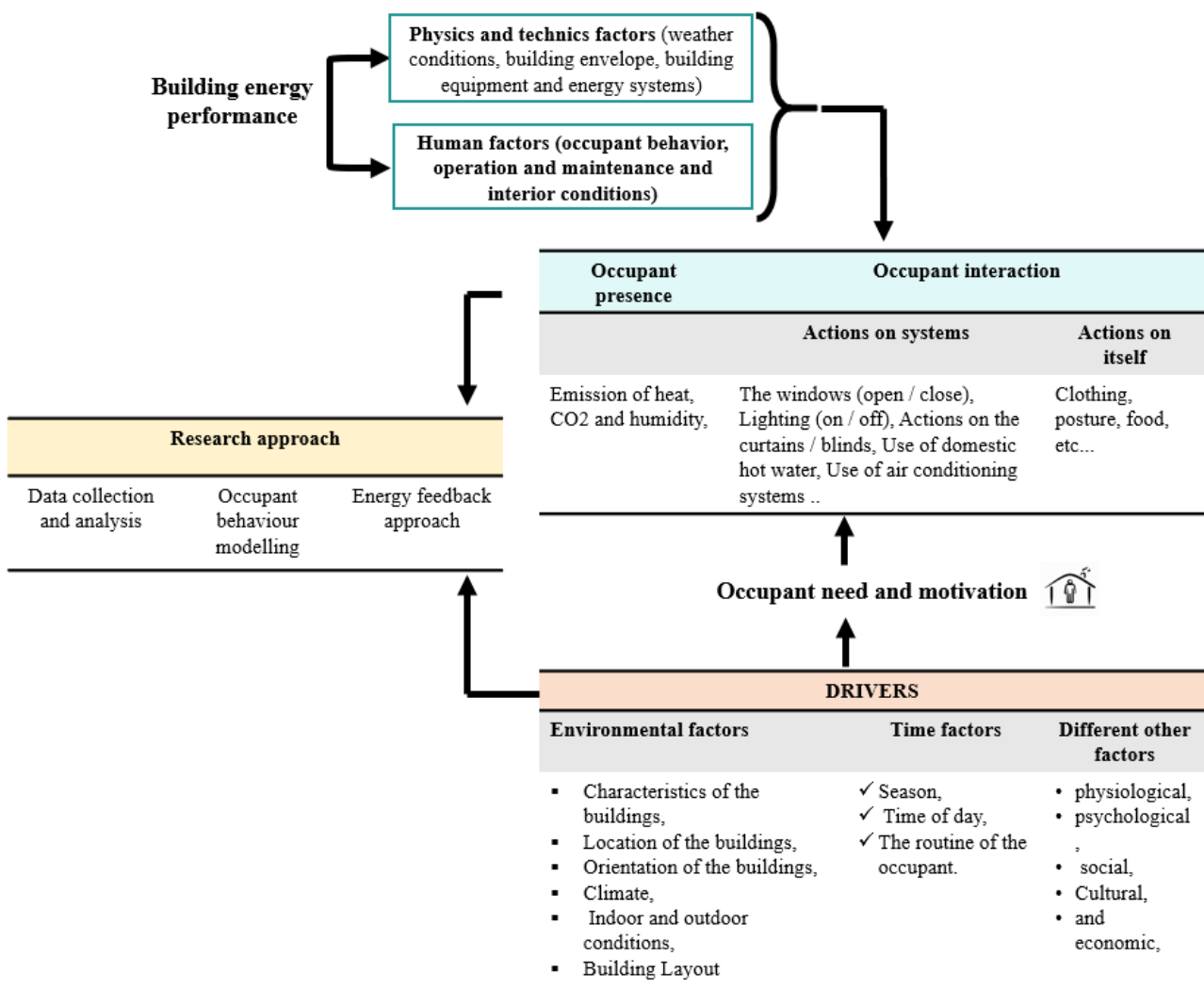


Figure 12: Technical framework on building energy performance, occupant behavior, drivers and aspects.

The monitoring approach will be our main method to analyze and understand the behavior of occupant in the selected case studies. This will allow a development of methodology of analysis and treatment of data collection. Thus, the elaboration of Key Performance Indicators will be necessary to define a tool that support the building energy managers in this occupant behavior analysis. The project supports the strategy of Near Zero Energy Buildings (NZEBS) and represent an innovative concept that introduces a toolkit that focus mainly on the assessment of occupant behavior in residential buildings.

CHAPTER II

Case studies

Monitoring and assessment of pilot projects



Chapter II: Case studies

Monitoring and assessment of pilot projects

II.1 Introduction

The state of the art presented in the previous Chapter affirms the scientific importance of the integration of occupant behavior in building energy performance studies. The main three approaches for the study of the occupant behavior topic were presented, and based on it, the monitoring approach was selected as a principal key for this research project. This approach was also developed in the European HEART project where this study is integrated to proceed to the analysis of the building energy performance. The objective of this Chapter is to present and analyze different case studies considered in the development of this research.

The first section of this Chapter will present in detail the case study of the H2o2o European HEART project developed in collaboration with EST METROPOLE HABITAT (a French social housing provider) in Lyon. This monitoring activity concerns a social housing and was our main focus from the start of the research for two reasons: 1) The high interest of the elaboration and the tracking of several phases of the monitoring activity from the outset until the acquisition phase of the data, and 2) the valuable contribution to the development of the database of HEART project. However, the COVID-19 had a significant impact on the finalization of the monitoring activity and on the acquisition of measures. For this reason, the collection of other data bases was essential to provide a complete study. HIKARI* project was one of the sources of data bases collected. The monitored building is considered as a smart residential building where a high level of measurement was developed in term of energy and occupant behavior. In addition, a data base for private residential building was collected from PREBAT* project concerning two buildings with various apartments. The projects were developed and monitored in Lyon for different duration and represent different characteristics. The second section will present PREBAT project and the third section HIKARI project. The final section of this Chapter will analyze the main differences and similarities between the case studies.

As presented previously, this study will adopt different databases with the view to transform data into knowledge about the occupant behavior patterns in these case studies. The HIKARI project includes detailed measures about occupant behavior interaction which allow to provide a direct analysis. On the contrary to the other case studies, a deep analysis on data and advanced reflection and technics should be developed in order to analyze the occupants' interactions. These occupants' interactions are not measured directly by sensors for the HEART and PREBAT projects as they are measured for the HIKARI project.

II.2 Case study 1: HEART project, French case study

“All the details of the monitoring activity of this case study was developed in this research as our contribution to HEART European project”


II.2.1 Generalities

The case study was monitored by an in-situ instrumentation. It is situated in RESEDAS Street, Saint Priest (23 km from Lyon) and contains 6 blocks and 26 dwellings with different typology. The global surface of the building is over 1000 m² and was completed in 1960.



Figure 13: Site localization Source-Google Earth

Table 3: Identity record of HEART case study

	Year of construction	1960			
	Surface SHAB	>1000 m ²			
	Typology	T₁	T₂	T₃	T₄
	Number	8	12	4	2
	Average Surface (m²)	30	40	60	77
	Heating energy	Individual gas boiler			
	Heating type	Individual			
	DHW type	Individual			

II.2.2 Monitored apartments

The monitoring approach is a critical task to achieve, especially with the different considerations that should be taken with respect to the occupants: privacy and ethical issues. In this perspective, nine dwellings were selected for the instrumentation (**Figure 14**). The general and technical information about the apartments instrumented are presented in **Table 4** below.

Table 4: General information about the apartments instrumented in HEART project (French case Study).

Floor level	Dwelling	Typology	Living area (m ²)	Occupants	Climatic Zone
Ground floor	2	T ₂	41	1	H1C
	16	T ₁	30	o (vacant)	
	18	T ₂	40	2	
	23	T ₂	40	1	
1 st floor	11	T ₃	60	1	
	20	T ₃	60	5	
	23	T ₂	40	o (vacant)	
	24	T ₂	40	1	
Duplex	26	Duplex	77	5	

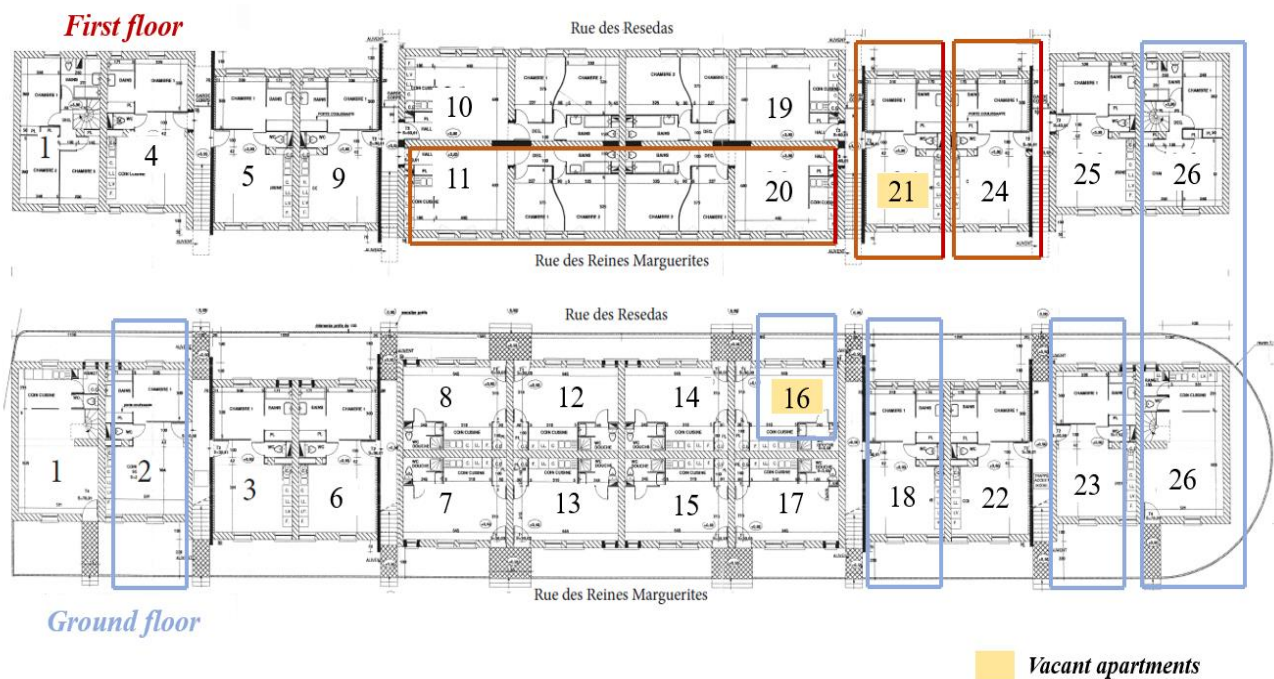


Figure 14: The plan of the building and the selection of the dwellings for instrumentation.

II.2.3 Instrumentation details

The instrumentation adopted for the French case study of the HEART project is presented in four main parts:

⇒ Indoor Environmental conditions/ quality:

The measurements in this part are the temperature, relative humidity and CO₂. The selected sensor measures the three parameters with display possibility. For each apartment one sensor is placed in the living room and the second one of the bedrooms. The technical characteristics of the sensor employed are presented in **Figure 15**.

- Temperature
- Humidity
- CO₂



TECHNICAL CHARACTERISTICS

Humidity	
Sensor	Capacitive
Measuring range	0...100% RH
Resolution	0.1% RH
Accuracy (@ 23 °C)	± 1.8 %RH (0...80 % RH) ± [1.8 + 0.11 * (RH -80)] % RH (remaining range)
Sensor operating temperature	-40...+105 °C (R.H. max=[100-2*(T-80)] @ T=80...105 °C)
Temperature drift	±2% over the whole operating temperature range
Long-term stability	0.5% / year
Temperature	
Sensor	Sensor integrated in humidity module
Measuring range	-40...+105 °C
Resolution	0.1 °C
Accuracy	± 0.2 °C in the range 0...+60 °C ± (0.2 - 0.05 * T) °C in the range T=-40...0 °C ± [0.2 + 0.032 * (T-60)] °C in the range T=+60...+105 °C
Long-term stability	0.05 °C / year
Carbon dioxide (CO₂)	
Sensor	Non-dispersive infrared rays (NDIR)
Measuring range	0...5000 ppm
Resolution	1 ppm
Accuracy	±(50 ppm+3% of measurement) @ 20 °C and 1013 hPa
Operating temperature	-5...50 °C
Response time	T ₉₀ < 120 s (air speed= 2 m/s)
Stability	5% of measurement/5 years
Temperature drift	0.1% f.s. / °C

Instrument	
Transmission frequency	Factory configurable at choice among: 868 MHz, 902-928 MHz, 915-928 MHz, 921-928 MHz or 915,9-929,7 MHz depending on the frequency in use in the country of installation
Transmission range	300 m (E, J)/ 180 m (U) in open field (can be reduced in presence of obstacles or adverse atmospheric conditions)
Logging interval	10, 15, 30 s / 1, 2, 5, 10, 15, 30, 60 min
Power supply	Non rechargeable lithium thionil chloride (Li-SOCl ₂) internal battery, 3.6 V, AA format, 2-pole Molex 5264 connector
Battery life	1.5 years typical (without repeaters, measurement and log interval 2 min)
Operating conditions	-10...+70 °C / 0...85 %RH non condensing
Dimensions	135 x 126 x 33 mm
Weight	200 g approx.
Housing	LURAN® S 777K

Figure 15: Specification of the interior condition's sensor [98].

⇒ Outdoor Environmental conditions:

A weather station has been installed on the roof to measure the outdoor air temperature (**Figure 16**).



Figure 16: Exterior sensors installed on the façade of the building.

➤ Energy consumption:

The evaluation of the energy performance in buildings depends mainly on the energy consumption. This consumption could be the result of technical and human factors. In the context of this project, it is important to measure the different sources of consumption for a complete assessment of the building energy performance before and after the renovation. Thus, the parameters targeted for monitoring the energy use in HEART project are:

- **Heating:** volumetric gas pulse meter (one per boiler: at the entrance and exit)
- **Domestic Hot Water:** Volumetric gas pulse meter (one per balloon),
- **Lighting:** electric impulse meter (for each dwelling at the electrical box and designed to be dissociated from overall consumption),
- **Electrical consumption:** electric impulse meter (one par dwelling at the electrical box).



Figure 17: Connectors sensors of energy consumption.



Figure 18: Energy consumption of DHW sensors.

➤ Communication system:

The data acquisition system used is a wireless radio communication base. This base unit presented in **Figure 19**, received the data from the data loggers installed and transferred it to the Cloud. The transmission was ensured through the SIM card installed in the data acquisition system. Additionally, an interface was designed to ensure the access to the measurements and track the details of the instrumentation.

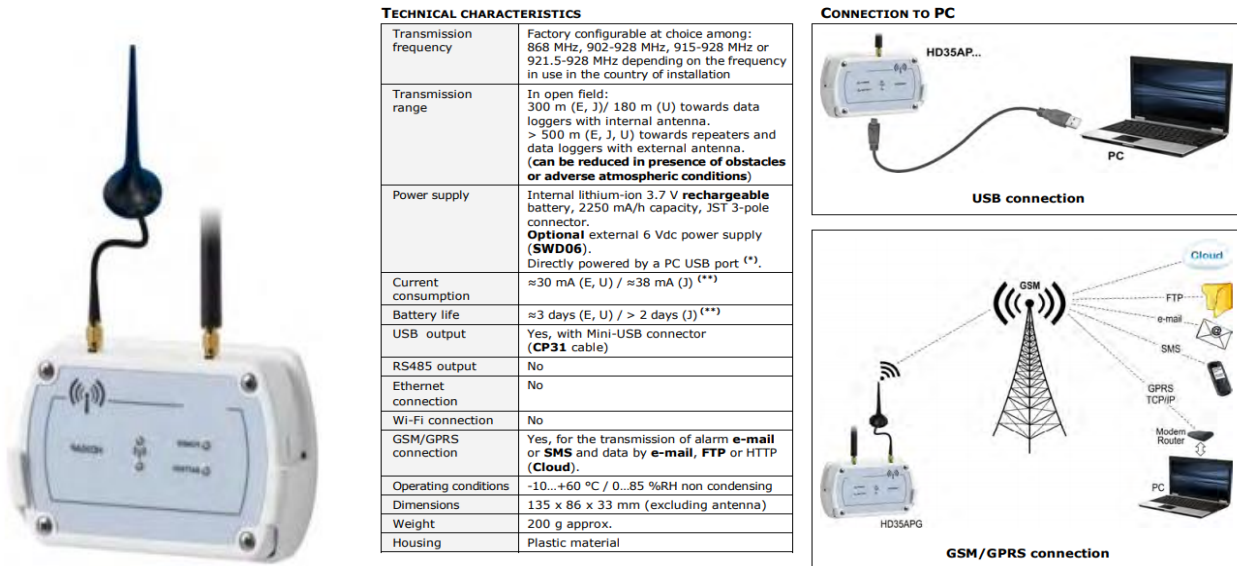


Figure 19: Specification of the communication system [99].

II.2.4 Buildings and Systems characteristics

The technical information about the monitored apartments in the French case study of HEART project are presented in this section.

Building envelope: materials, inertia and insulation

- Low floor: Concrete
- Intermediate floor: Very light wooden floors
- The building is a two-storey with an attic. The walls are made of brick.
- Ground floor: walls in solid concrete or double-brick wall
- Tiled roof: wooden frame
- Unmanned ventilated roof spaces (2 spans isolated by loose glass wool, other spans not insulated)

According to the thermal resistance measurements, the apparent conductivity of the wall envelope is $\lambda=1,71$ W/m.K.

Windows characteristics, blind and shades systems

- PVC joinery in double glazing from 1992, openings (with manual roller shutters)



Heating systems and Domestic hot water

- Individual wall-mounted boilers also ensuring the production of DHW for each dwelling.
- Radiators have been placed in all apartments. They are fitted with thermostatic valves.



Ventilation

- The ventilation is mechanized.
- Fresh air is supplied through air intakes in the roller shutter boxes.
- A technical duct, located in the bathroom, crosses the different levels and allows the extraction of stale air from each apartment.

II.3 Case study 2: PREBAT project

PREBAT* is the building energy research and experimentation program that was developed by the French government in the context of climate plan 2004-2012. The aim of PREBAT project is to experiment new solutions for improving the energy efficiency of new and existing buildings. Since 2006, the regions and the regional offices of ADEME (Ecological Transition Agency) have supported the realization of almost 3,000 low-consumption buildings as part of the demonstration buildings program. 200 of these buildings have been monitored for the assessment of energy use and thermal comfort over two years. The monitoring approach included also observations and surveys for better understanding the occupant's energy use, the tenure of buildings and the comfort perception [100].

The collection of the data monitored in the context of PREBAT project was performed in collaboration with **Dr. Bassam MOUJALLED**.


II.3.1 "AMPLIA" case study

II.3.1.1 Generalities

This case study was developed in the context of PREBAT project of the Rhône-Alpes region and completed in 2013. The concept of this project is to perform a high level of energy building performance while adopting the approach of building with positive energy. The case study is

constituted of 66 apartments with 8 floors and 2 levels in the basement (from studio to 6-room duplex).

Table 5: Identity record of AMPLIA case study [101].

	Address	Confluence district
	Year of construction	2013
	Surface SHAB	>4000 m ²
	Number and type of dwelling	66 apartments (from studio to 6 room)
	Heating energy	Gas condensing boiler
	Heating type	Collective
	DHW type	Collective
	DHW energy	Solar DHW production + gas
	Applicable thermal regulations	RT 2005
	Renewable energy	Photovoltaic+ solar collector

II.3.1.2 Monitored Apartments

The major approach to analyze the performance of the energy building performance developed by CEREMA center-east (center for studies and expertise on risk, environment, mobility and planning) is to monitor the real energy use in the apartments from almost two years. Based on the collected measurements, a deep analysis was developed in order to explore the behavior patterns of the occupants in these three apartments, especially that during the monitoring activities it was impossible to collect relevant information about the occupancy.

Two apartments were monitored and integrated in this research. These case studies are situated in different locations and have a different orientation and surface (**Table 6**).

Table 6: General information about the apartments instrumented of “AMPLIA” case study.

Floor level	Dwelling	Typology	Living area (m²)	Orientation	Climatic Zone
Ground floor	A	T ₃	76	Situated in Ouest corner North West and South West	HiC
1st floor	B	T ₃	83	South East	

II.3.1.3 Instrumentation details

The parameters monitored in the context of PREBAT project for AMLPIA case study are presented in the following paragraphs:

- **Indoor Environmental conditions/quality:** As synthesized in the Table 7, the three parameters selected for the characterization of indoor conditions are the indoor temperature, relative humidity and CO₂ concentration. The living room was the reference position for the measurement of these parameters in the apartments.
- **Energy consumption:** To evaluate the energy use, the three main indicators are monitored: 1) General electricity consumption (kWh), 2) Heating consumption (kWh), and 3) Domestic hot water (kWh).
- **Outdoor Environmental conditions:** The weather station used in this monitoring activity represents different measures such as: Outdoor temperature (°C), exterior humidity (RH), wind speed (m/s) and the solar radiation (W/m²).

II.3.1.4 Buildings and Systems characteristics

The building envelope of the “AMPLIA” case study is made by reinforced concrete with exterior insulation. The windows are in wood with aluminum and the glazing is double or triple for some apartments, depending on their orientation. In addition to this, various solar protection were installed for this case study as blinds, roller and shutters with adjustable slats. Each apartment is composed by space design promoting natural ventilation for summer comfort. The remains details are described below (Table 7).

Table 7: synthesis of the parameters monitored in AMPLIA case study.

Dwelling	Interior conditions			position
	Temperature (°C)	Humidity (RH)	CO ₂ (ppm)	
A	✓	✓	✓	living room
B	✓	✓	✓	living room

Dwelling	Energy consumption		
	General electricity consumption (KWh)	Heating consumption (KWh)	DHW (KWh)
A	✓	✓	✓
B	✓	✓	✓
Exterior conditions			
outdoor Temperature (°C)	Exterior Humidity (RH)	Wind speed (m/s)	Sunshine (W/m ²).

Building envelope: materials, inertia and insulation

- Exterior wall: 20cm concrete wall insulated from the outside by 20 cm of mineral wool of Panolene type façade ($\lambda = 0.032 \text{ W / m.K}$, $R = 6.25 \text{ m}^2\text{K / W}$, $U = 0.147 \text{ W / m}^2\text{.K}$)
- East gable: 20cm concrete wall insulated from the outside with 30cm of mineral wool of the Panolene façade ($\lambda = 0.032 \text{ W / m.K}$, $R = 9.38 \text{ m}^2\text{.K / W}$, $U = 0.101 \text{ W / m}^2\text{.K}$)
- Floor on the outside: concrete slab of 20 cm insulated under its entire surface by 16cm of Fibrastyroc Clarity Fixing with 8, staples per m^2 ($R = 3.25 \text{ m}^2\text{.K / W}$)
- Roof terrace and attic: 20 cm concrete slab insulated in the upper part by 20 cm of expanded polystyrene type ROOFMATE ($R = 6.9 \text{ m}^2\text{.K / W}$ and $U = 0.139 \text{ W / m}^2\text{.K}$)



Windows characteristics & blind and shades systems

- South and west façade: BIEBER wood joinery, double glazing, $U_w = 1.3 \text{ W / m}^2\text{.K}$.
- North and west East: Joinery BIEBER mixed wood / aluminum, triple glazing, $U_w = 1 \text{ W / m}^2\text{.K}$.
- Adjustable solar shading



Heating systems and domestic hot water

- Gas condensing boiler for heating production and DHW supplement.
- Modulating burner from 8 to 100% - Useful efficiency up to 110.3% on PCI Low Nox boiler
- Solar DHW production + gas boiler backup



Ventilation

- Double flow ventilation with counter flow plate heat exchanger (80% efficiency)
- Filters G4 return and F7 suction
- Fan power: 1000 W

Renewable energy production

- Photovoltaic production by 800 m² of polycrystalline sensors
- Production of solar hot water by 105 m² of solar collectors

II.3.2 “LES GENTIANES” case study

II.3.2.1 Generalities

This case study was developed in the same context as the project PREBAT described above. The apartments were divided into four buildings and delivered in 2010. Three buildings have very high energy performance, and one has low consumption. In addition, this latter building adopts a high environmental quality with the following priority targets: (1) integrated choice of systems, products and construction process, (2) energy management, and (3) the hygrothermal comfort.

Table 8: Identity record of LES GENTIANES case study [102].

	Address	Confluence district
	Year of construction	2010
	Surface SHAB	>4000 m ²
	Number and type of dwelling	16 apartments (from 2 rooms to 4)
	Heating energy	Gas condensing boiler + thermal solar panel
	Heating type	Collective
	DHW type	Collective
	DHW energy	Gas condensing boiler + thermal solar panel
	Applicable thermal regulations	RT2005

II.3.2.2 Monitored apartments

For this research two apartments were monitored and integrated. Their locations and surfaces are different but they have the same orientation (**Table 9**).

Table 9: General information about apartments instrumented of “LES GENTIANES” case study.

Floor level	Dwelling	Typology	Living area (m ²)	Orientation	Climatic Zone
3 rd floor	1	T ₃	56 m ²	North-South	H1C
Ground floor	2	T ₄	81 m ²		

II.3.2.3 Instrumentation details

The measured parameters are identical to the “AMPLIA” case study presented in the above section.

II.3.2.4 Buildings and Systems characteristics

The principal technical characteristics of “LES GENTIANES” case study are:

Building envelope: materials, inertia and insulation
<ul style="list-style-type: none"> ▪ Mixed wood / concrete ▪ Low floor: 150 mm from fiber (vegetable wool) ▪ High floor: 320 mm of cellulose wadding ▪ Exterior walls: 120 + 50mm of mineral wool ▪ Wood frame panels surround the building
Windows characteristics & blind and shades systems
<ul style="list-style-type: none"> ▪ Not provided
Heating systems and domestic hot water
<ul style="list-style-type: none"> ▪ Gas collective condensing boiler + 60 m² of thermal solar panel ▪ DHW is provided by the condensing boiler and thermal solar via 6000L tank
Ventilation
<ul style="list-style-type: none"> ▪ Controlled Mechanical Ventilation double flow. ▪ Ventilated roof ▪ Natural ventilation in summer
Renewable energy production
<ul style="list-style-type: none"> ▪ Photovoltaic production by 800 m² of polycrystalline sensors ▪ Production of solar hot water by 105 m² of solar collectors.

II.4 Case study 3: HIKARI project

II.4.1 Generalities

HIKARI* project is considered the first building group with positive energy and mixed use in France. This innovative project was developed in collaboration between the city of Lyon, the Japanese New Energy and Industrial Technology Development Organization (Nedo), Toshiba and Bouygues IMMOBILIER. HIKARI project was divided into three buildings: HIGASHI, MINAMI and NISHI with a 12 000 m² of total floor area (**Figure 20**). This group of building was intended for use in three categories: offices (63%), Dwellings (29%) and Shops (8%) [103].




Figure 20: Overview of HIKARI buildings (OLIVIER GUERRIN,2015).

One of the main objectives of the HIKARI project was to develop strategies concerning the production, storage, management and optimization of energy. The occupant's behaviors are essential factors to integrate for a complete assessment of building energy performance. As part of this research, the occupant behavior was evaluated and identified in residential building. For this reason, MINAMI building which represents the building with dwellings was the object of our study.

II.4.2 Monitored apartments

The MINAMI building is composed of 36 apartments with different typology (from 1 bedroom "T2" to 3 bedrooms "T4"). In this research, one apartment T4 will be studied and analyzed. This apartment is located on the 8th floor and consists of 3 bedrooms, 2 bathrooms, 1 living room, 1 kitchen, 1 toilet and corridors. It is oriented to the south and located in the H1C climatic zone.

Table 10: Identity record of HIKARI case study

	Address	Confluence, Quai Antoine Riboud, 69002 Lyon
	Year of construction	2010
	Total Surface	12 000 m ²
	Surface SHAB	2 959 m ²
	Number and type of dwelling	36 apartments (Shops on the ground floor) from T2 to T4
	Level of floors	8 floors and 1 basement.
	Heating energy	Gas condensing boiler + thermal solar panel
	Heating type	Collective
	DHW type	Collective
	DHW energy	Gas condensing boiler + thermal solar panel
Applicable thermal regulations	RT2005	

II.4.3 Instrumentation details

The monitoring system in MINAMI building is extremely important to ensure the efficiency of the installed systems, to calibrate the real conditions with the storage systems and to control all deficiencies. Furthermore, advanced sensors were installed to monitor the occupant behavior. The monitored data developed in this project are divided into 4 types: Interior conditions, energy consumption, and occupant data.

- ⇒ **Indoor Environmental conditions/ quality:** As well in this case study, the indoor conditions are represented by the indoor temperature (°C), the relative humidity and the CO₂ concentration. The sensors were installed in the living room and in different rooms of the apartment with a time step of 10 minutes for storing the measurements.
- ⇒ **Monitoring of occupant behavior and energy data:** This data base provides more specificity regarding the occupant's presence and its interaction with its indoor environment, and it is considered as a high-level database because it corresponds exactly to the main objective of this research. As presented in the following **Table 11**, the motion detection and the interactions with windows, light and thermostat are measured for a time step of 10 minutes. In addition, the lighting power is measured in two forms: instantaneous and accumulated. The data base is then rich and various, and the parameters cited are the only ones exploited for this research.

Table 11: synthesis of the parameters monitored in HIKARI project.

Occupant behavior	Energy data
Occupancy, Mention sensor (0=no detection; 1=detected)	Lighting power: <ul style="list-style-type: none"> • Instantaneous power=W; • Accumulated power=Wh.
Light On/OFF (0=offline; 1=online)	
Window Open/Close (0=close; 1=open)	
Set-point regulation (°C)	

As presented in Table 11, the parameters monitored in this instrumentation are different than the other case studies presented in this chapter. These differences are due principally to the objective from the instrumentation, the systems types and energy supply. In HIKARI buildings, two types of energy supply are detected: lighting and general power that includes heating, Domestic Hot Water and others electricity supply, contrary to HEART and PREBAT projects where each energy supply is measured separately. Furthermore, it was important for the HIKARI project to monitor the occupants' interactions by developing a monitoring approach that focus on measuring directly the windows opening, light-on and set-point regulation.

II.4.4 Buildings and Systems characteristics

The concept of positive energy of HIKARI buildings necessitate efficient energy systems for local energy production. The renewable energy sources are the main pillar for developing a sustainable building with positive energy. In this context, the electricity, DHW, heating and cooling were covered by three types of renewable energy sources: Solar, Biomass and Geothermal. In addition, thermal storage was designed to size the energy production systems.



Heating systems and domestic hot water
<ul style="list-style-type: none"> ▪ Cogeneration (Biomass), <div style="text-align: center;">  </div>

Figure 21: Cogeneration system: COGENGreen.

Ventilation
<ul style="list-style-type: none"> • Mechanical air extract systems.
Cooling system
<ul style="list-style-type: none"> • Absorption chiller <div style="text-align: center;">  </div> <p style="text-align: center;"><i>Figure 22: Absorption chiller System from YAZAKI.</i></p>
Renewable energy production
<ul style="list-style-type: none"> ▪ Photovoltaics modules and cogeneration (solar and biomass)

II.5 Conclusion & discussion

In this Chapter we have presented the considered case studies in the development of our research. The HEART project case study was our principal in-situ experimentation and we were directly involved in its design and realization. This case is completed by two other existing case studies. The experience of developing and managing the various phases of monitoring activity was very advantageous in term of: understanding the importance of the monitoring approach, managing the several stakeholders for completing the implementation, and exploring the inconvenience and the barriers of the monitoring approach. For this reason, this case study was presented first with all possible details, even if the finalization of this database was affected by the COVID 19 sanitary conditions but we succeed to overcome some induced barriers. In this respect, the PREBAT and HIKARI projects were proposed to complete the research with the several measured parameters and the details were presented in the previous sections.

In order to assess and better understand how this research will be developed in the following chapters, a comparative synthesis is presented in **Figure 23** and **Figure 24** where the level of data availability and details for the three projects is compared using a simplified weighting method. The three aspects compared are: i) The general information about the apartments instrumented, ii) the technical data, and iii) the instrumentation details. In the synthesis below, the three aspects are presented in tables with a list of indicators. In this context, the weighting method has been adopted to assess and compare the level of data availability and details by three classifications: 1) data available in details, 2) medium level of the data

provided, partial data, and 3) low level of data, data not available. Each classification will correspond to a color and symbol that will be illustrated in the synthesis tables.

The results of weighting method confirm a near level in the first part of general information about the apartments instrumented for the three projects. For a deep analysis of the orientation impact on the occupant behavior, it is essential to gather the accurate orientation of each apartment. Similarly, for the technical details, the same projects are missing the information about the windows characteristics and blind and shades systems.

With respect to the instrumentation details, the level of parameters measured is varying between the three projects. The HIKARI project provides direct measurements about the occupants' interaction, but not a direct measurement of heating, DHW and outdoor conditions. The time step provided by this project is the higher comparing to others.

The PREBAT project was characterized by higher level in the measurements of outdoor conditions, however the lighting consumption was measured only by "LES GENTIANES" case study. In addition, not all of the energy consumption was measured hourly, but only the heating and electricity consumption could be exploited for the "AMPLIA" case study and the lighting consumption in "LES GENTIANES" case study for a time step of one hour for all the parameters.

The HEART project provides a direct measurement of energy consumption: lighting, DHW and heating for a minimal time step of one hour. Contrary to the indoor and outdoor conditions, the time step proposed in the cloud are: 15 min, 1 hour, 1 day, 1 week and 1 month.

Despite the differences identified in the comparative synthesis, this variation is very important to explore the multiple possibilities and perspectives to the exploitation of data which will depend on the availability and the level of various details. The following chapters will present various proposals on the methodology adopted for the data analysis, and how to collect the maximum information about the occupant's behavior in these case studies.

Comparative of data availability & details

Weighting the level of availability and details:

- ★ Data available in details
- ⊙ Medium level of the data provided, partial data
- ↘ Low level, data not available

- HEART project → A
- PREBAT project → B
- HIKARI project → C

☉ General information about the apartments instrumented

	A	B (I)	B (II)	C
<i>Localization</i>	★	⊙	⊙	★
<i>Year of construction</i>	★	★	★	★
<i>Surface/living area</i>	★	★	★	↘
<i>Applicable thermal regulations</i>	↘	★	★	★
<i>Floor level</i>	★	★	★	★
<i>orientation</i>	★	★	⊙	⊙
<i>Climatic zone</i>	★	★	★	★
<i>Type of the apartment</i>	★	★	★	★
<i>Heating type</i>	★	★	★	★
<i>DHW type</i>	★	★	★	★

☉ Technical data

	A	B (I)	B (II)	C
<i>Building envelope</i>	★	★	★	↘
<i>Windows characteristics</i>	★	★	↘	↘
<i>Blind and shades systems</i>	★	★	↘	↘
<i>Ventilation</i>	★	★	★	★
<i>Heating energy</i>	★	★	★	★
<i>DHW energy</i>	★	★	★	★
<i>Renewable energy exploitation</i>	X	★	★	★

Figure 23: A comparative synthesis of the collected data (1).

Comparative of data availability & details

Weighting the level of availability and details:

- ★ Data available in details
- ⊙ Medium level of the data provided, partial data
- ↘ Low level, data not available

- HEART project → A
- PREBAT project → B
- HIKARI project → C



⌚ Instrumentation details

	A	B (I)	B (II)	C
<i>Indoor conditions (Temperature, relative humidity and CO₂)</i>	★	★	★	★
<i>Outdoor conditions</i>	⊙	★	★	↘
<i>Heating consumption</i>	★	★	⊙	⊙
<i>Set-point regulation (°C)</i>	↘	↘	↘	★
<i>DHW consumption</i>	★	⊙	⊙	⊙
<i>Lighting consumption</i>	★	↘	★	★
<i>Electricity consumption</i>	★	★	↘	⊙
<i>Occupancy, Motion sensor</i>	↘	↘	↘	★
<i>Light On/Off</i>	↘	↘	↘	★
<i>Window Open/Close</i>	↘	↘	↘	★
Time step	<ul style="list-style-type: none"> ▪ 1 hour for energy consumption; ▪ 15 minutes for indoor and outdoor conditions. 	1 hour	1 hour	10 minutes

Figure 24: A comparative synthesis of the collected data (2).

CHAPTER III

Data - driven analysis

Occupant behavior: A comprehensive analysis of the drivers affecting the occupant's interactions in smart residential building



Chapter III: Data-driven analysis

Occupant behavior: A comprehensive analysis of the drivers affecting the occupant's interactions in smart residential building

III.1 Introduction

Nowadays, the monitoring activities are key elements in the assessment and the prediction of building energy performance. This approach provides a realistic track of the relevant parameters affecting the building energy efficiency, especially in smart residential buildings where the major investments were performed in terms of technologies and innovative strategies. The building energy performance depends generally on both technical and human factors. In this respect, several levels of monitoring could be proposed depending on the final objective from the monitoring approach. If the objective of the monitoring approach is to assess both aspects, a high level of measurements is required.

This research focuses mainly on residential buildings where the data collection is challenging. Furthermore, the estimation of the occupancy schedules in residential buildings is more difficult to assess compared to the case of office buildings, and the qualitative approach as survey & questionnaires are not sufficient to analyze the occupant's interactions with high accuracy.

Our first case study is considered as a part of a smart residential building presented in Chapter II. The measurements collected are regarded as high level because they include direct measures about the occupant's interactions with windows, artificial lighting and thermostat. In addition, various technical data about the monitored building were collected. Besides, this research bears interest on occupant's interaction in the residential building. The data collected were carried out for a period of one year and presented under three categories: (a) occupant data, (b) energy data and (c) interior conditions. In order to complete the database by the exterior conditions, a weather station situated 15 km from the case study will be integrated in the analysis (**Figure 25**).

This Chapter represents the first analysis on the occupant's behavior in smart residential building in order to investigate several occupants' interactions, and to assess the relevance of the measured parameters. The parameters operated for the description of the presence and the various interactions between the occupants and their interior environment are: motion detection, windows open/close, light on/off and thermostat modification. The main objectives from this analysis are:

- Explore the database to learn more about the occupant behavior in smart residential buildings.
- Identify the drivers affecting the occupant's interaction with windows, thermostat and lighting.

- Make a general assessment of the data analyzed and provide recommendations.

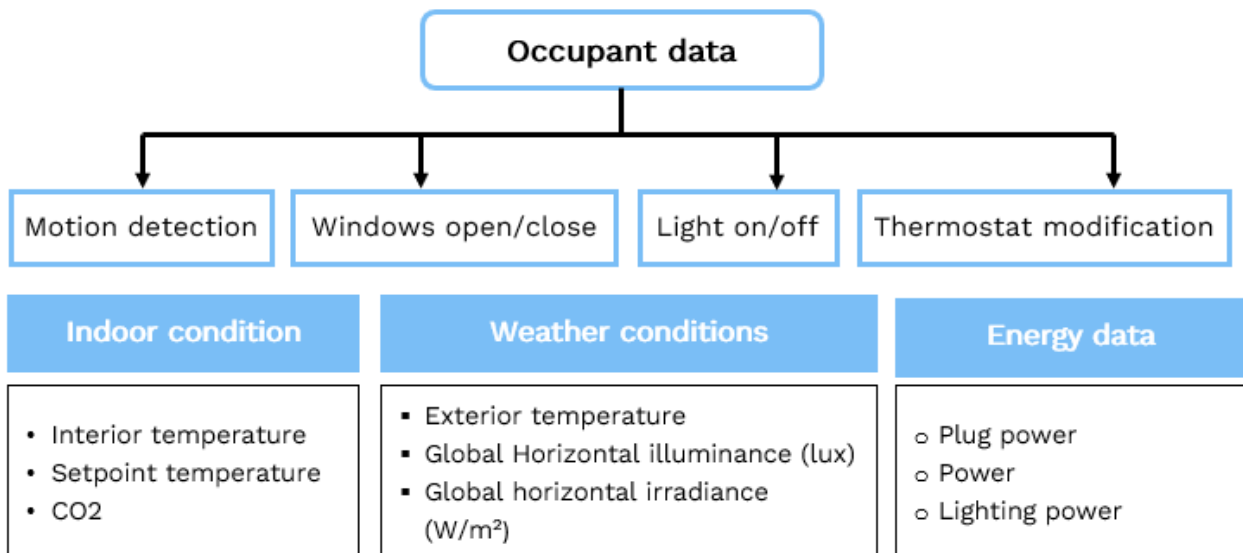


Figure 25: Synthesis of the monitored parameters in HIKARI case study.

This study is organized into three main sections: (1) characterization of the windows opening interaction, (2) analysis of thermostat use, and (3) exploration of the mechanical lighting activity interaction. Thereafter, the methodology and the analysis of the potential parameters affecting the three main interactions will be presented separately in sections. The final section will highlight the most important recommendations about the monitoring activities of the occupant’s behavior in smart buildings (Figure 26).

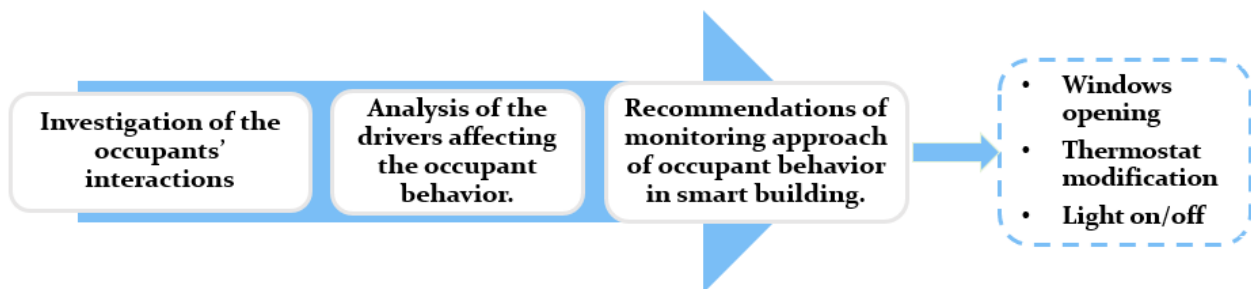


Figure 26: Methodology framework of the HIKARI database analysis.

III.2 Occupant behavior analysis: windows opening

The daily occupant’s interactions with their environment with the systems implies an impact on building energy performance, and windows opening is considered as one of the most important interactions in residential and office buildings [104][105]. A full understanding of the real windows opening in buildings depends on the type of buildings and the quality of data collected.

In order to perform an effective analysis of the windows opening, a complete database about the occupant’s windows interaction while combining the quantitative & qualitative approach is the best compromise to answer the following questions:

- What are the characteristics of the occupant's windows opening and their controllability?
- What are the main drivers affecting the occupant's windows opening?

The database of HIKARI case study as described in Chapter II is an in-situ measurements that provide direct indication about windows interactions. The measures provide two values for indicating the closing and opening of the windows (0=close; 1=open) and the sensors are installed: Stay: 2 sensors; Kitchen: 1 sensor; Room 1 and 3: 1 sensor for each room; Room 2: 2 sensors.

III.2.2 Methodology of analyzing windows opening in HIKARI case study

The approach adopted in this section, is the Knowledge Discovery in Databases which consists of the extraction of useful information from the measured parameters. The organization of the analysis as presented in **Figure 27**, is divided into four principals' phases. The data selection is the first aspect to identify in the process of the data analysis. In this phase we answer three questions:

- What is the adequate period to analyze and why?
- What are the locations where the windows opening is measured?
- What are the parameters connected to windows interactions?

The selection of the winter and summer period was mainly based on the big differences of the exterior conditions and routine day of occupants. The analysis of these seasons will provide an important comparison between the drivers affecting the occupant's interaction with windows in the two seasons.

The monitoring activities in the Smart building HIKARI were designed to monitor all the windows opening. In order to understand accurately the occupant's windows opening, the analysis of the several spaces in the apartment is explored. Furthermore, and based on the literature review summarized in the previous section, the parameters supposed to be as major parameters connected to windows opening and provided by HIKARI data base are: Windows opening detection, outdoor and indoor temperature, day time, CO₂ concentration and motion detection.

Thereafter, it is crucial to process the data by preparing and organizing the final data set while identifying the missing one. Afterwards, the next step is to extract the graphs and to analyze the relevant correlation between the windows opening and the parameters evaluated. This multidimensional analysis allows a deep perception of the major factors affecting the occupants' windows opening.

A focus on the daily frequency of windows opening will be presented for the winter and summer season. The analysis is based on the percentage of days when the occupants open the windows on the period indicated (example: a percentage of 50 % indicates that the windows' openings are detected within half a month (15 days), the windows openings considered are superior or equal to the time interval of 10 min) .

III.2.3 Analysis of windows opening drivers in winter season

III.2.3.1 Contextual drivers: time of day and room type

According to the first observations regarding the windows opening in winter, we can suppose that the time of day and room type have an important role in this case study. To explore the effect of these factors on the windows opening, the analysis was carried out for each room separately. In addition, the time of day was divided into four classifications as shown in **Figure 28**. This classification was based on the hypothesis that there is no night ventilation in winter, and the main four intervals of the day: 1) morning, 2) lunch time, 3) afternoon and 4) evening were based on the usual day life in France. Firstly, in *the kitchen*, around 46% of windows opening was detected in the morning from 8:00 am to 12:00 pm. Secondly, 33% of windows opening was identified between 2:00 pm and 7:00 pm, and around 10% at lunch time and evening period. The presence of occupants in the kitchen is more probable in morning and afternoon, and the cooking activity implies opening windows. The windows' interaction could be affected also by the technical factors of the kitchen, and by the occupants' preferences.

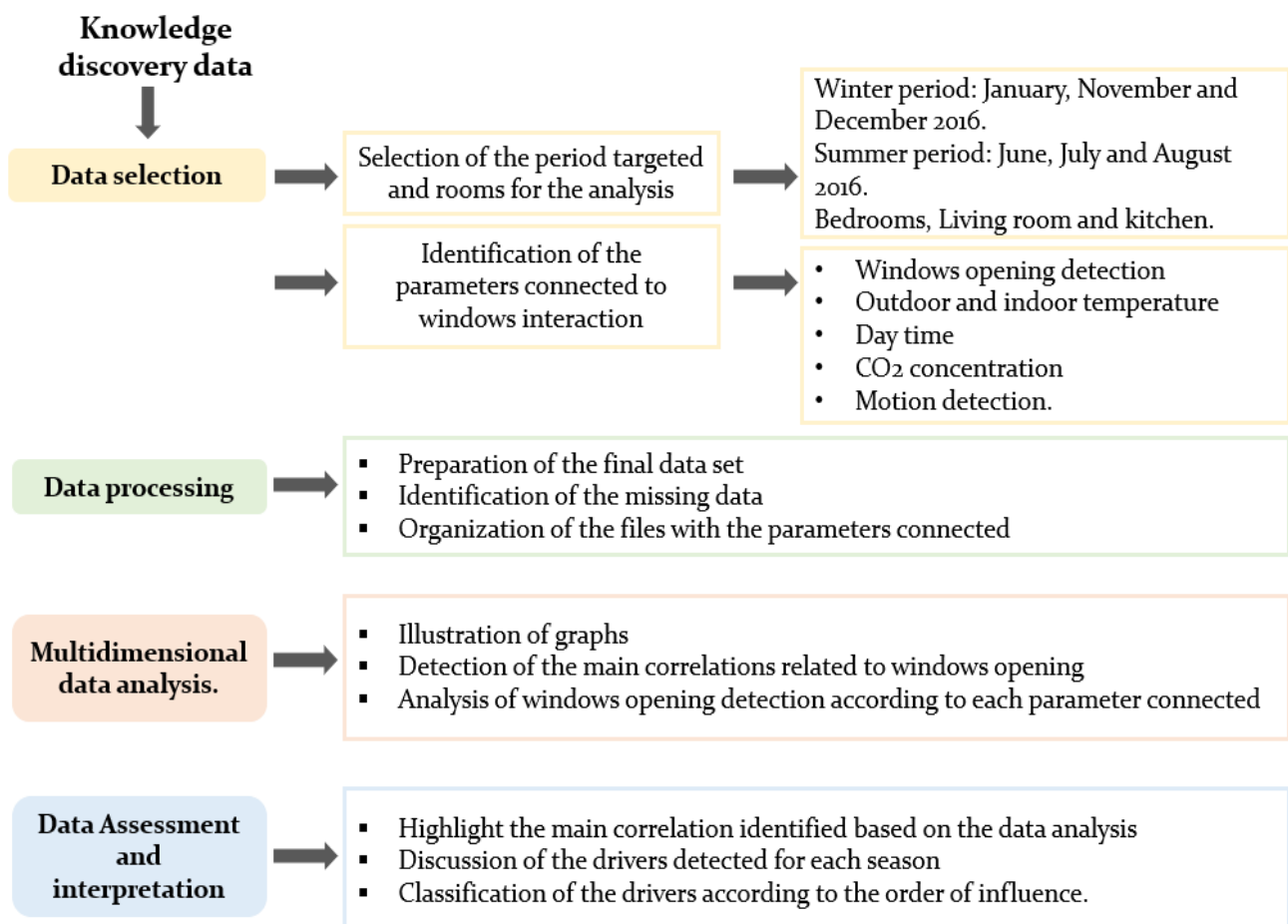


Figure 27: Methodology framework of windows opening analysis.

Contrary to *the bedrooms*, all the openings detections were in the morning between 7:00 am and 10:00 am. In this respect, it is obvious that the windows opening in the morning is a habit for the occupants and reflects their needs to refresh the air in the room after a long night's sleep. The morning opening is not daily and varies in winter season. The behavior of the occupants of bedroom 1 shows more need to open the windows in the morning than the other rooms, especially bedroom 3 where only two openings were detected during the 3 months which could reflect several suppositions: absence of occupants, unoccupied/visitors' room or just no personal need to open the window. In January, as for bedrooms 1 and 2 we observe other openings during the week end around 12:00 pm and 4:00 pm. For *the living room*, only four openings windows were detected in the winter period. Two openings were detected in weekends and two others in the evening.

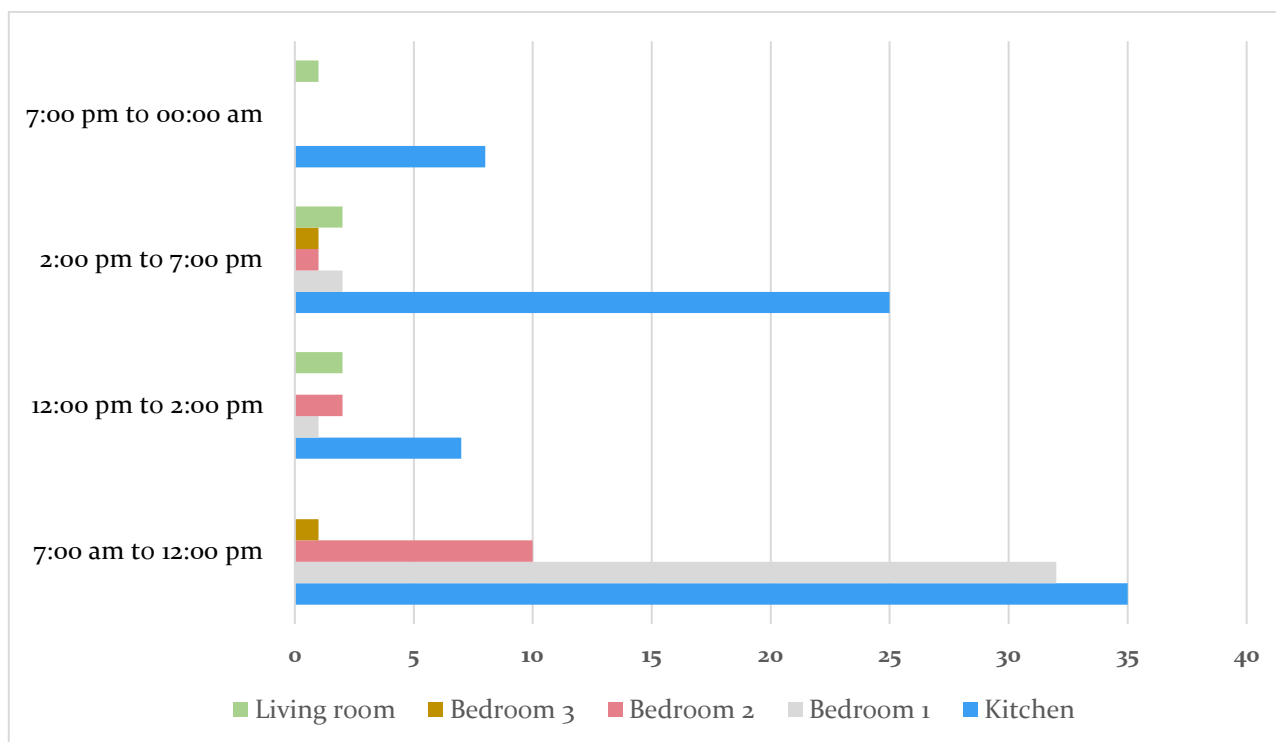


Figure 28: Frequency of windows opening in winter according to time day for each space in the apartment.

III.2.3.2 Environmental drivers

The HIKARI case study is considered a smart building with high building energy performance. The Heating in the building ensures the thermal comfort to the occupants and gives them the possibility to adjust the indoor temperature degree according to their preferences. For this reason, the *indoor temperature* wasn't considered in this study as a driver affecting the opening of windows in winter season.

Regarding the *outdoor temperature*, its maximum value identified is 18.1 °C monitored on November 1, and -2.9°C as its minimum value detected on December 2. As an example of the analysis, **Figure 29** shows the evolution of exterior conditions compared to windows opening in bedroom 1 and 2 in the period from January 1 to January 10 (the analysis of living room and kitchen in the same period is presented in the Appendix A). The outdoor temperature is very

low compared to the indoor temperature, then in this period of year the occupants in general search to maintain an interior thermal comfort. Thus, it is concluded that the exterior & indoor temperatures have no impact on windows opening behavior in winter.

However, the increase of outdoor temperature at the beginning of the day corresponds to the majority of windows openings in these rooms, which coincides also to wake-up and departure time. Consequently, wake-up and departure time are considered as a main driver for windows' openings for this case study.

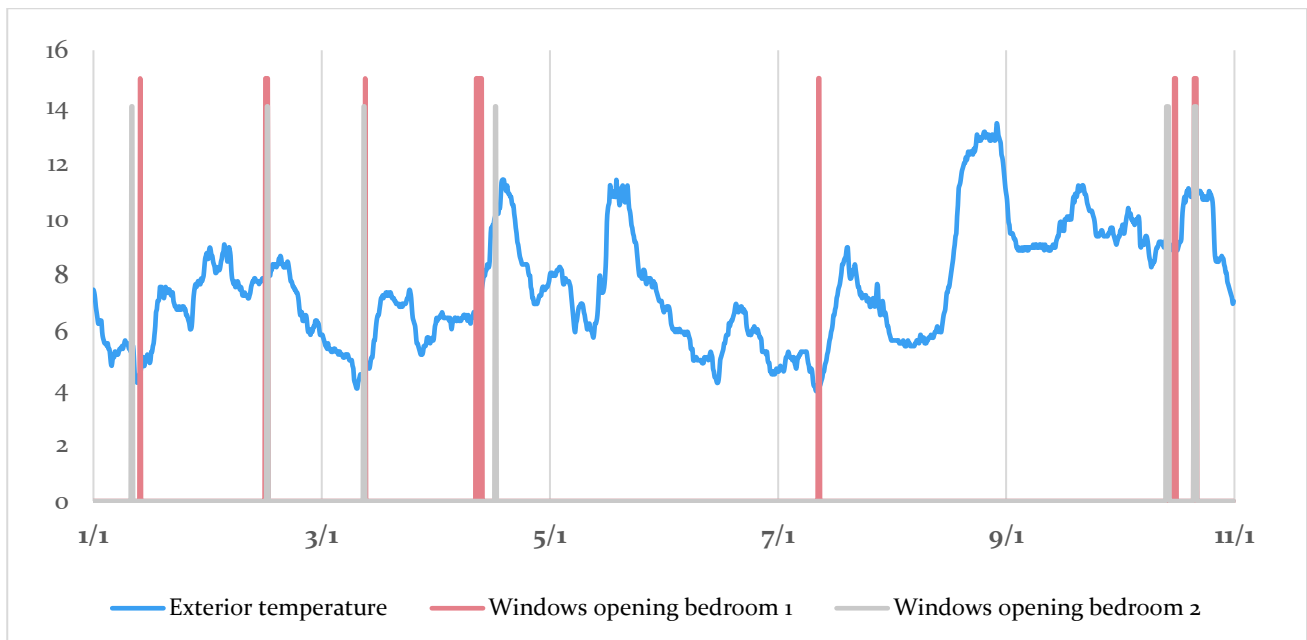


Figure 29: Evolution of the outdoor temperature according to windows opening in bedroom 1 and 2 (from 01/01 to 01/10).

Regarding the *interior air quality* in the bedrooms and the living room (there is no measurement of CO₂ concentration in the kitchen), **Figure 30** shows the evolution of the CO₂ concentration function of the window openings of bedroom 1 and bedroom 2 over the period from January 10 to 19. As presented, the analysis will focus on the month of January and on bedrooms 1 and 2 for the significant frequency of windows opening in this month compared to other months, and in these spaces comparing to other spaces (living room and bedroom 3). The windows openings of the bedrooms detected in this period were mainly on the morning where the CO₂ concentration varies between 400 ppm and 600 ppm. By analyzing the peaks of CO₂ concentration in the two bedrooms and in the other period (from 01/10 to 01/11, Appendix A), no windows openings were identified. Accordingly, we can conclude that the CO₂ concentration and air quality doesn't present a factor influencing the windows openings in this apartment. which was mostly affected by the need to refresh the space in the morning, or after cooking activities which reflect a day routine.

Nevertheless, being aware of the importance of interior air quality and its impact on human health and well being become necessary, especially with the actual sanitary conditions (COVID 19). The lack of knowledge about this aspect could explain the no-reaction to the huge increase of the concentrations of CO₂ values detected.

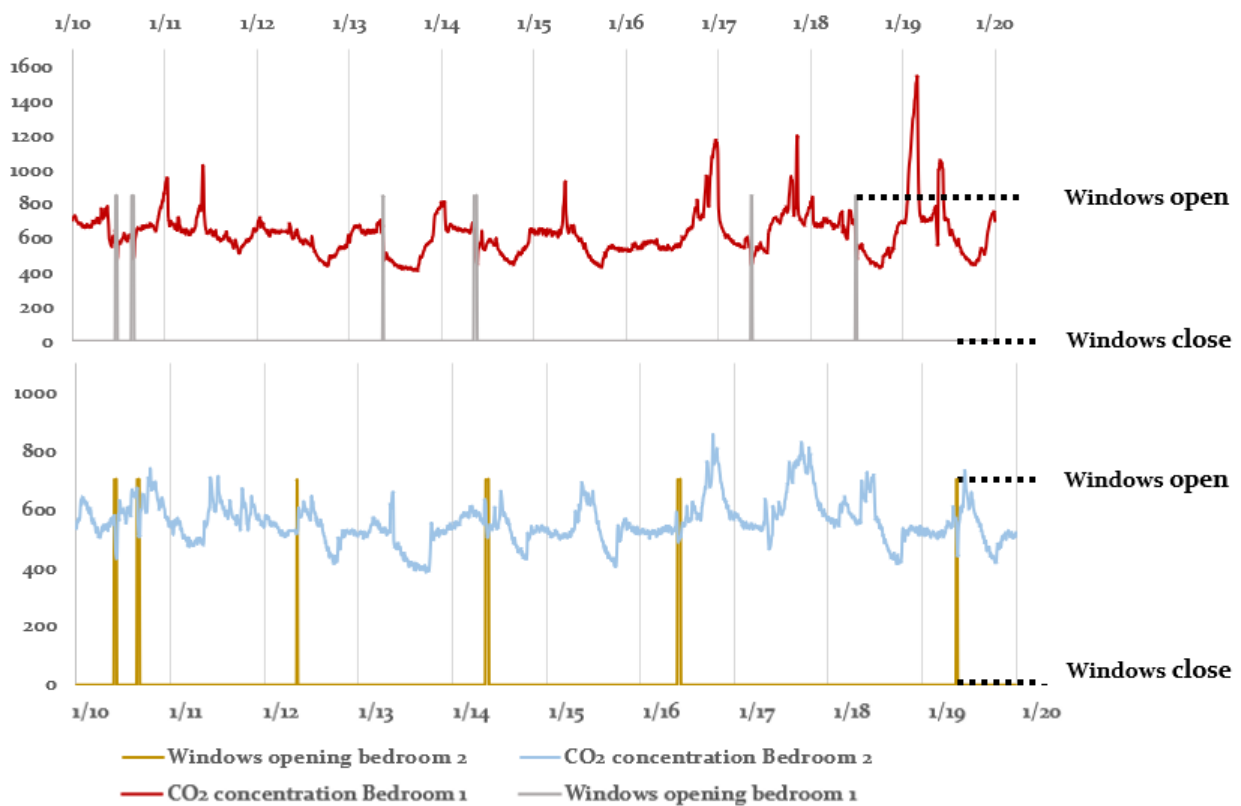


Figure 30: Evolution of CO₂ concentration function of the windows opening in bedroom 1 and 2 in the period of January 10 to 19.

III.2.4 Analysis of windows opening in summer season

III.2.4.1 Contextual drivers: Time of day and type of room

It is obvious that the windows opening in summer is more frequent than in winter because the need to refresh the air is more important. The adopted analysis of the windows opening in the summer is similar to that in winter : each room is analyzed separately and the time is classified into five periods: (1) morning, (2) lunch time, (3) afternoon, (4) evening, and (5) night.

The **kitchen** reveals 70% of windows opening in June and July, and 50% openings in August. In the morning, the windows opening before 12:00 p.m, presents a high frequency of opening compared to other times of day. During the day from 12:00 p.m. to 6:00 p.m. the frequency is very low compared to the evening. The night ventilation is detected six times in July, three times in August and one time in June. Regarding the detection of windows opening in **living room**, two sensors were installed (stay 1 & stay 2), which indicate the presence of two windows and the schedules opening are not completely similar for both. During the three months, representing summer season, the frequency of daily windows opening is around 27%. The majority of openings were identified in the early morning and late evening. One sensor detects

three night ventilations comparing to the other sensor where only one night ventilation was identified. The second window was characterized by long period opening (*Figure 31*).

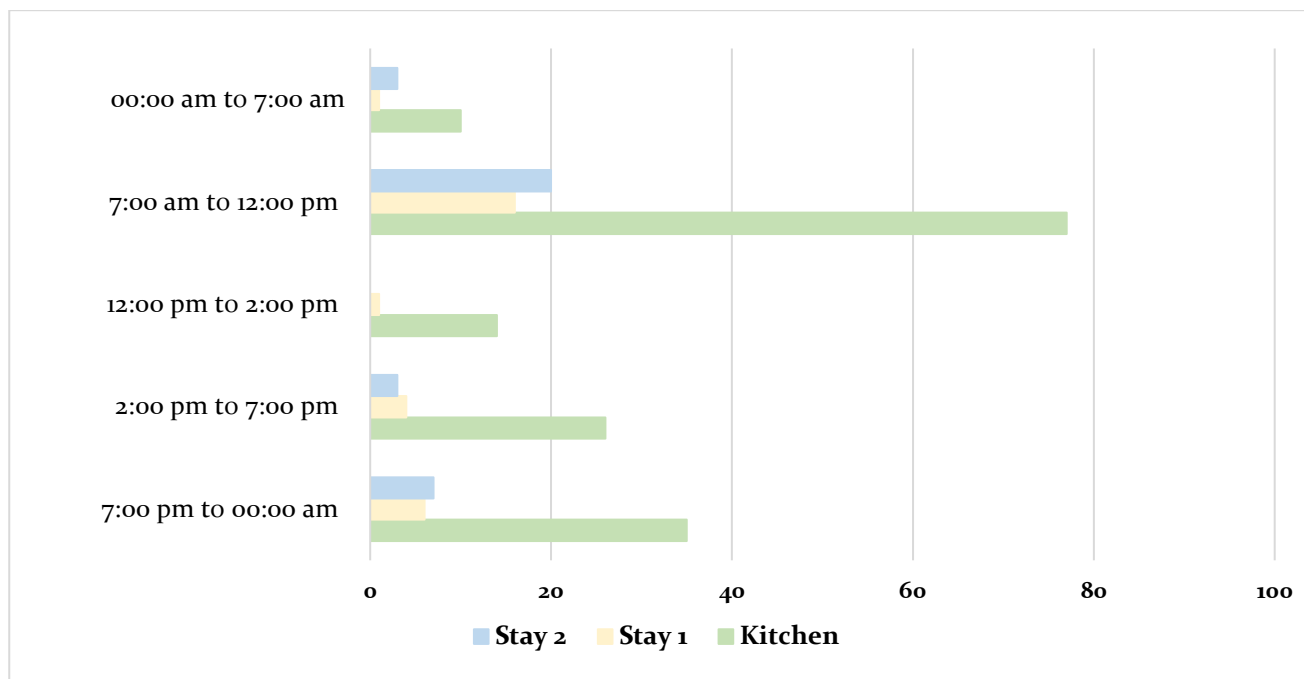


Figure 31: Windows opening frequency in summer according to time for kitchen and living room.

The windows opening in **bedrooms** is more observed in the early morning and most frequent in July. Bedroom 1 is the room with more openings in the morning and night ventilation. During the whole period of summer, twenty night ventilations were detected, including fourteen especially in July. In bedroom 2, two sensors were installed (two windows). The daily frequency of windows openings in bedroom 2 is around 17% for sensor 1 and 40% for sensor 2. In June and August more than 90% of openings are presented in the morning period and in July more openings were detected during the day with one night ventilation identified for sensor n°2. Concerning bedroom 3, only one sensor is installed and 32% of day window's opening were identified during summer period. All the window openings in this room were in the morning from 7:00 a.m to 12:00 p.m. in June and August. In July one night ventilation is identified and three other window openings between 2:00 p.m. to 6:00 p.m. (*Figure 32*).

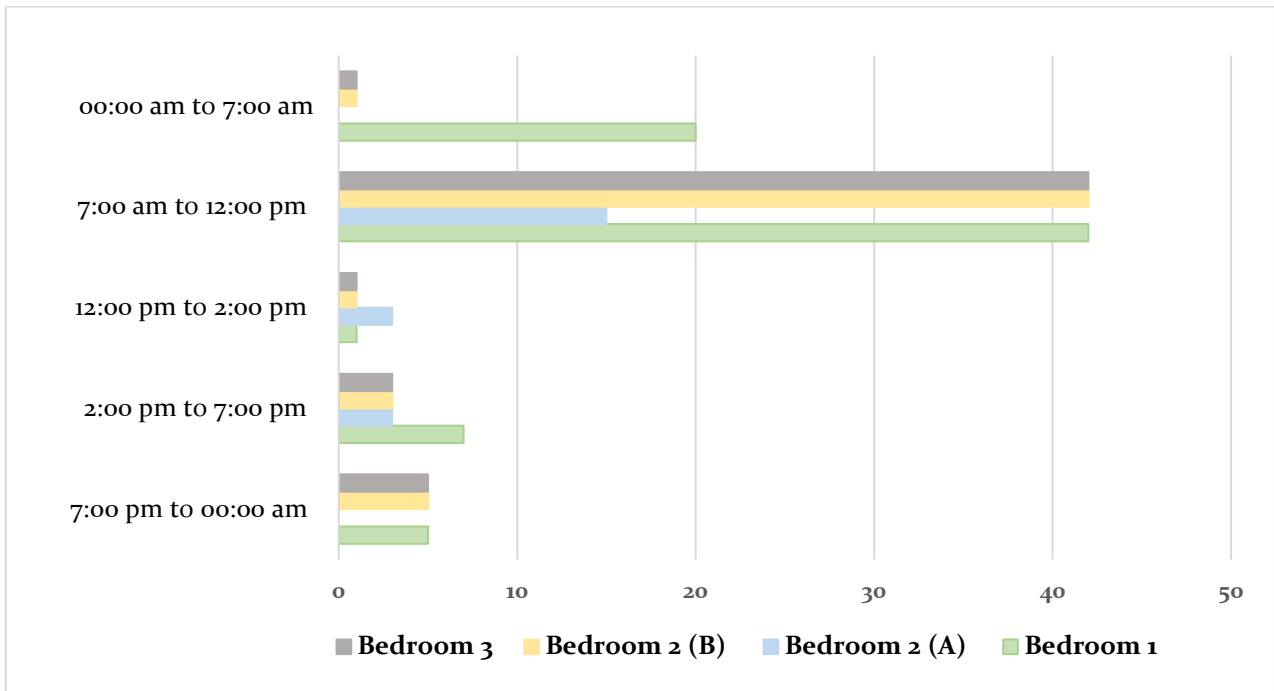


Figure 32: Windows opening frequency in summer according to time for the three bedrooms.

The majority of window openings identified in the summer are more presented in the morning before 12:00 p.m. and afternoon starting at 6:00 p.m. The outdoor temperature and solar radiation are higher between 12:00 p.m. and 6:00 p.m. So, during this period of the day, it is possible that the occupants avoid the opening of windows to limit the overheating of the apartment. **Figure 33** shows an analysis of the opening of windows in the kitchen and bedrooms for the three months representing the summer period. July is the month with more opening frequency, and the three bedrooms represent approximate percentage of windows opening. However, it must be considered that the windows' openings in summer period can inform us more about the scenario of occupant's presence in the apartment. Based on the analysis of windows openings in different spaces of the apartment, the possibility of an absence of 10 days is estimated in August from 09 to 19 and can be considered as a vacation period. As for the night ventilation, it is appointed that it wasn't a daily routine for the occupants but, more frequently adopted by the occupants of bedroom 1 compared to the other rooms.

The next section will allow a better analysis of the environmental conditions and their contribution to the windows interaction.

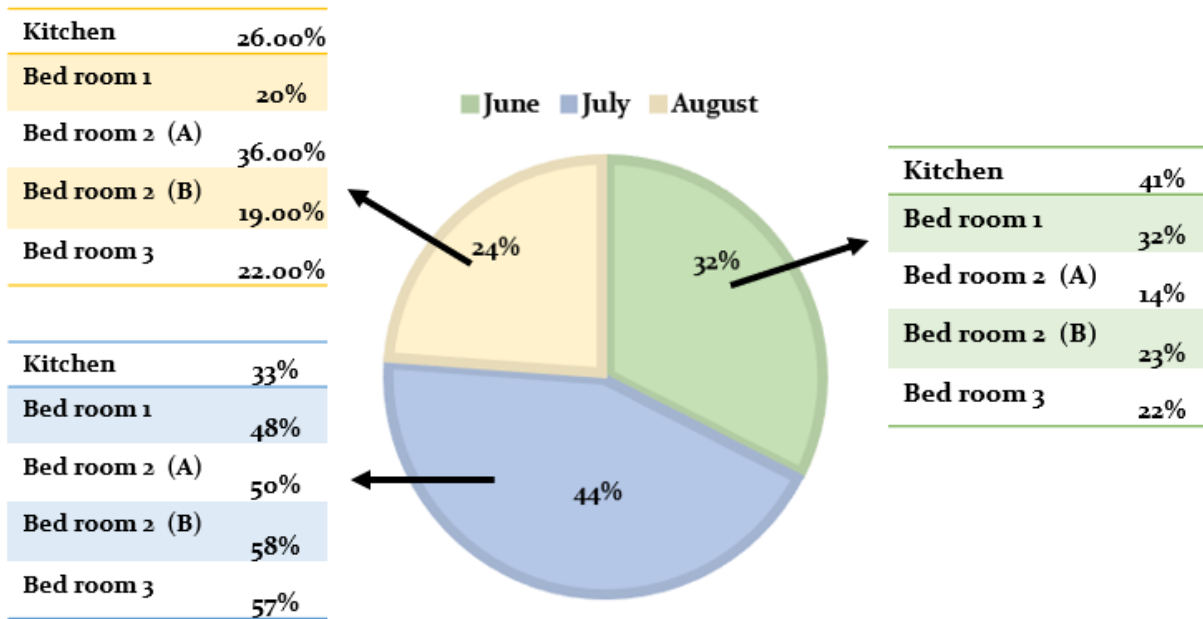


Figure 33: analysis of the windows opening in summer according to each month for kitchen and bedrooms.

III.2.4.2 Environmental drivers

The analysis of the windows opening in the summer was developed according to the environmental drivers: CO₂ concentration, interior and outdoor temperature in each space in the apartment. Based on the measures identified, a critical investigation was carried out to analyze and compare the evolution of the environmental parameters with windows' openings.

The *indoor temperature* in different spaces varies between 20°C and 28°C, and some spaces/rooms are warmer than others. For example, in August, the minimal temperature in the bedroom 1 was 25°C compared to bedroom 2 where the temperature doesn't exceed 26°C in all summer. This variation of interior conditions depends not only on the orientation and emplacement of these spaces, but also on other factors as the number of occupants and the adopted ventilation scenario. To analyze the impact of the indoor temperature on the windows interactions, the monitoring results have been analyzed in order to define the range of indoor temperature where the majority of windows' openings were performed.

In this respect, three possibilities are proposed: 1) The temperature increases, but the occupants are absent, so no interaction is expected, 2) the temperature increases and the occupants are present, but no interaction was identified, so the indoor temperature doesn't present a driver for windows opening in this case, and 3) the temperature increases and the occupants are present with a detection of windows opening, so the indoor temperature is a driver. Based on the analysis, it is concluded that if the indoor temperature exceeds 26°C and the occupants are present in the space, the opening of windows is more probable and its frequency is higher.

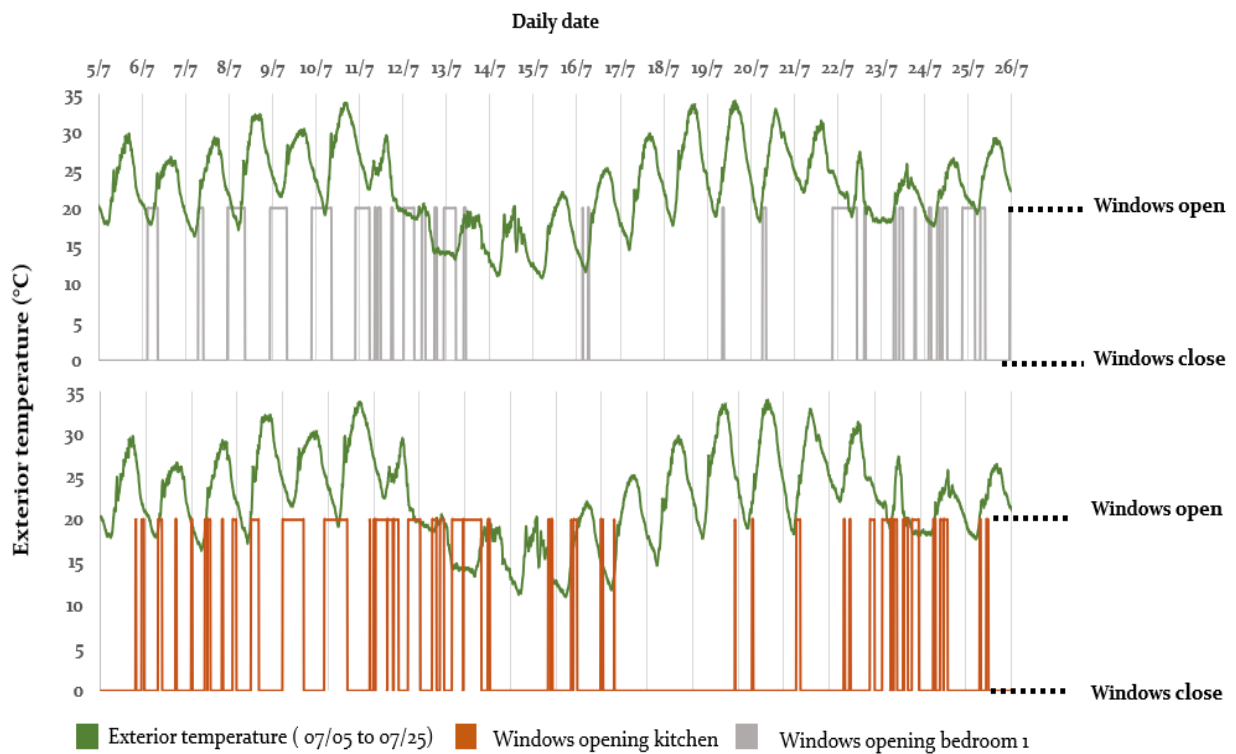


Figure 34: Evolution of outdoor temperature compared to windows opening in bedroom 1 and kitchen from 07/05 to 07/25.

Regarding the **outdoor temperature**, the correlation is more noticeable between the opening of windows and the increase of outdoor temperature. Especially in bedrooms, where the increase of the temperature in the morning is linked to windows' opening but with different frequencies. However, these interactions cannot be explained only by the increase of exterior conditions, but also by the need of the occupants to refresh the air of their bedrooms after a night of sleeping. **Figure 34** shows the evolution of the outdoor temperature compared to the opening of windows in bedroom 1 during July that represents the month with more opening frequency in summer. In the kitchen, the time of occupant's presence and type of activity is different and require more ventilation especially in summer. For this reason, the windows are more open and several times a day. Similarly, for the living room several window's openings were detected which depend on the time presence in the space and the occupant's personal need (**Figure 74**).

In summer, the **night ventilation** is considered as a principal need to the occupants and one of the interesting phenomena to analyze. **Table 12** presented below represents a list of the night's ventilation detected with an average of the exterior and indoor temperature during the period from 00:00 am to 7:00 am. As shown in **Table 12**, if the indoor temperature is equal or superior to 24.5 °C the possibility of adopting a night ventilation is more probable and we can identify that the indoor temperature is the main driver affecting the window's openings during the night. Hence, the interior conditions are improved. This solution was more adopted by the occupants of bedroom 1 compared to the occupants of other bedrooms. This

need is due to the several technical factors in addition to personal ones related to the occupants.

By analyzing the evolution of the *CO₂ concentration* and windows openings in different spaces in the apartment, no significant connection was identified.

Table 12: Average of interior and outdoor temperature during the night ventilation for bedrooms.

Bedroom 1	Average of outdoor temperature at night (°C)	Average of indoor temperature at night (°C)
23/06	22	25
28/06	17	25
29/06	19	25.9
30/06	19.5	26
01/07	19.7	26
02/07	19	26
06/07	19	25.9
08/07	19	26.6
09/07	22.6	26.5
10/07	21	27
11/07	24.5	28
12/07	19	26.8
13/07	14	24.5
16/07	13	25
21/07	23.4	27
24/07	18.5	26.6
25/07	20.4	26.5
26/07	21	26.9
08/08	17.6	27
Bedroom2	Average of outdoor temperature at night (°C)	Average of indoor temperature at night (°C)
23/07	18.4	24.9
Bedroom3	Average of outdoor temperature at night (°C)	Average of indoor temperature at night (°C)
11/07	24.5	28

III.2.5 Results & discussion

The windows interactions analysis is based on the occupants presence in the apartment or in a room/space, but the no windows interactions doesn't indicate the absence of occupants in the space or in the apartment. Based on the study presented above, the opening of windows varies depending on :

- **Season:** Winter and summer (exterior conditions).
- **Time of day**
- **Room type:** Kitchen, Stay, bedroom 1, bedroom 2 and bedroom 3.
- **Interior air conditions:** Indoor temperature.
- **Day routine, presence time and personal needs and preferences.**

During **winter season**, the kitchen and bedroom 1 were characterized by a high frequency of windows opening compared to other spaces in the apartment. In the kitchen, the frequency is important in the morning (46%) and in the afternoon (33%) which reflects the time when the meals were in preparation. Regarding the bedrooms, most of the openings were detected in the morning, which reflects a sort of needs/routine. The exterior and interior conditions doesn't represent any correlation with the opening of windows in winter, especially in the case of smart building where a thermal comfort is guaranteed for the occupants. However, the outdoor temperature represents a main factor to not open the windows in order to maintain the thermal comfort in the apartment. The analysis of CO₂ concentration indicates high values in some period, but no windows opening was detected to improve the air quality.

In summer, the opening of windows is more frequent for all the spaces compared to winter season, but still bedroom 1 and the kitchen are the spaces with more openings frequencies. In the bedrooms, the openings are more detectable in the morning. These interactions can be explained by two suppositions: 1) the increase of the outdoor temperature and 2) the occupant's need to refresh the air in the room (morning routine). In the kitchen, the need of aeration is more important due to cooking activity that increases the temperature and affects the air quality. Regarding the living room (stay), it is estimated that the presence of occupants in the space and their personal needs have a major role in opening the windows. Less openings were identified between 12:00 p.m. and 7:00 p.m. It is concluded that in summer period the majority of occupants avoid the heat waves in this time of day. For the night ventilation, the indoor temperature is considered as a major driver for opening windows. Instead, it is important to notice that other factors influence the thermal comfort satisfaction as physiological factors, number of occupants in the room and its orientation. The evolution of the CO₂ concentration and windows opening doesn't reveal a significant correlation.

III.3 Occupant behavior analysis: thermostat use

The conception of thermostat-use and set-point regulation was developed in order to optimize the heating use in houses and increase the energy saving potentialities. But studies ensure that the efficacy of a thermostat depends on several factors and the misuse of the tool can increase the energy consumption instead of minimizing it [48][106][107][108].

The adaptation of the thermostat in the context of application is mandatory and considered as one of the factors influencing the efficient use. The study by Peffer et al. [48] shows that the thermostat control can save 9% of energy consumption if an appropriate use is ensured. Actually, three main thermostat categories can be identified: manual, programmable and smart thermostat. The choice of the type of thermostat to integrate in an apartment must be based on the answers of these questions: how will the tool be exploited by the occupants? how can we help the occupants to use it properly?

In the monitored apartment, the data base provides measurements of the set-point regulation in °C for each thermostat. The defined time step in this monitoring activity is 10 min.

III.3.2 Methodology of analyzing thermostat use in HIKARI case study

The approach adopted in this section is the Knowledge Discovery in Databases explained in the section above. The organization of the analysis is presented in **Figure 35** and divided into four principal phases. The first one of data selection represents the period classification targeted for the analysis based on the heating period, and the rooms where the thermostat regulation was measured. To provide a complete analysis, all the rooms will be integrated in the analysis for the whole heating period. The second one concerns the organization of the files and data cleaning. Thereafter, a multidimensional analysis was adopted to analyze the set-point regulation during the period targeted with highlighting the major drivers influencing it.

No information was provided to identify if there is a default set-point regulation. In this respect, the modification identified at midnight were removed from the analysis, and considered as automated.

III.3.3 Analysis of thermostat modification in heating period: overview and drivers

This part of analysis presents an overview of the total thermostat use and the modification of the set-point temperature in the heating period for a year of measurements. For a detailed analysis, the heating period was divided into two periods of the year: **i) Period A** from 01/01 to 03/31, **ii) Period B** from 10/15 to 12/31. The analysis includes each thermostat installed in the bedrooms, bathrooms and in the living room.

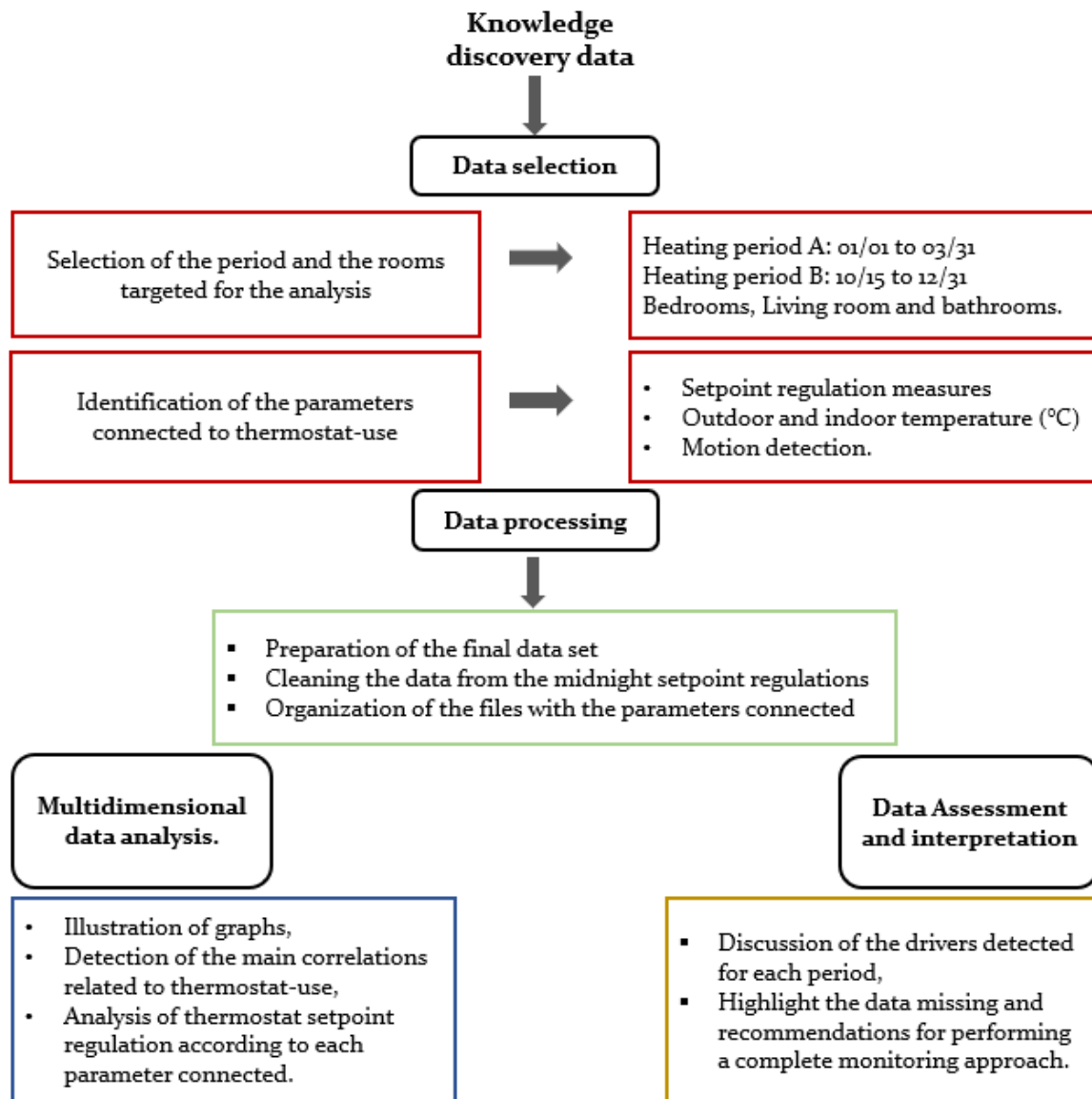


Figure 35: Methodology framework of thermostat-use analysis.

For the two **bathrooms** of the apartment, no set-point regulation was identified during the heating period. According to the recorded measurements, the temperature fixed by the occupants in period A is 22 °C and it is low compared to the temperature detected in period B: 24°C. This latter can be explained by the season transition that generates a decrease of almost 10°C in outdoor temperature degree between the 1st of September and 15th of October which impacts directly the interior conditions (**Figure 76** and Appendix A). This transition also creates a thermal shock which leads the occupants to want to maintain the identical thermal sensation. For this reason, 24°C is the higher degree temperature allowed to be regulated by the occupants and was activated only in the second period directly after the season transition. In contrary to the period between January and March, the occupants were used to the interior and exterior conditions, and with the increase of outdoor temperature their heating need decreases.

The information about the temperature activated by default in this context is necessary to precisely analyze the drivers. Considering the psychological driver explained above, the possibility that the occupants were not aware of this temperature is also possible.

In *period A*, the scenario of the set-point temperature for the regulation of *bedroom 1* is identical to *bedroom 2* with 23°C (fixed by the occupants) for the first twenty days of January then 22 °C until the end of the period. Almost similar conditions for *bedroom 3*, but with more 20 days of 23°C set-point temperature was detected (fixed by the occupants). Period A was characterized by lower set-point temperatures compared to period B. The set-point temperature in period B is explained by the increase of the outdoor temperature in this period which corresponds to the end of winter season and the beginning of the spring (**Figure 75**). Consequently, the sensation of heating need decreases.

Regarding *bedroom 1*, the minimal temperature noticed in *period B* is 21°C and based on the analysis of motion detection, no motion was identified during the week from 12/19 to 12/26. This indicates that the occupants of bedroom 1 were absent and regulated the temperature to a lower degree which could reflect a good conscience about the energy consumption and set-point temperature for the regulation.

The maximum temperature identified in bedroom 1 is 24°C regulated for only six days in December. The decrease of outdoor temperature in period B can generate a more heating needs in room 1, and such decrease conduct the occupants to increase the set-point temperature. The same conclusion explains the set-point regulation of *bedroom 3* that vary from 22°C to 24°C (**Table 13**).

Differently, in *bedroom 2* one set-point regulation is detected in period B after one day of the heating activation from 24°C to 22°C. The temperature adopted by the occupants of this room wasn't identical to others, and the presence of the occupants in the room was confirmed by the analysis of data motion measures. In this respect, the only suppositions deduced from this analysis are that the 22°C temperature degree is a personal choice and is considered as the optimal temperature to the occupants of this room, especially that no other details are presented to explore other possibilities (**Table 13**).

Concerning the *living room*, the higher temperature identified was 22 °C and the lowest was 18°C used only for nine days, except on February 9 and 10 where the occupants adopt a temperature of 24°C. A detection of presence by motion measures explains the regulation temperature of these two days, where several motions were detected in the afternoon. Moreover, a lower outdoor temperature was identified on February 10th, which explains the need of heating that day. Therefore, it is concluded that the presence in a space and its duration have an impact on the set-point regulation. The most-preferred temperature detected for almost 79% of the heating period in the living room is 22°C (**Table 14**).

Table 13: Overview of setpoint regulation in the bedrooms.






Period A	Temperature from 01/01 to 01/21 (°C)	Temperature from 01/21 to 03/31 (°C)	Period B	Temperature from 10/15 to 12/13 (°C)	Temperature from 12/13 to 12/19 (°C)	Temperature from 12/19 to 12/31 (°C)	curve Evolution
Bedroom 1	23	22	Bedroom 1	22	24	21	
Period A	Temperature from 01/01 to 01/21 (°C)	Temperature from 01/21 to 03/31 (°C)	Period B	Temperature from 10/15 to 10/16 (°C)	Temperature from 10/16 to 12/31 (°C)		
Bedroom 2	23	22	Bedroom 2	24	22		
Period A	Temperature from 01/01 to 02/09 (°C)	Temperature from 02/09 to 03/31 (°C)	Period B	Temperature from 10/15 to 11/28 (°C)	Temperature from 11/28 to 12/31 (°C)		
Bedroom 3	23	22	Bedroom 3	22	24		

Table 14: Overview of setpoint regulation in living room.

Living room	Temperature from 01/01 to 01/30 (°C)	Temperature from 01/30 to 02/01 (°C)	Temperature from 02/01 to 02/09 (°C)	Temperature from 02/09 to 03/31 (°C)	curve Evolution
Period A	22	21	18	22	
Living room	Temperature from 10/15 to 12/06 (°C)	Temperature from 12/06 to 12/13 (°C)	Temperature from 12/13 to 12/31 (°C)		Evolution curve
Period B	22	21	20		

III.3.4 Results & discussion

The analysis of thermostat-use in the monitored apartment was performed based on the heating period, and it was divided into two analysis periods: periods A & B. All the spaces where the measurements were realized have been taken into consideration: bedrooms, bathrooms and living room. As explained above, the identification of the drivers affecting the

set-point regulation is the final objective of the study. However, an evaluation of the data collected for this interaction will be highlighted in section III.5.

According to this research, the thermostat-use varies and depends mainly on the space. The type of room/space reflects two principal aspects: the attendance time in the space and the activity type. The bedrooms are the spaces where the occupants spend the maximum time compared to other rooms in the apartment where the level of activity is the lowest [31]. Consequently, various set-point regulations were identified which indicates an important need of thermal comfort in the bedrooms, contrary to the bathrooms where no set-point regulation was identified, and in the living room where only few modifications were observed. The outdoor temperature represents also a crucial role in the thermal need identification. The higher temperature regulated was during period B from 15/10 to 31/12 after the season transition. The decrease of the outdoor temperature increases the heating need and the memories remember the heat felt in summer, so the body doesn't accept this temperature diminution immediately (adaptive thermal comfort). The personal preferences can justify also the differences of set-point temperature in the bedrooms. Regarding the living room, it is observed that the occupants may increase the temperature if they spend a long time in the space.

III.4 Occupant behavior analysis: lighting use

The electric lighting is responsible for almost 12.8% of final electrical consumption in France households and around 325 and 450 kWh/year [109]. The average household lighting per day is 6.7 hours, which reflects the indispensability of lighting in our routine life. Nowadays, especially with the sanitary situation related to COVID 19, the occupants spend more time at home, which increases the visual comfort requirements and need duration. Thus, the interior lighting must respond to three challenges: (1) to ensure safety in the homes, (2) to provide the visual comfort necessary for the multiple tasks and according to the preferences of each person, and (3) to meet the energy efficiency strategies in residential buildings.

The efficiency of lighting use depends on several factors as the technical features of the dwellings, the characteristics of the lighting systems and the level of daylight exploitation. Nonetheless the occupant energy behavior plays a major role in choosing the best options to reduce the lighting use while satisfying their needs.

The monitored parameters in the database collected present a large information about several aspects of lighting use in the apartment such as: illuminance, light on/off and lighting power. These latter are monitored in the kitchen (three light sources), living room (two light sources) and the bedrooms (one light source in each room). In this respect, this study will focus on the lighting use patterns in winter and summer season for the various spaces of the apartments.

III.4.2 Methodology of analyzing lighting-on

The methodology adopted in this section is identical to the approach performed in the window opening analysis presented in section III.2.2. The parameters available in the data

base and exploited in this study are: light on-off, day time and the global horizontal illuminance. Based on the Knowledge Discovery in Databases approach, the principal goal is to extract (patterns, information) knowledge from the measures provided by the monitoring activity in this case study, and especially in this section about the use of artificial lighting on the apartment. The knowledge identified has informed us more about the occupant's interaction with lighting in the apartment: i) provide a classification of frequency of lighting use per timeslot and month, ii) what drivers affecting the lighting interaction based on the analysis. In order to perform a complete analysis, all the measurements in all the monitored spaces have been analyzed. In addition, the season impact was studied by analyzing three months of winter and three months of summer.

III.4.3 Analysis of lighting use drivers in winter season

III.4.3.1 Contextual drivers: Time and type of the room

The analysis of lighting use, according to the time of day was performed by observing the daily lighting use in each space/room. In this context, the day was classified into five time slots: 1) morning (7:00 a.m. to 12:00 p.m.), 2) lunch time (12:00 am.to 2:00 p.m.), 3) afternoon (2:00 p.m. to 7:00 p.m.), 4) evening (7:00 p.m. to 00:00 a.m.) and 5) night (00:00 a.m. to 7:00 a.m.). In addition to the study of the daily light use frequency in specific time slots, an analysis related to the month frequency will be provided. This analysis is based on the percentages of days when the occupants use the lights in rooms (example: a percentage of 50 % indicates that the lighting use is identified only for 15 days of the total 30 days of a month).

The first observational analysis affirms that the lighting use in **bedrooms** was characterized by this time slots order: 1) afternoon, 2) evening, 3) morning, 4) and 5) night as shown in **Figure 36**. The majority of the daily frequency of light use was detected in the afternoon from 2:00 p.m. to 7:00 p.m. Besides, more analysis was carried out in this time slot to better understand the lighting behavior. Thus, it was concluded that in bedroom 1, 70% of the lighting use were performed between 5:00 p.m. and 7:00 p.m., in bedroom 2 and 3 a percentage of 80% was detected. The latter reveals that the arrival time is one of the main drivers affecting the light use, but also the need of visual comfort is present, especially that sunset in Lyon city starts around 5:00 p.m. [110]. Furthermore, an analysis regarding the duration was performed for the period of lighting use that exceeds one hour. In the bedrooms, the long durations of lighting use were classified in the same order as the frequency of the time slots presented above. The maximum duration was identified in bedroom 1 (BR1) where the lighting was on during the whole the afternoon period (five hours) on the 2nd of December. Other duration around three hours were detected in January and December.

The **Table 15** shows an overview of the frequency of lighting use in bedrooms for the three months representing the winter period.

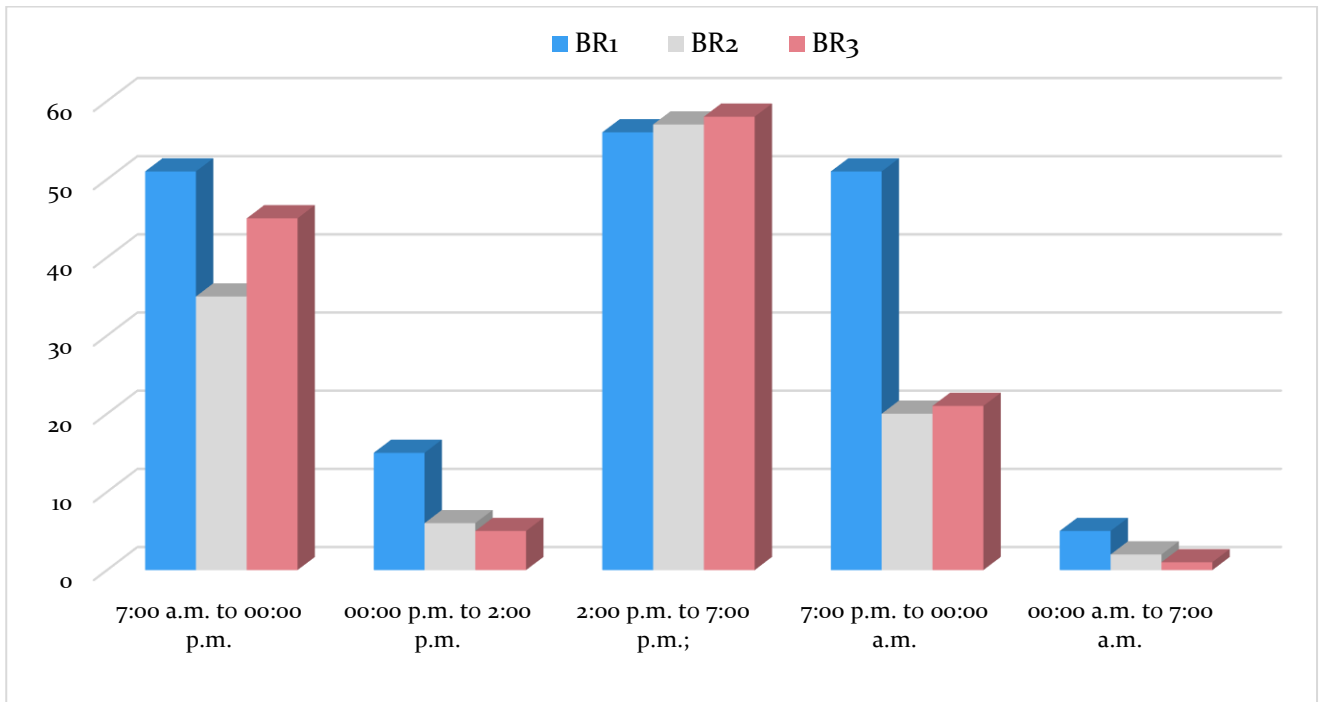


Figure 36: Synthesis of the artificial lighting use in the bedrooms according to each time slot (winter).

December represents the month with less lighting use for the three bedrooms. It could indicate a period of absence, especially it coincides with Christmas holidays in France. January and November frequency varies to a similar percentage in the three bedrooms. The room with higher lighting use is bedroom 1, then bedroom 3 and finally bedroom 2. In this context, more investigation about the reason of these observations will be investigated in the following section focusing on environmental drivers in order to provide a complete analysis.

Table 15: Frequency of daily light use, according to each month in winter and summer season.

Winter								
Bedroom 1			Bedroom 2			Bedroom 3		
January	November	December	January	November	December	January	November	December
64%	66%	61%	77%	56%	51%	64%	73%	51%
Summer								
Bedroom 1			Bedroom 2			Bedroom 3		
June	July	August	June	July	August	June	July	August
43%	48%	22%	33%	48%	22%	36%	51%	16%

Concerning the **living-room**, two sensors were installed to monitor the lighting use, which indicates the presence of two bulbs. The majority of the light-on detection concern the sensor 1 (bulb 1). The frequency of daily light use in winter is classified into the following order: 1) 00:00 a.m. to 7:00 a.m. 2) 7:00 a.m. to 00:00 p.m. 3) 00:00 p.m. to 2:00 p.m. 4) 2:00 p.m. – 7:00 p.m. and finally 5) 7:00 p.m. to 00:00 a.m. 1) (**Figure 77**, Appendix A). The higher frequency

was observed in January and November with few lightings uses in December. Accordingly, the lighting use with a duration superior than one hour is present in January and November with a maximum duration of 4h30 min in a time slot.

As regards to **kitchen**, three different measurements from three bulbs have been revealed. The frequency of using the light in the time slot from 7:00 p.m. to 00:00 a.m. is more remarkable, especially for sensor 2 and 3. On the second order, the time slot of 2:00 p.m. to 7:00 p.m. is the time where the lighting is also activated frequently during winter season. Thirdly, the morning time slot reflects the wake up and departure of the apartment time. The kitchen was characterized by an intense use of lighting in November, and with a longer duration compared to January and December (**Figure 37**).

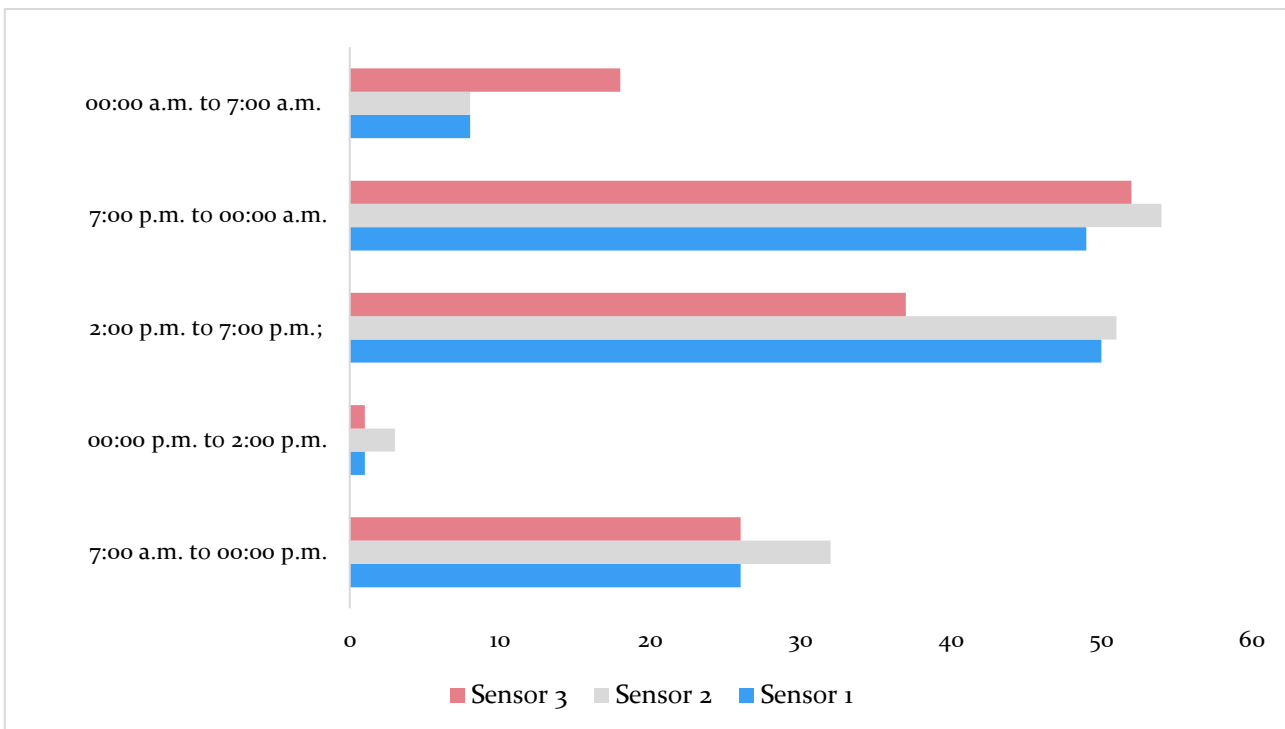


Figure 37: Artificial lighting use in the Kitchen according to each timeslot during winter season.

III.4.3.2 Environmental drivers

The analysis of the environmental drivers is based on the parameters monitored in the database. In this respect, the weather station provides measurements about the exterior **global horizontal illuminance and irradiance** that have a direct connection with the use of artificial light. For winter analysis, it was decided to focus on November where the length of day light is lower than October, also because in December we identified an absence period of occupants. **Figure 38** outlines the evolution of the global horizontal illuminance and the light-on in the various spaces of the apartment during ten days in November. The several charts affirm that the majority of the light-on are observed where the illuminance is equal to zero, more specifically just after the end of the day. During this period, the exterior illuminance starts to decrease around 5:00 p.m. and the sunrise is around 5:30 p.m. This observation corresponds to the previous analysis where the arrival time was identified as one

of the main drivers affecting the lighting use in the apartment. Some few observations of the light-on were detected also before the start of the day where the need of visual comfort is also present. **Figure 38** illustrates that the long duration of lighting use was detected in kitchen and in the living room (stay).

III.4.4 Analysis of lighting use drivers in summer season

III.4.4.1 Contextual drivers: Time and type of the room

Based on the same approach presented in the previous section III.4.3, the primary observations confirm an identical frequency of daily light use in **bedrooms**, except in bedroom 2 the frequency in the time slot of 00:00 p.m. to 2:00 p.m. is higher than the evening time slot (7:00 p.m. to 00:00 a.m.)

In summer the sunset in the city of Lyon (France) is around 9:00 p.m. and we suppose that the visual need is not considerable in the time slot of 2:00 p.m. and 7:00 p.m. However, this time slot presents the higher daily use frequency comparing to others. Due to the relevance of the arrival time as driver identified in the literature, an additional analysis dividing the time slot of 2:00 p.m. - 7:00 p.m. into two categories is necessary to understand where the lighting use is more present and when the arrival time (starts at 5:00 p.m.) is the main factor affecting the lighting use in this time slot. In bedroom 2, the same frequency of lighting use is observed after and before 5:00 p.m. Regarding **bedroom 1** the higher frequency of lighting use was detected from 2:00 p.m. to 5:00 p.m. and the supposition of the arrival time as main driver is not valid. Contrary to **bedroom 3** where 60% of the lighting use is revealed after the arrival time from 5:00 p.m. to 7:00 p.m.

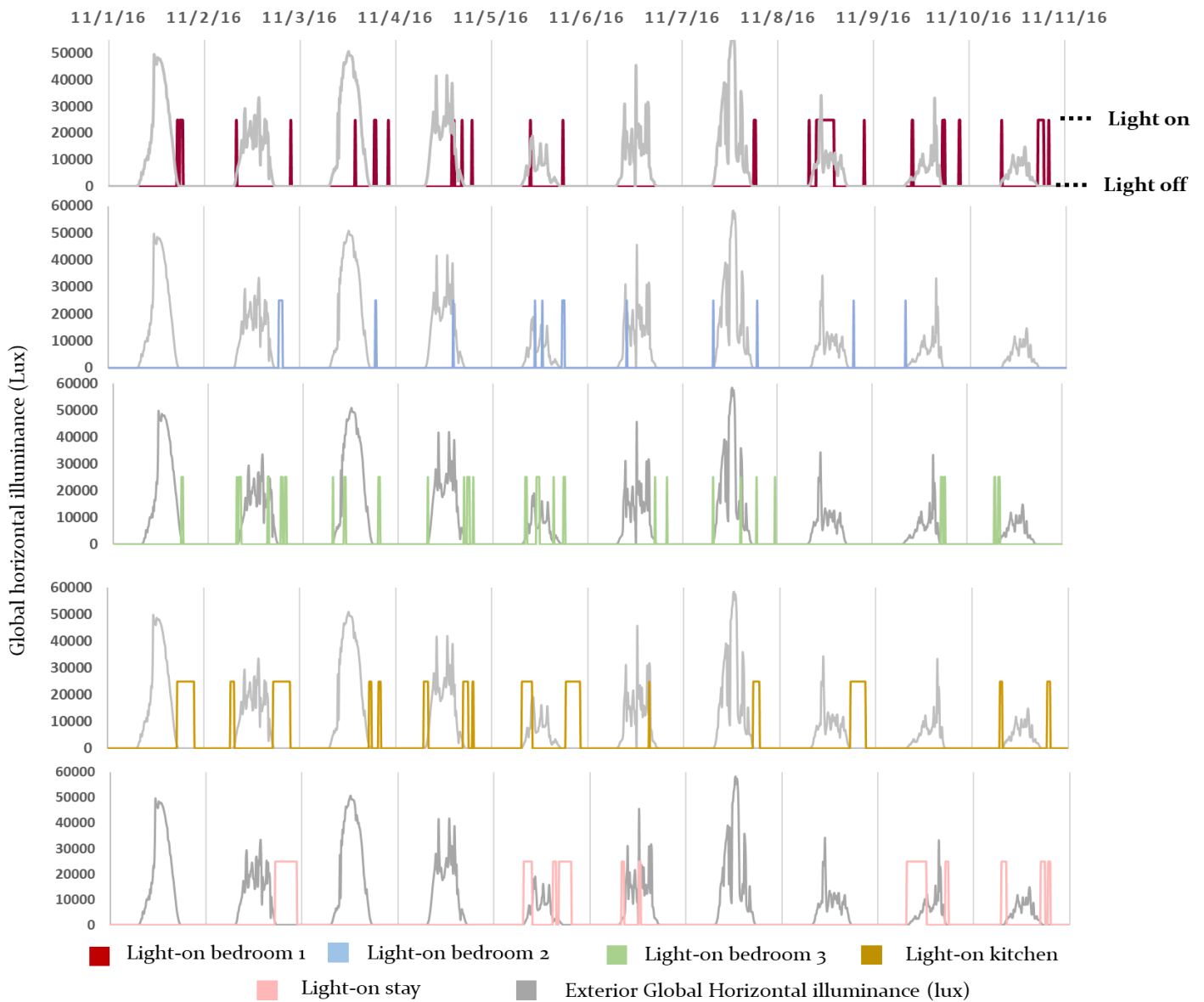


Figure 38: Correlation analysis of artificial lighting use and exterior illuminance in the period of 11/01 to 11/10 in the various spaces of the apartment (winter).

The routine day of the occupants is an important information to perform complete conclusions. The workers, the occupants who are unemployed and the presence of children attending school could provide more explanation about these observations. In addition, it should be noted that the frequency of lighting use is doubly higher in winter than in summer in this time slot. The duration of the lighting use is also less important than winter with a maximum duration of three hours and 20 minutes detected on the 1st of August in bedroom 1 and classified in the same order as the daily frequency presented in **Figure 39**.

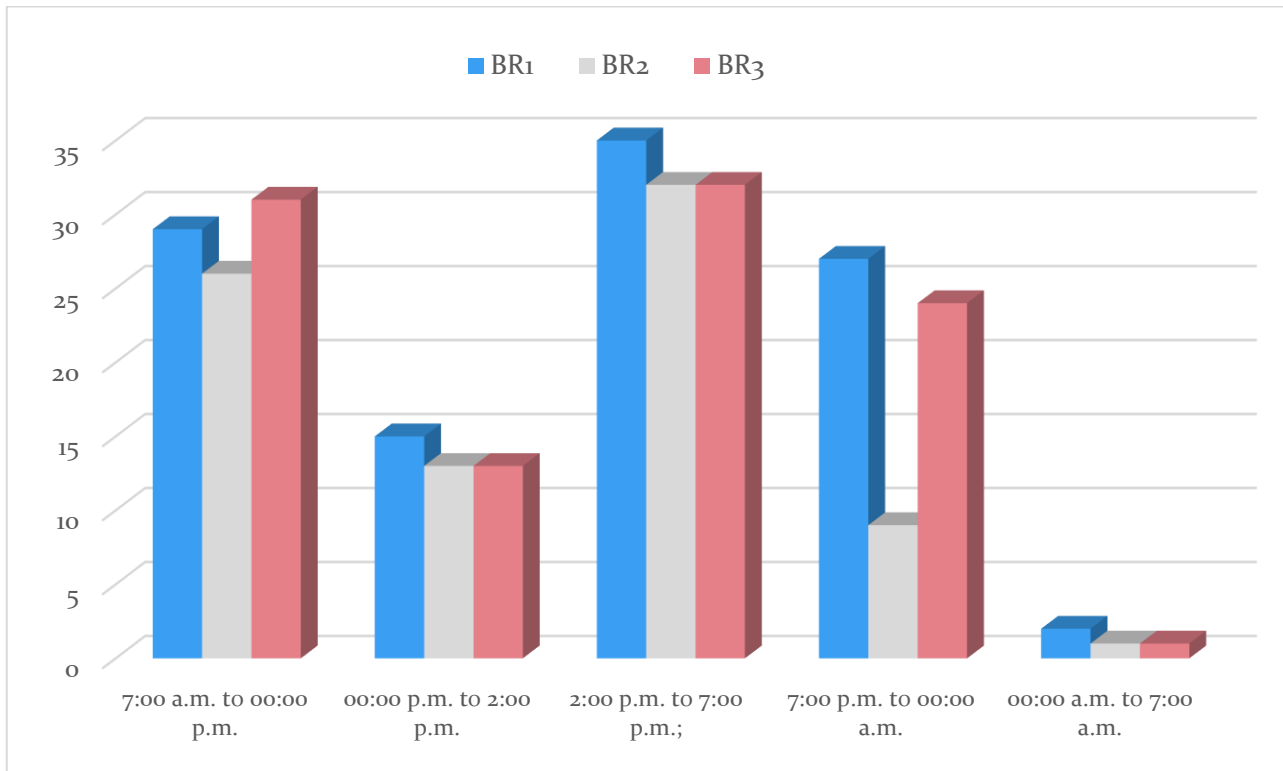


Figure 39: Artificial lighting use in the bedrooms according to each time slot (summer).

The month of July was characterized by a higher frequency; almost 50% of the daily lighting use compared to other months. In bedroom 1 we identify more days of lighting use in June than in bedroom 2. Contrary to August, only 22% are detected as the maximum frequency of daily use in the three bedrooms. In this context, the absence for summer holidays is a factor explaining this low frequency.

The higher frequency of lighting use in **living room** in summer was observed in the time slot of 7:00 a.m. to 00:00 p.m., followed by the time slot of 2:00 p.m. to 7:00 p.m. The majority of the observations were identified by sensor 1. The few observations of the lighting use of sensor 2 matches the same order as sensor 1 in daily lighting use frequency. The type of space reflects the specific activity related to it and the time slots where the occupants use mainly the living-room are presented in the **Figure 78** and Appendix A. June and July were characterized by the majority of the use of lighting and where the duration was superior than one hour.

Regarding the **kitchen**, three sensors were installed to measure the lighting use as presented in **Figure 40**. Sensors 1 and 2 were the sensors with the highest utilization, especially in the time slot of 7:00 p.m. to 00:00 a.m.(evening) followed by the time slot of 7:00 a.m. to 00:00 p.m. The month of July was characterized by a higher frequency of lighting use followed by June. The long duration in the summer was considered negligible compared to that in winter.

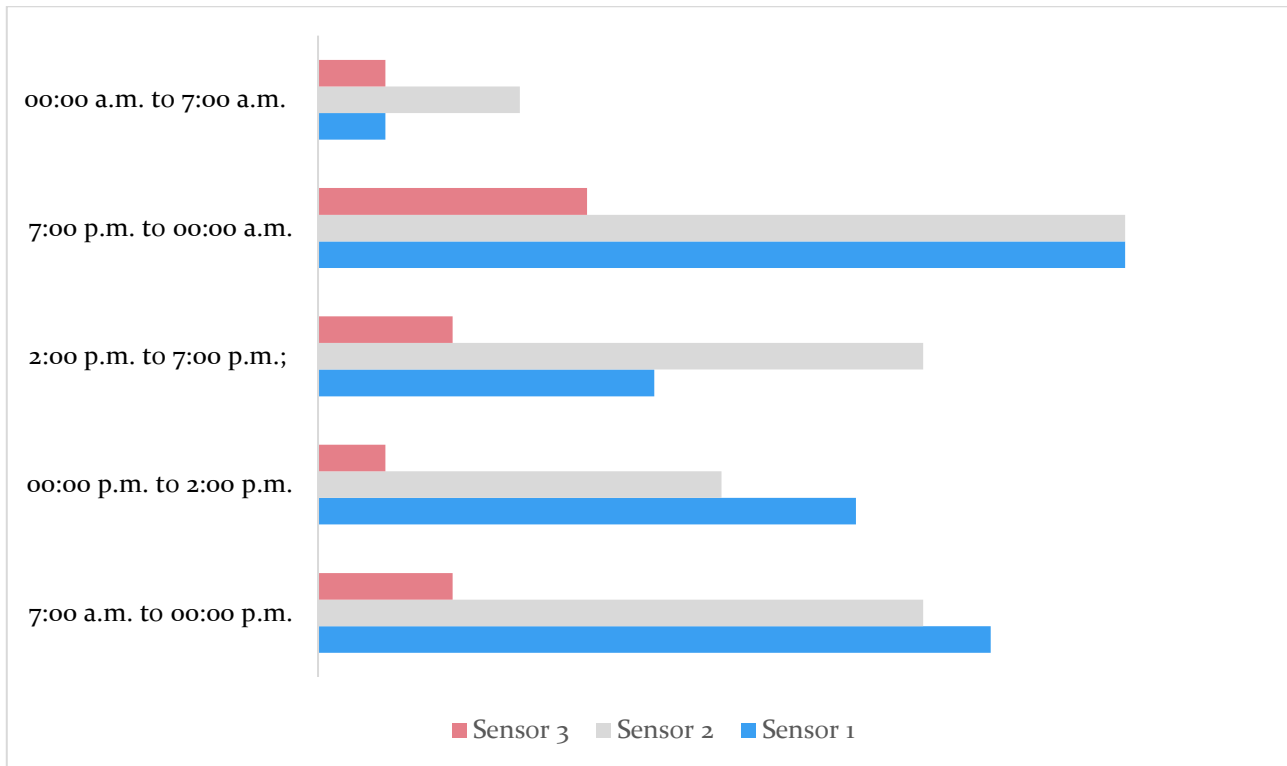


Figure 40: Artificial lighting use in the Kitchen according to each timeslot for summer.

III.4.4.2 Environmental drivers

Similarly, to the analysis of winter season, **Figure 41** shows an analysis between exterior **global horizontal irradiance** on the period of 06/05 to 06/14. The selection of this period and global horizontal irradiance was identified according to the availability and the quality of data. In summer some missing data were identified which limits the choose of the analysis period.

The observations in this study demonstrate that the majority of light-on were at the end of the day where the need of visual comfort increases. Some interactions were detected during the day with different frequency between the spaces. No specific correlation was detected regarding the lighting use during the day and the exterior illuminance. In the analyzed period, the sunset starts around 9:00 p.m. in Lyon, and the multiples light-on were observed in bedroom 1 and 2, compared to the living room (stay) and kitchen where the use of artificial lighting is not intense. The routine day, the presence of all the occupants as well as the technical information of the various spaces could justify more this frequency of daily lighting use.

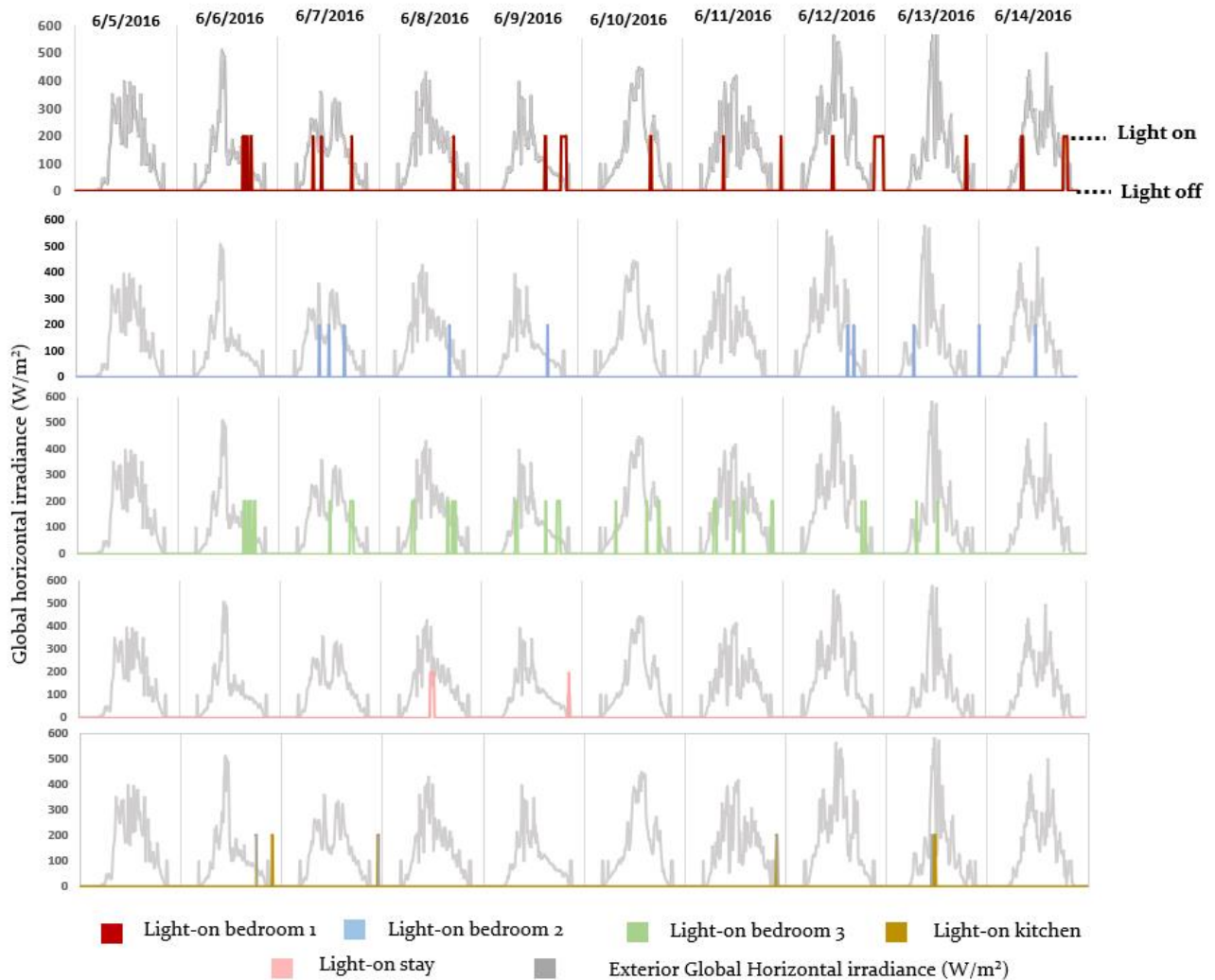


Figure 41: Correlation analysis of artificial lighting use and exterior illuminance in the period of 06/05 to 06/14 in the various spaces of the apartment (summer).

III.4.5 Results & discussion

The analysis of the light-on in the apartment studied was divided into two periods of the year (winter and summer) since the environmental parameters are more influencing on the occupant's behavior. Accordingly, the main objective is to study the drivers affecting the lighting use in the two seasons based on the parameters available in the database. The results show that the occupant interaction with lighting is mainly due to:

1. Arrival and departure time;
2. Exterior illuminance and length of the day;
3. Day routine and occupant's habits;
4. Type of space (activity in each space that impacts the duration of the light use).

The drivers were the same for the two seasons, but the frequency and the duration of the lighting use in summer was lower compared to winter where the day length is short and the need of visual comfort is higher.

III.5 General assessment of the monitoring activity of this case study

The monitoring activities are considered as a functional process in the assessment of projects effects, especially where original solutions are integrated and where the investment is important. In this case study, as presented in Chapter II several technologies and solutions were included in the development of this smart residential building. Accordingly, an important supervision of several parameters was elaborated.

The relevant conclusions about *the occupants' interaction with windows* and the drivers affecting this interaction led us to think about the utility to obtain additional data in order to increase the accuracy of the analysis. The openings of windows in winter are not similar to the summer. The main drivers of windows' openings in winter are presented in a personal need to refresh the rooms at wake-up time, room type and time of day. In this context, it is important to search more about other drivers as the cultural, physiological, economic and social drivers to complete the analysis and explain the other aspects that can justify the openings in the other times of the day, and the difference of frequencies between the rooms. The absence of technical details about the position and orientation of windows limits the complete analysis of the reasons about windows' openings in that space at a specific time. Similarly, the presence of more than one window in a space and the opening of one window more frequently than other reflects a personal preference, and reflects some advantages of the emplacement and the size of the opened windows. In summer, it will be important if the details of room occupancy are provided to further analyze the need of night ventilation in the three bedrooms (e.g., whether the room is occupied by one person or more). Thus, it is important to highlight again that an occupant interaction could depend on several factors, not only one, which provides a strong connection between the personal human factors and the technical factors influencing the occupant energy behavior.

To analyze the drivers affecting the windows openings especially in winter, a time step of **10 min is not accurate**. The exterior conditions in this period are hard and the duration of the opening could be sometimes less than 10 minutes. Otherwise, some short openings are also probable in summer season. However, this remark leads us to rethink about the definition of the occupant behavior, and whether an interaction less than 10 minutes is considered as an important interaction that affects the building energy performance.

Regarding the *thermostat modification*, the data collected for this analysis were sufficient to provide several conclusions and suppositions. However, to complete the analysis other information are required, such as: technical information about the rooms (emplacement, orientation), routine of the occupants and the level of understanding of the role of the thermostat. The qualitative data about the occupants could be difficult to reach and gather, but the quantitative data about the apartments and the tools installed are mandatory to build a comprehensive conclusion.

One of the issues to analyze completely the occupant's set-point of temperature regulation is the information about the type of thermostat exploited in the apartment. If the thermostat

proposes a self-regulation, the analysis should consider and eliminate the self-regulation programmed by the tool. In the observation of the temperature regulation, some modifications were done in the midnight which could reflect a self-regulation. For this reason, the midnight modifications weren't taken into consideration in this study.

The modification of the set-point temperature doesn't provide a direct sensation of the temperature desired by the occupants. As shown in **Figure 79**, the set-point temperature and the real indoor temperature represent a gap that varies from 1°C to 4°C. This difference depends on several factors as the ventilation and the type of heating system. The assessment of the interior thermal comfort by the occupant's is changeable and the modification of the set-point temperature is generally not a daily interaction. For this reason, the time step of 10 min is assessed as an acceptable time step to analyze the drivers of the occupant thermostat interaction.

For the analysis of the **lighting use**, it is concluded that the main two drivers are the presence of the occupants in the apartment (arrival and departure time) and the natural daylight. The presence of qualitative data to confirm the routine day is considered as a valuable input to approve the reached conclusions. In addition, the technical information about the space, especially the orientation, window size and the presence of exterior barriers that limit natural light to enter are also important data to analyze the lighting use from all sides. The objective is to gather all the data possible to justify the frequency of the daily lighting use.

By analyzing the data collected for the light-on and the lighting power (**Figure 80**), it is deduced that the installation of a lighting power sensor can replace the light on/off sensor if the objective is to detect when the lighting is on, and to understand the drivers of this interaction.

The data exploration of the windows, thermostat and lighting interaction provide a pertinent conclusion about the drivers affecting these interactions and the frequency use. Moreover, the connected analysis of these interactions could provide an additional information about the routine day, the absence period (as presented in **Figure 79** an absence is identified in the last days of December) especially if these absences/presences are confirmed for all the spaces. In this respect, the motion data could be exploited to complete this analysis, however the limit of these measures consist on the only detection of the occupant's movements that affect the accuracy of the information targeted, then we cannot know whether the occupant is still in space without moving or is absent.

III.6 Conclusion

The most complexity of the occupant behavior study comes from the multiplicity of the parameters and variables that should be taken into consideration. In this research, the monitoring approach implemented in the smart residential building represents various data that provide relevant measures about the energy occupant behavior. The windows opening, thermostat use and light-on were the three aspects targeted for this research section.

To proceed to the analysis of a database, it is essential at first to establish the final objective of the study. The description of the occupant behavior, the analysis of the drivers affecting the behavior and the assessment of data collected on a residential smart building are the principal purposes of this chapter. Accordingly, the extraction of pertinent information based on the measured parameters is the main key of the analysis. For that purpose, we employed the methodology of Knowledge Discovery in Databases in order to:

- 1) Select the convenient parameters to study for each interaction with the period targeted;
- 2) Prepare, clean and organize the data;
- 3) Analyze the data by focusing on the time dimension and the environmental factors;
- 4) Highlight the main correlation and discuss the drivers detected for the three interactions studied.

The windows interaction was influenced by the season, where the openings in summer are very important than in winter. The day time connected to the room type plays also a crucial role. The majority of the windows' openings in the rooms are identified in the morning which reflects a personal routine and need. The kitchen was characterized by important frequency of windows opening due to the cooking activity that requires more ventilation. In the living room, the use of windows is more affected by presence time in the space. The interior and exterior conditions are an important factor affecting the frequency of windows' openings in summer, contrary to winter where the outdoor temperature could present a factor to not open the windows. In summer, the occupants need more ventilation, they also avoid the heat waves. For this reason, the night ventilation and the early openings are privileged.

The analysis of set-point regulation is affected mainly by the type of space. The thermal comfort need is more important in the spaces where the occupants are present the most (bedrooms). Then, the decrease of the outdoor temperature (season transition) creates a need to assure the thermal comfort which affects automatically the thermostat use and the regulated temperature. The personal preferences and technical information about the spaces could explain more the thermostat use in the various spaces. Regarding the lighting use, the main drivers affecting the occupant's interaction with artificial light are: day time (departure and arrival), exterior illuminance, type of space that also reflects the presence in a space. The study of this interaction shows that the drivers are identical for the two seasons, but the frequency of lighting use in the winter is very high compared to the summer due to the low exterior illuminance in winter.

Based on the analysis of the drivers affecting the occupant behavior, it is deduced that the connection between several parameters is indispensable for the study. One of the additional outcomes from a connected analysis is to identify the scenario of presence and absence, especially for the longer period. Moreover, the necessity to link the measures collected with the technical information of the space measured are also crucial to provide a complete analysis. To confirm all the outcomes of the analysis, the qualitative data collected from surveys and questionnaires could be very useful.

The assessment of the time step recommended for the various parameters depends mainly on the objective from the measures. A deep analysis of the several aspects of ventilation and lighting could require a time step less than 10 minutes. Contrary to the thermostat use, the interaction is not daily and 10 min is highly sufficient to detect the set-point regulation. In addition, it is deduced that the sensors of power lighting and light on/off provide an identical description of the light use and the installation of one of them is sufficient.

The following diagram represents a synthesis of the Chapter outcomes (*Figure 42*)

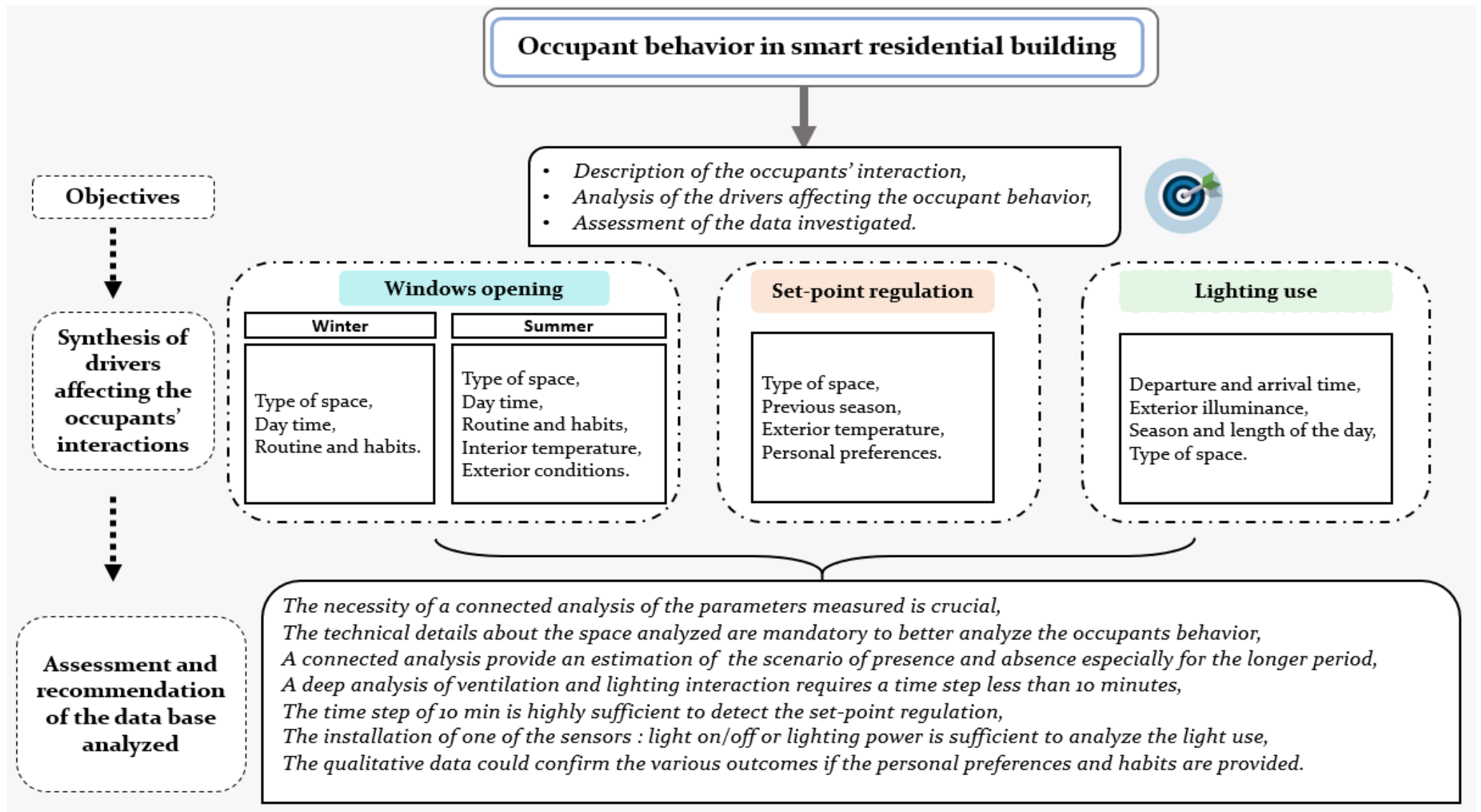


Figure 42: Synthesis of the occupant behavior analysis in smart residential buildings.

CHAPTER IV

Data - driven analysis

Comparative analysis of occupant's energy use in private and social residential building



Chapter IV: Data-driven analysis

Comparative analysis of occupant's energy use in private and social residential building

IV.1 Introduction

The energy use in residential buildings reflects a certain pattern of occupants' interaction with their environment. These interactions are divided into several types and levels depending on the type of systems presented in the houses and used by the occupants. The previous Chapter focuses on the analysis of occupant behavior in a smart residential building where direct measures about the occupants' interactions with windows, thermostat and lighting were provided. By contrast, the data base exploited in this Chapter provides energy data that which represents the energy consumption in the houses, and indirectly indicates the occupant's interactions. In this case, a different approach should be adopted to successfully meet the challenge of analyzing the occupant behavior based on the energy data consumption.

The first analysis study presented in this Chapter will concern the data collected from PREBAT project, which represents the second typology of building investigated in this research: private building (Chapter II, section II.3). Based on the data collected, three interactions will be explored: lighting use, heating-use and general electricity consumption during the winter and summer season.

The third typology is a social housing and will be investigated and developed in the final section of this chapter. It aims to evaluate the energy consumption in residential building before and during the lockdown period. Based on the monitoring activity developed and represented in Chapter II (section II.2), a comparative analysis was performed in order to investigate the COVID19 impact on the use of lighting and heating and general electricity consumption. **Figure 43** represents the methodology framework of this chapter.

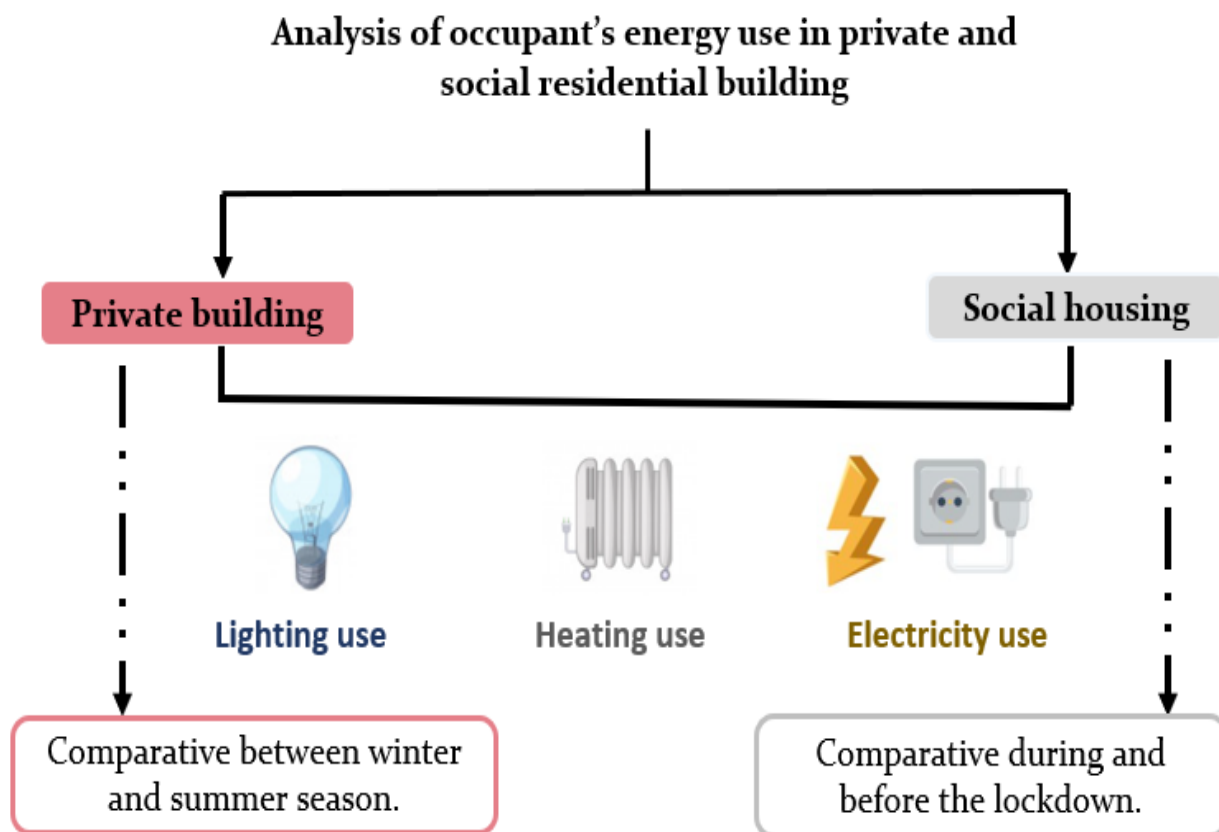


Figure 43: Methodology framework of Chapter IV analysis.

IV.2 Occupant's energy use: lighting use

Light is one of the important necessities in our daily life, and has a profound effect on its quality. In residential sector, the energy consumption related to the lighting use represents 12% of a household's electricity consumption [111]. The annual energy consumption of office buildings is around 6 TWh/year [112] implies the implementation of energy saving potentialities. Thus, to develop and recommend the best strategies for lighting use optimization it is essential at first to understand how this lighting is used, and what main drivers are affecting the occupants' interactions with artificial light. This analysis was initiated in the previous Chapter and will be continued in this section in the case of private buildings.

The analysis will highlight the energy use in winter and summer seasons for two apartments of PREBAT project (LES GENTIANES case study). Based on the parameters identified in the data base, the analysis will include the day time observation to provide an overview of the lighting use. Besides, the exploration of sunlight meter will be integrated to better understand the impact of daylight on occupant's interaction with artificial lighting.

IV.2.1. Methodology of analyzing lighting use in LES GENTIANES case study

To evaluate the lighting use in 'LES GENTIANES' case study, the general process is divided into three main steps: 1) Analysis of the occupant's lighting use, 2) Analysis of the drivers affecting the lighting use, and 3) Interpretation of the results and recommendations.

The Knowledge Discovery in Databases has been exploited continuously in this chapter. The measures provided in ‘LES GENTIANES’ case study are mainly energy consumption data. These types of measures necessitate an indirect reflection to reach a relevant conclusion about the occupant’s interactions, especially when the consumption is general and no specification by space is provided. According to the data collected, this research section will be conducted during winter and summer seasons in order to assess their impact on the lighting use. The parameters selected for the development of this study are the hourly lighting meter, that is, time day and exterior solar radiation. On the basis of the three processes presented in **Figure 44** and developed in this part of research, a comparative analysis will be carried out with the view to analyze the differences in lighting use for two apartments located in the same building.

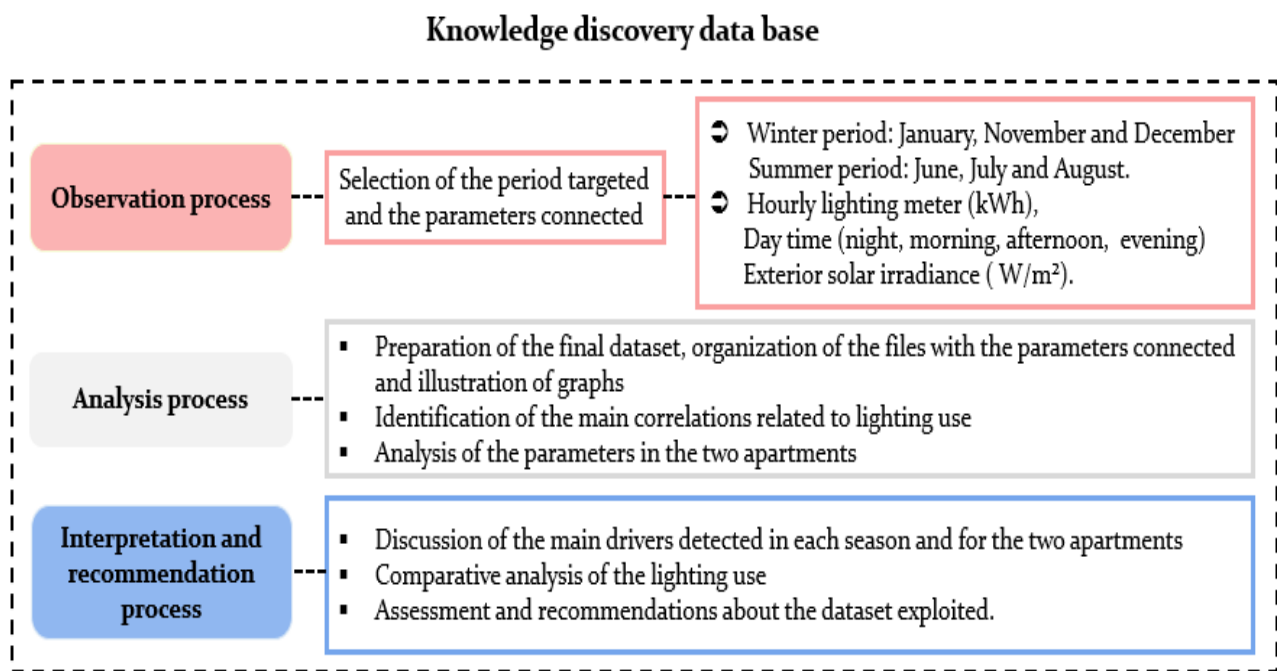


Figure 44: Technical framework of lighting use analysis in ‘LES GENTIANES’ case study.

IV.2.2 Analysis of lighting use in winter season

In this section, the hourly lighting meter measurements in daily winter season were exploited for the analysis. **Figure 45** shows the evolution of the daily lighting consumption for the first 10 days of the three months representing winter season, however the analysis was carried out for all the period targeted. The analyzed measurements represent a general consumption of the apartments, and no direct measures about the lighting use in each space were provided. Consequently, the analysis of the lighting use in the rooms cannot be analyzed, and the estimation of the occupant’s presence in spaces cannot be predicted by these types of measures.

The exploration of this section will be based on the hourly lighting meter measurements in daily winter season. **Figure 45** shows the evolution of the daily lighting consumption for the first 10 days of the three months representing winter season. The analyzed measurements

represent the consumption for the entire apartments. In these apartments no direct measures about the lighting use in each space are provided. Consequently, the analysis of the lighting use in the rooms cannot be analyzed, and the estimation of the occupant's presence in spaces cannot be predicted by these types of measures.

IV.2.2.1 Contextual driver: Time of day

The analysis of the contextual drivers focuses mainly on the frequency of lighting use according to the time slots defined in the methodology (section IV.2.1, **Figure 44**). The three months representing winter season were analyzed based on the peaks superior to: **0.2 kWh** detected in apartment 1, **0.3 kWh** identified in apartment 2 in each time slot, and **1 kWh** as superior threshold for both apartments. These threshold values were specified based on the lighting meter analysis between the two apartments where we identified that the values/peaks superior than 0.2 kWh are the most significant to analyze for apartment 1 (0.3 kWh for apartment 2). The same analysis was performed for the selection of the threshold identified in the following analysis of this chapter.

Apartment 1 was characterized by a higher frequency of lighting use in evening from 6:00 p.m. to midnight (**55%**). This time of day could correspond to the arrival time of occupants and sunset time in the winter. In the evening, 25% of lighting use frequency were detected, followed by 17% in the morning (**Figure 46**). To better assess the lighting use patterns, the general frequency analysis was divided into two categories of lighting use: 1) during the weekdays, and 2) over the weekend. The weekdays represent more use in the evening and afternoon, contrary to the weekend where the lighting use varies during the day. Thus, 74 % of the general lighting use in the evening were identified during the weekdays, which confirms the suppositions of the arrival time considered, contrary to the weekend, when no fixed schedule could be supposed. Regarding the morning and night use, 75% of the frequencies detected are observed in the weekend. The partitioning of lighting use in the afternoon shows approximately the same percentages for both weekdays and weekend with a minor increase during the weekend (**Figure 81**, Appendix B).

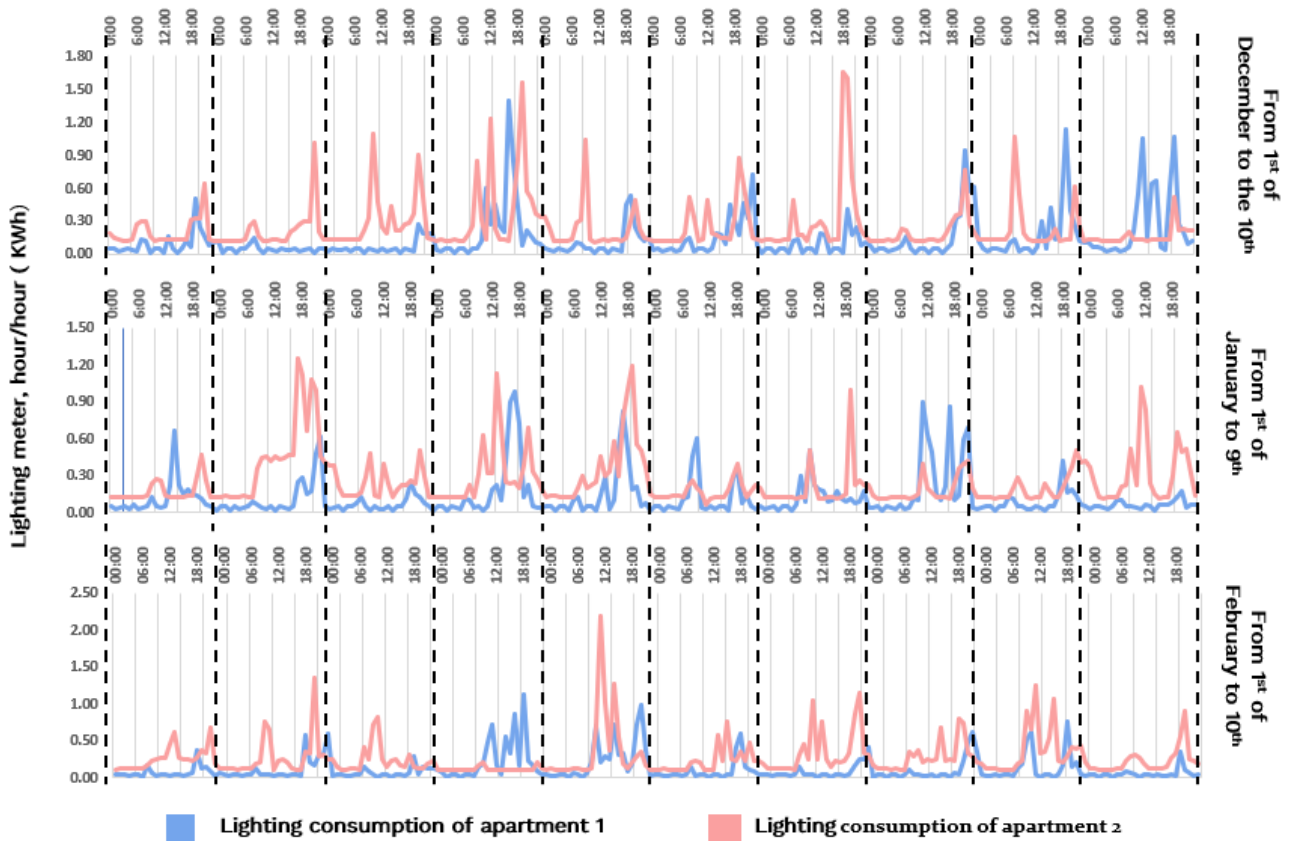


Figure 45: Lighting consumption in winter season for the LES GENTIANES case study.

The comparative analysis of the lighting use in weekdays and weekend separately gives an idea whether the occupants have a routine during the week. The detected lighting use in the evening with the highest frequency and during all the weekdays in apartment 1 proves that the majority of the occupants are absent during the day, and we could suppose that they have a fixed departure and arrival time.

By analyzing the peaks superior to 1 kWh independently, apartment results 1 show a 60% of the peaks in December when the sunset is around 5:00 p.m. in the city of Lyon. Conversely to apartment 2, the peaks superior to 1 kWh are multiples and distributed almost equally between December, January and February. The majority of peaks superior to 1 kWh were detected in the weekends in apartment 1. Regarding apartment 2, 75% of these peaks are represented during the week, and 8:00 p.m. is the time with higher number of peaks superior to 1 kWh.

Apartment 2 represents practically the same percentages of the frequency lighting use in morning from 7:00 a.m. to 12:00 p.m. (42%) and in evening from 6:00 p.m. to 11:00 p.m. (39%) with a minor increase in the morning, followed by the afternoon which represents only 17 % of peak frequency (**Figure 46**). The analysis division of both weekdays and weekend reveals that the peaks are predominantly presented during the weekdays with a percentage superior to 68% for all the time slots analyzed (**Figure 81**, Appendix B). The presented percentage during the week, both in morning and evening doesn't reflect a supposition of a fixed departure and arrival time. The lighting use in the morning indicates certainly the presence of one occupant or more all day long. In this respect, the qualitative data play an important

role to understand the nature of the occupant’s daily life (workers, retired, presence of children and babies etc.) that influence necessarily the occupant’s presence time and the lighting use.

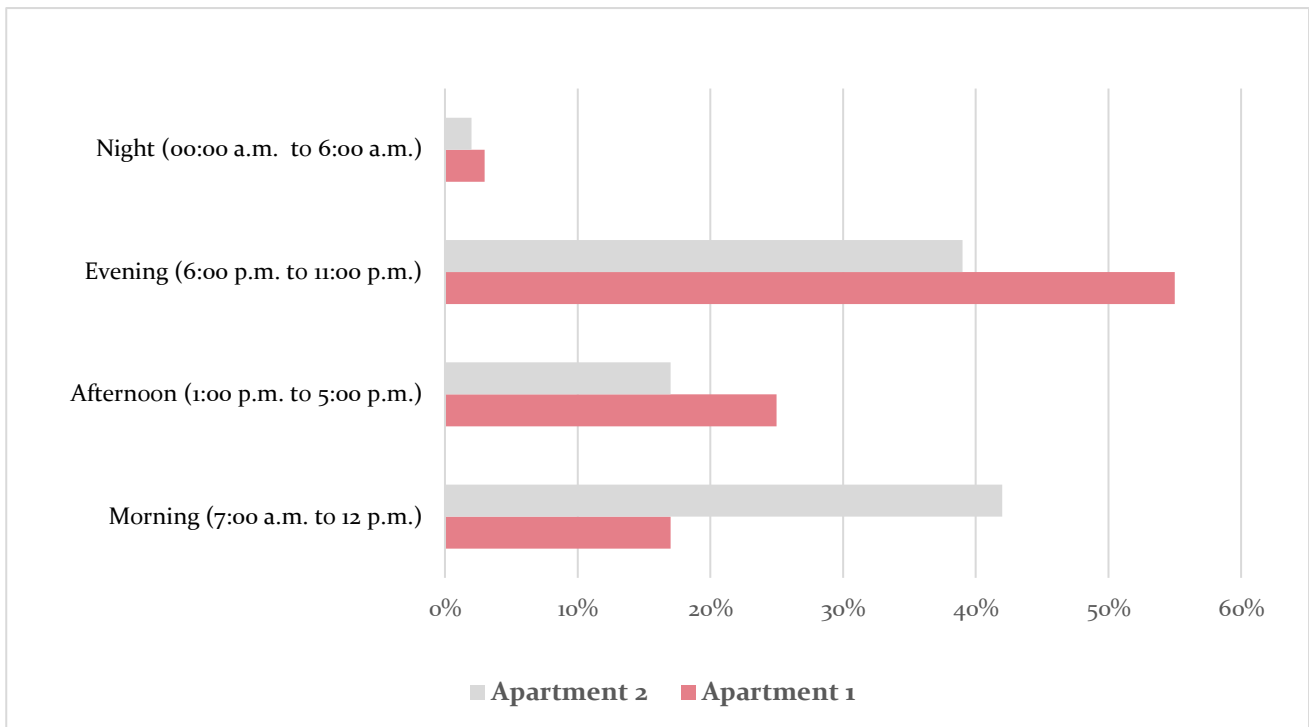


Figure 46: Peaks frequency of lighting use in winter according to time day for apartment 1 and 2 for the “LES GENTIANES” case study.

It is noticed that the peaks superior to 1 kWh are 80% higher in apartment 2 in comparison with apartment 1. This difference is due mainly to differences in surface (apartment 2: 81 m², apartment 1: 56m²) which could implicate a higher number of occupants and consequently an increase of lighting needs. As shown in Figure 45, the lighting consumption in apartment 2 is more important than apartment 1.

IV.2.2.3 Environmental driver: exterior solar irradiance

The impact of daylight on the use of artificial light was confirmed in the review presented in “Chapter III, section III.4.1”. The database of ‘LES GENTIANES’ case study provides hourly measures of exterior solar irradiance (W/m²) that will be exploited in order to analyze its connection between the peaks of lighting use in the analyzed time slots. Table 16 represents the average exterior solar irradiance per time slot during the three months representing winter season. Accordingly, we can conclude that **apartment 1** uses artificial light mainly when the exterior solar irradiance is between 43 W/m² and 62 W/m². Similarly, for the peaks superior to 1 kWh, 60 % of these peaks were identified when the exterior solar irradiance is around 45 W/m².

Regarding apartment 2, the use of artificial light is higher also in the morning when the exterior solar irradiance exceeds 204 W/m². Moreover, the peaks higher than 1 kWh in **apartment 2** were analyzed according to exterior solar irradiance, it was observed that 25 %

of these peaks were identified during the day when the exterior solar irradiance is between 200 (W/m²) and 700 (W/m²). In this case, when no technical information about the orientation and the emplacement of the apartment is provided it is not possible to give a final interpretation. More investigation is required to see if natural daylight is limited by an exterior barrier, and whether the occupants benefit from it. Otherwise, the lighting use at this time could be a personal preference and it might not be affected by any exterior drivers.

Table 16: Average of exterior solar irradiance per time slot in winter season.

	00:00 a.m. to 6:00 a.m.	7:00 a.m. to 12 :00 p.m.	01:00 p.m. to 6:00 p.m.	07:00 p.m. to 11:00 p.m.
December	43.62 (W/m ²)	93.21 (W/m ²)	156.39 (W/m ²)	43.03 (W/m ²)
January	49.22 (W/m ²)	137.70 (W/m ²)	201.95 (W/m ²)	49.37 (W/m ²)
February	66.15 (W/m ²)	204.33 (W/m ²)	329.94 (W/m ²)	61.72 (W/m ²)

IV.2.3 Analysis of lighting use in summer season

Similarly, the analysis of this section will focus on the similar thresholds of peaks investigated in winter season.

IV.2.3.1 Contextual driver: Time of day

Figure 47 represents the evolution of lighting consumption in the first ten days of the three months representing summer period for the two apartments while the results were based on the analysis of the total period. The peaks in apartment 1 are more frequent in the evening with a percentage of 43%, and in the afternoon with a percentage of 36%. The peaks in the morning are around 18% and at night 3%. In addition, another representation of the number of peaks is realized according to the time of day. For **apartment 1**, the weekdays represent the majority of peaks from 6:00 p.m. to 10:00 p.m., contrary to the weekend during which the lighting peaks are randomly represented, but with more peaks at 10:00 a.m. and 7:00 p.m. as shown in **Figure 48**. The drivers affecting the use of artificial lighting in the weekdays and weekend are parallel with the ones estimated in the analysis of winter season. The routine of day, presence and absence, arrival and departure time have a crucial role in the use of light in apartment 1.

The investigation elaborated for the peaks superior to 1 kWh reveals that the higher amount of lighting energy consumption is observed during the weekend and on August 15, public holiday. Apartment 1 confirms that the rest/vacation days necessitate more presence and increase the need of lighting use. Moreover, it is deduced that the peaks superior to 1 kWh are decreased by 50% in summer.

In apartment 2, the lighting use and peak variation are various and different compared to apartment 1. Indeed, in this case, 37% of peaks were detected in the evening, followed by 34

% in the morning and 29 % in the afternoon. The latter shows that the frequency of lighting use of peaks is almost the same for all the time slots with a minor increase in the evening. However, the frequency analysis according to the weekdays and weekend reveals that 70 % of lighting use and frequency of peaks are represented during the weekdays as shown in **Figure 82** (Appendix B).

The analysis of numbers of peaks in apartment 2 shows that the higher number of peaks is detected during the weekdays in the morning at 9:00 a.m., followed by the evening at 08:00 p.m. **Figure 49** also shows that during the weekdays other peaks are detectable at 11:00 a.m., 01:00 p.m. and at 10:00 p.m. In the weekend, the numbers of peaks are lower and varied. This analysis of peaks indicates a random pattern of lighting use in apartment 2. As concluded in the winter analysis, additional data could confirm the drivers of this lighting use. In conclusion, the occupants in this apartment 2 are more present during the weekdays in comparison with the occupants of apartment 1, which requires a higher need of lighting in the several time slots.

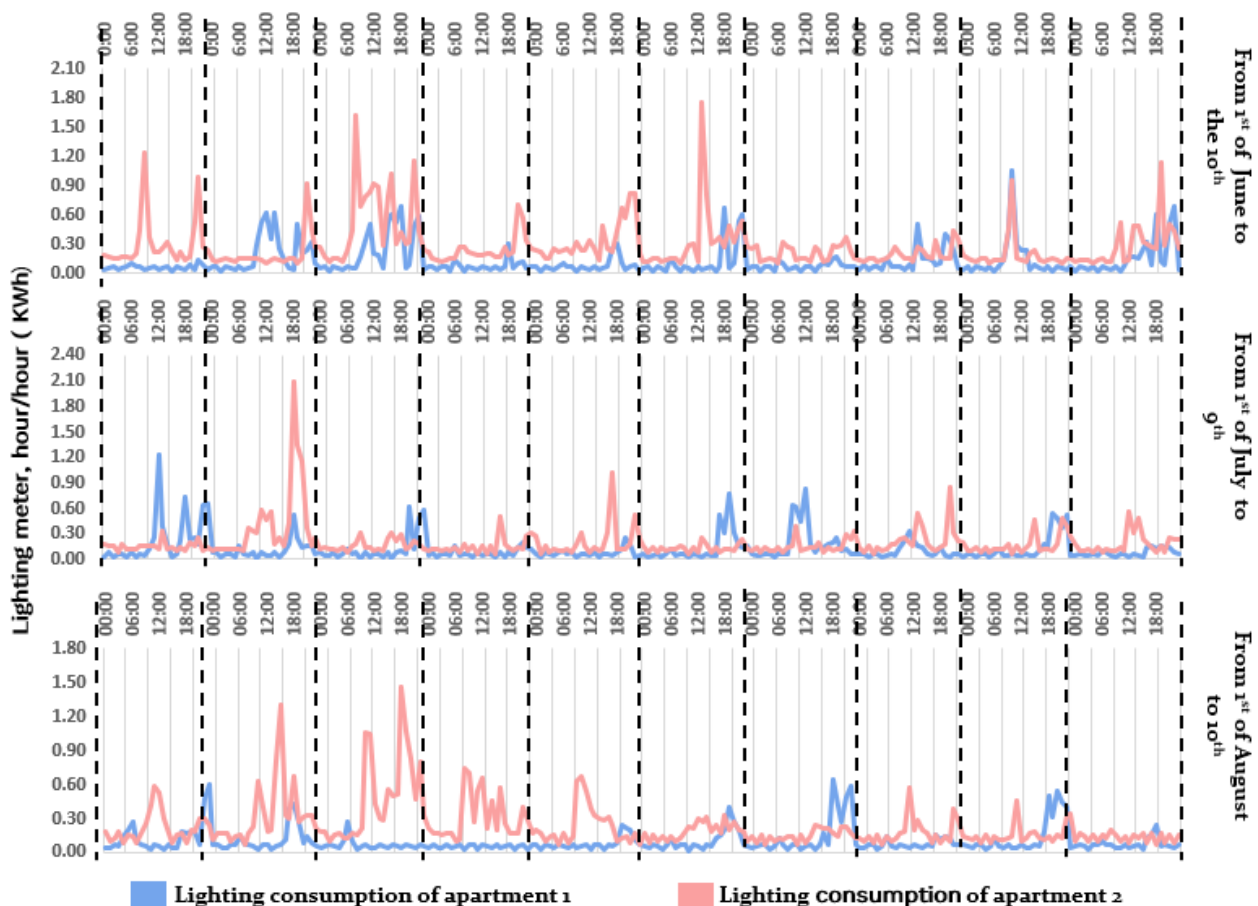


Figure 47: Lighting consumption in summer season for the “LES GENTIANES” case study.

In parallel, 62 % of the peaks superior to 1 kWh in apartment 2 were detected during the week. The highest number of these peaks was identified at 9:00 a.m. and 7:00 p.m. On July 2nd, the highest peak of 2.09 kWh was detected at 6:00 p.m. June represents almost 50% of the peaks superior to 1 kWh, followed by 34% in July. In apartment 2 the peaks superior to 1 kWh were decreased in summer by 58%.

IV.2.3.2 Environmental driver: exterior solar irradiance

For apartment 1, the frequency of lighting use is higher in the late evening during the variation of exterior solar irradiance is between 30 and 45 W/m². However, the higher number of peaks detected at 6:00 p.m. corresponds to an average of exterior solar irradiance around 233 W/m², which doesn't reflect a direct connection between the lighting use and the exterior solar irradiance.

By analyzing the exterior solar irradiance corresponding to 9:00 a.m. and 8:00 p.m. where the number of peaks is higher in apartment 2, it is concluded that the average of exterior solar irradiance in the morning (9:00 a.m.) is around 130 W/m², and in the evening around 92 W/m². Based on these observations, it is difficult to link the exterior solar irradiance to the lighting use patterns. Hence, the personal preferences and needs play a major role in summer.

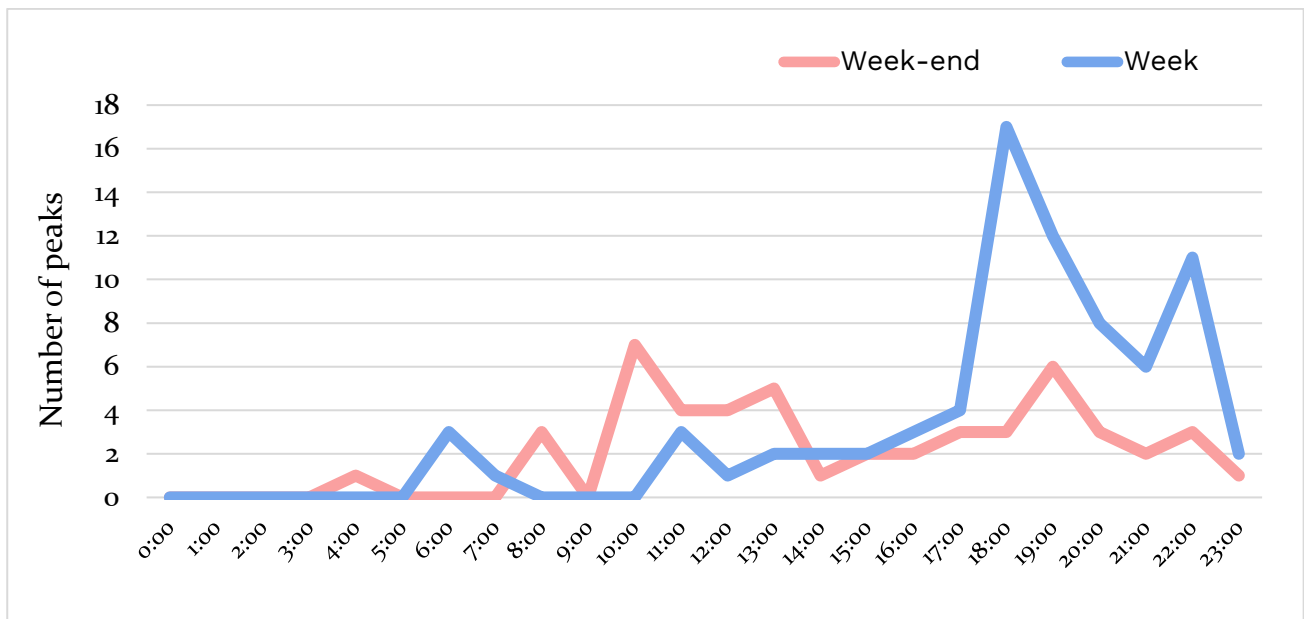


Figure 48: Number of peaks in apartment 1 during summer season, according to the time of day.

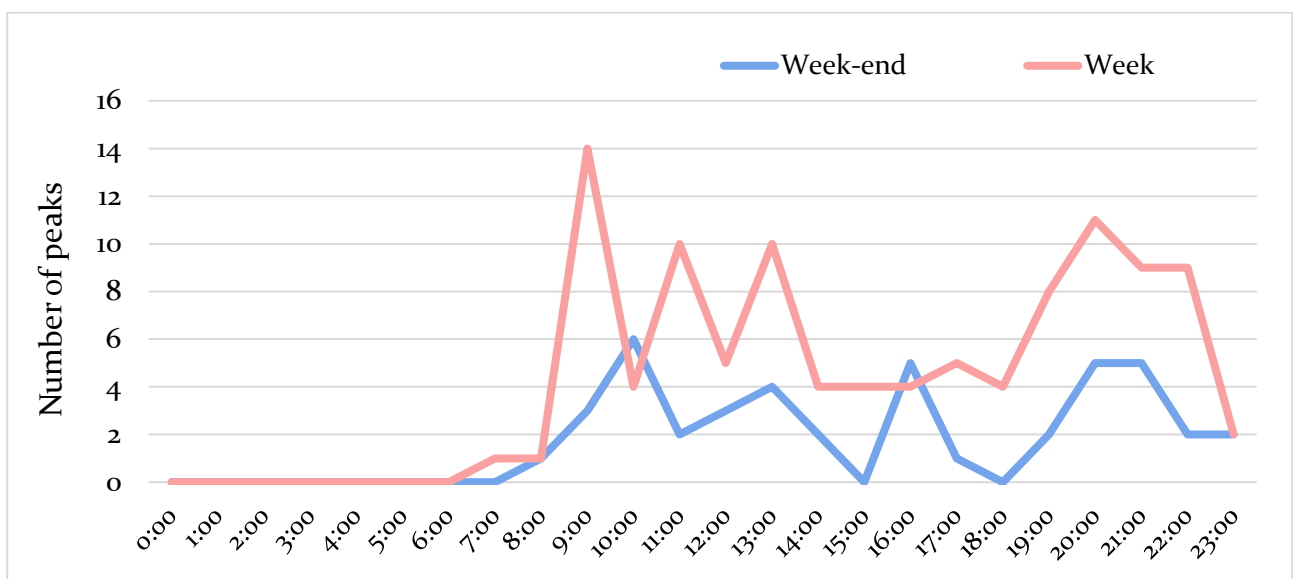


Figure 49: Number of peaks in apartment 2 during summer season, according to the time of day.

IV.2.4 Results & discussion

Based on the analysis developed above, two occupants' patterns were identified in terms of lighting use. The first occupant pattern was represented by apartment 1 where it is clear that the lighting use is impacted by the arrival and departure time (contextual drivers), and by the exterior solar irradiance (environmental drivers), especially in winter. The lighting use in this period is detected on a daily basis during the evening in the weekdays (arrival time). As well, the frequency of the lighting use is higher essentially when the exterior solar irradiance is inferior to 60 W/m^2 .

The second occupant pattern concerns apartment 2 where the frequency of lighting use is higher both in the morning and evening. The lighting use is also more important during the weekdays compared to the weekend. In this case, it wasn't possible to associate the exterior irradiance and departure time as drivers, especially when no details are provided about the benefit from the daylight and the occupant's routine. However, it is deduced that the occupants of this apartment don't have a fixed occupancy schedules during the weekdays.

By analyzing the peaks superior to 1 kWh in winter and summer seasons, 50% of peaks decrease was detected in summer. In apartment 1 the peaks superior to 1 kWh are presented in the weekend, contrary to apartment 2 where the weekdays represent the majority of these peaks.

The lighting use depends mainly on the occupancy presence. If a scenario of lighting use is repeated in a large period as the case of apartment 1 during the weekdays, we could propose a scenario of occupancy schedules. Nevertheless, the lighting use is unpredictable on the weekend for the two patterns. Thus, no occupancy schedules could be estimated.

The comparative analysis between apartment 1 and 2 is considered as a major process to learn about the possible variation of lighting use patterns. The difference between the occupants' patterns reflect the need to analyze and represent with more accuracy the occupant behavior.

IV.3 Occupant's heating behavior

The heating use in residential buildings represent around 65% of the final energy consumption in Europe [113]. The thermal comfort is one of the main issues in buildings, especially that its perception is perceived differently by the occupants. Thus, the development of personal comfort models is considered essential to improve the accuracy of the prediction of individual thermal comfort; such optimize the heating energy use [114]. At the same time, the understanding of the heating use patterns in residential building is a key issue to increase the analysis of building energy performance.

In parallel to the analysis presented in Chapter III (section III.3), this section will analyze indirectly the occupants' heating behavior by investigating the heating energy consumption in two apartments which are monitored in the context of 'PREBAT' project (AMPLIA case study) and presented in Chapter II.

IV.3.1 Methodology of analyzing heating use in AMPLIA case study

The descriptive analysis of heating consumption in these two apartments has been developed in the period from December to February. The parameters connected to the heating use are: the interior and outdoor temperature, exterior solar irradiance, and the set-point temperature. In order to generate a classification of the heating consumption according to the selected parameters, the approach of data mining clustering was adopted. The principle of clustering is to find similarities and generate groups in data sets. For this purpose, the K-means algorithm determined a set of k clusters and assigns each observation to a single cluster [115]. Based on the results of the Clustering, a comparison analysis of the thermal consumption relating to each apartment was presented during the winter period. **Figure 50** represents the general methodology adopted for the development of this research.

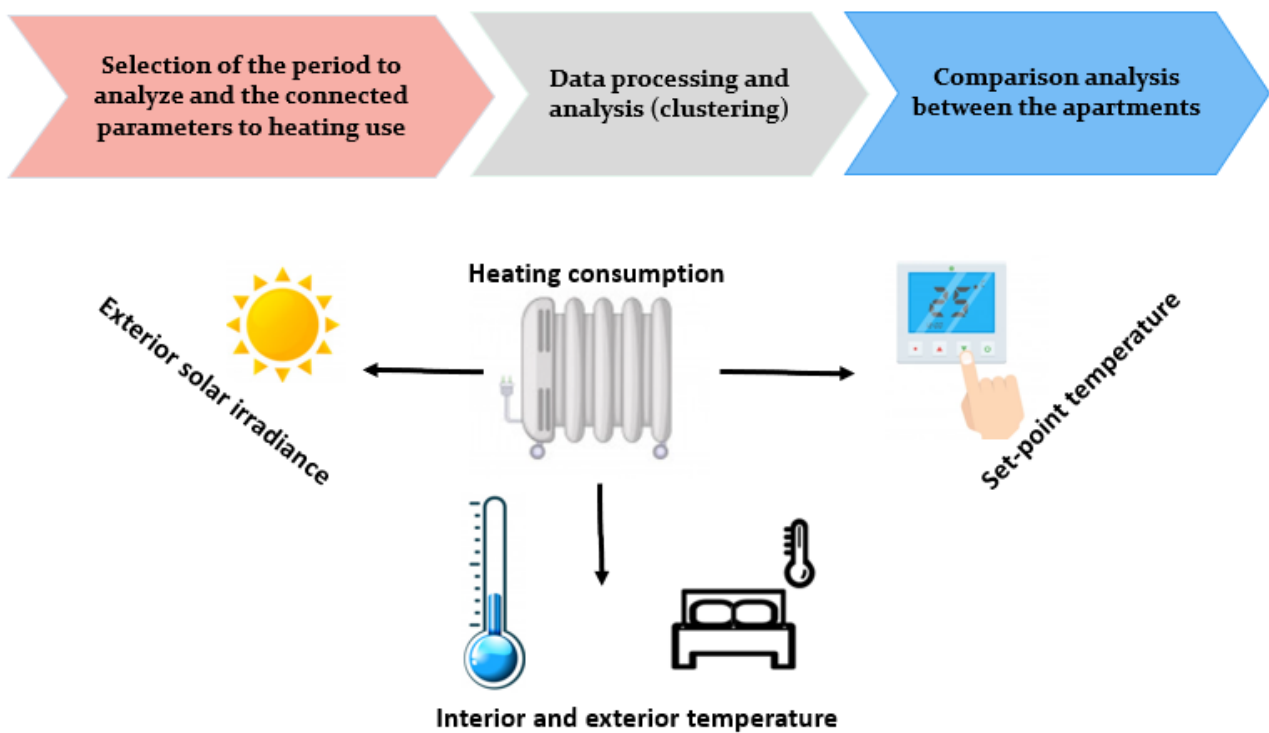


Figure 50: Methodology framework of occupant's heating behavior analysis.

IV.3.2 Clustering analysis of heating consumption

The exploitation of K-means clustering provided a partitioning of the connected parameters (outdoor temperature, exterior solar irradiance and indoor temperature) in terms of heating consumption for the two apartments studied. After the analysis of various cluster's number, ($K = 3$) has been selected as the most optimal number for this database. The clustering of heating consumption according to the outdoor temperature reveals three segments: 1) the largest number of observations (41%) on the 0-9 °C segment, 2) approximate percentage of observations (39%) for the segment of -5-0°C and 3) the lower percentage of observations (20%) for the segment of 9-16 °C. Regarding the exterior solar irradiance the majority of heating consumption's observations (76%) were detected on the 0-70 W/m² segment. 16% of

the observations concern the segment 70-250 W/m², and 8% of the observations regards the exterior solar irradiance values superior to 250 W/m².

The clustering of the indoor temperature indicates that the variation of these latter doesn't respect the setpoint temperature in winter season that varies between 19°C and 22°C. Based on the analysis, it was observed that the indoor temperature in apartment (A) achieves 14°C. Consequently, three segments were proposed by the clustering regarding the indoor temperature: *i*) 14-19 °c, *ii*) 19-20°C, and *iii*) 20-22 °C.

Table 17 in Appendix B represents the synthesis of the clustering results.

IV.3.3 Comparison analysis of heating consumption

In this part, we have proceeded to the assignment of the total heating consumption to each apartment during the period targeted based on the clusters presented in the section above. **Figure 51** illustrates the aggregation of the data deduced in order to provide a comprehensive analysis between the apartments. The use of heating in apartment (A) represents a higher amount of energy consumption compared to apartment (B). Thus, it is concluded that the exterior solar irradiance inferior than 75 W/m², and outdoor temperature between -5 °C and 0 °C constitute the main drivers influencing the occupant heating behavior in both apartments. Lower energy consumption is observed in the interval of 75-250 (W/m²) of exterior solar irradiance and 0 °C – 9 °C of outdoor temperature.

Regarding the indoor temperature, apartment (B) assures the winter thermal comfort contrary to apartment (A) where a lower indoor temperature is achieved (14°C). The heating consumption of apartment (A) shows a peak of 955 kWh at an ambient temperature varying from 14 to 19 ° C, and 634 kWh between 19 and 20 ° C. The thermal consumption of apartment (B) is at a minimum of 99 kWh between 19 and 20 ° C, and increases significantly between 20 and 22 ° C.

To better understand the heating use, the setpoint temperature of regulation was analyzed. The setpoint temperature of apartment (A) was set at 19 ° C, and the data analysis shows that it was regulated several times at 20 ° C. Regarding apartment (B), the setpoint temperature is fixed at 21°C and was regulated to 22 °C only three times.

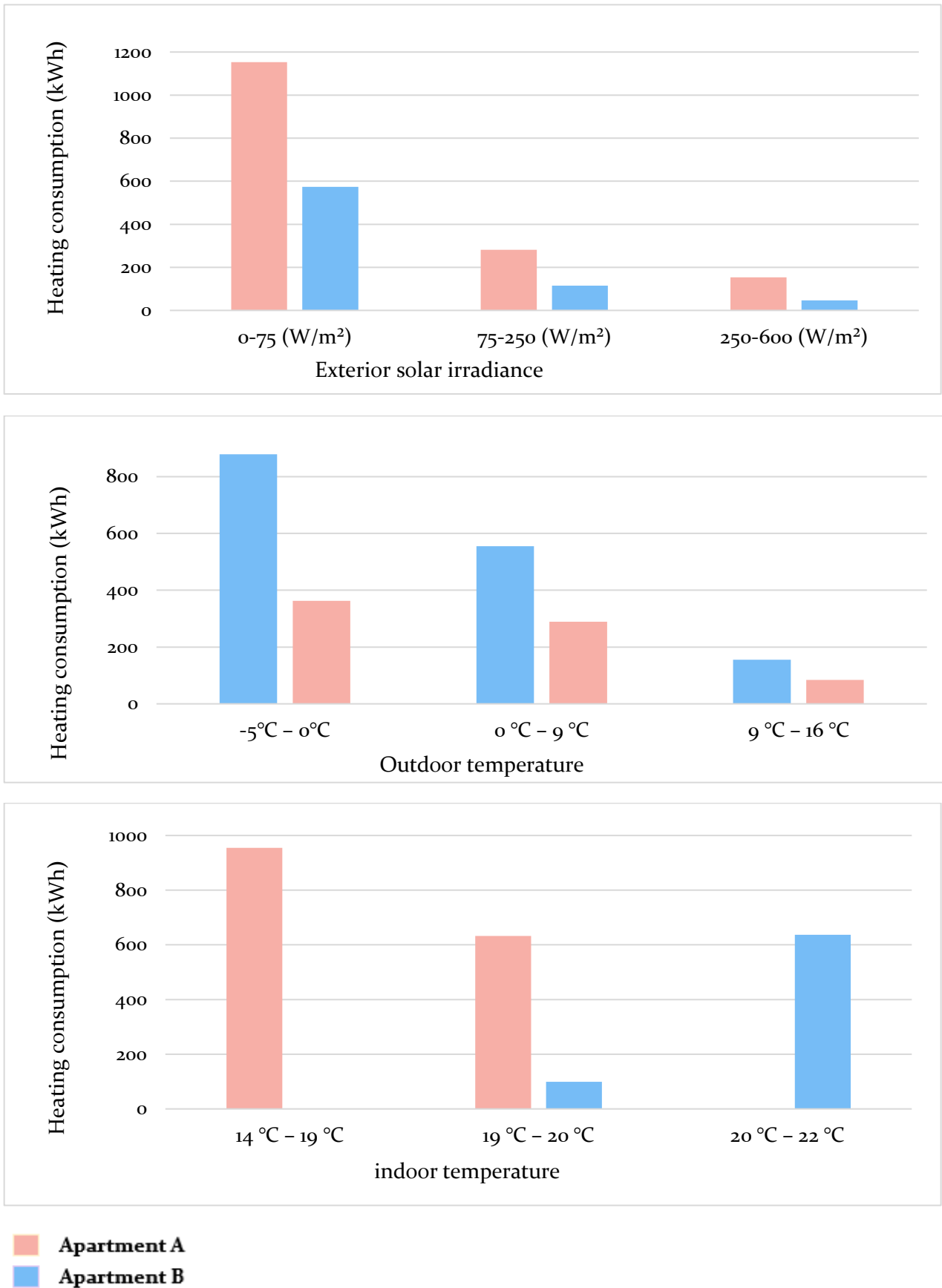


Figure 51: Results of clustering of heating consumption for the monitored apartments.

IV.3.4 Results & discussion

The heating occupant's behavior in the monitored apartments represents two different patterns. Firstly, the setpoint temperature detected in apartment (A) is 19°C and 21°C in apartment (B). The difference in the setpoint temperature could be explained by several reasons such as: the surface of apartment (A) which is inferior than that of apartment (B), personal preferences and orientation. Although the surface of apartment (A) is lower, the heating consumption in this apartment is very important in comparison with apartment (B) which has a loggia oriented to North-West face. Based on the analysis of PREBAT project, the results show that the presence of a loggia reduces the impact of outdoor temperature and decreases the need for heating in apartment B.

The comparison between the two apartments indicates that the exterior solar irradiance and outdoor air temperature are considered as relevant drivers influencing the heating use. These factors may not influence the apartments in a similar way for the other technical factors that vary for each apartment, such as: technical characteristics of the apartments, emplacement and internal gains. Indeed, by analyzing the indoor temperature in the period targeted, the apartment (A) shows sensible decrease in inside temperature, especially in January. The decrease achieves 14°C of inside temperature. Consequently, it is relevant to highlight the impact of windows openings frequency. If we suppose that the important decrease of indoor temperature (temperature inferior to 18°C) is due to the windows openings, it is deduced that the occupants of apartment (A) need to open the windows more frequently comparing to the occupants of apartment B. These openings influence the interior conditions and the thermal comfort in winter season.

The occupant's heating behavior in the analyzed case studies reveal the need to elaborate a comprehensive connection between the several parameters driving this behavior. Exterior conditions (temperature and solar irradiance), technical characteristics of the building and apartment, ventilation scenarios, personal need and preferences all form a circle of factors that should be taken into consideration when analyzing the heating use in residential building.

IV.4 Occupant's energy use: electricity consumption

The residential sector in France is responsible around 36% of final electricity consumption. Actually, electricity is one of the main energy sources in France and all over the world. It represents a major challenge of sustainable development and a key indicator to measure the energy gap between regions [116]. Electricity could be used for space heating, water heating, lighting, cooking, residential appliances and space cooling. Consequently, not only the occupant behavior affects the final electricity consumption, but also the level of equipment in electrical systems is an important factor to consider.

In this phase of our analysis, general electricity measures of two apartments were exploited with a view of studying the electricity use patterns. The measures of electricity in 'AMPLIA'

case study include three uses: lighting, residential appliances and cooking. The energy source used for heating and DHW is gas and solar production (Chapter II, section II.3).

IV.4.1 Methodology of analyzing the electricity consumption in AMPLIA case study

Similarly, to the previous section (IV.3), a descriptive analysis was presented to characterize the electricity use in winter and summer season. The parameters connected to the electricity use are: time of day and exterior solar irradiance (especially connected to lighting use). So, the clustering analysis and the comparison analysis was developed and outlined in the following sections. **Figure 52** outlines the framework of electricity use analysis.

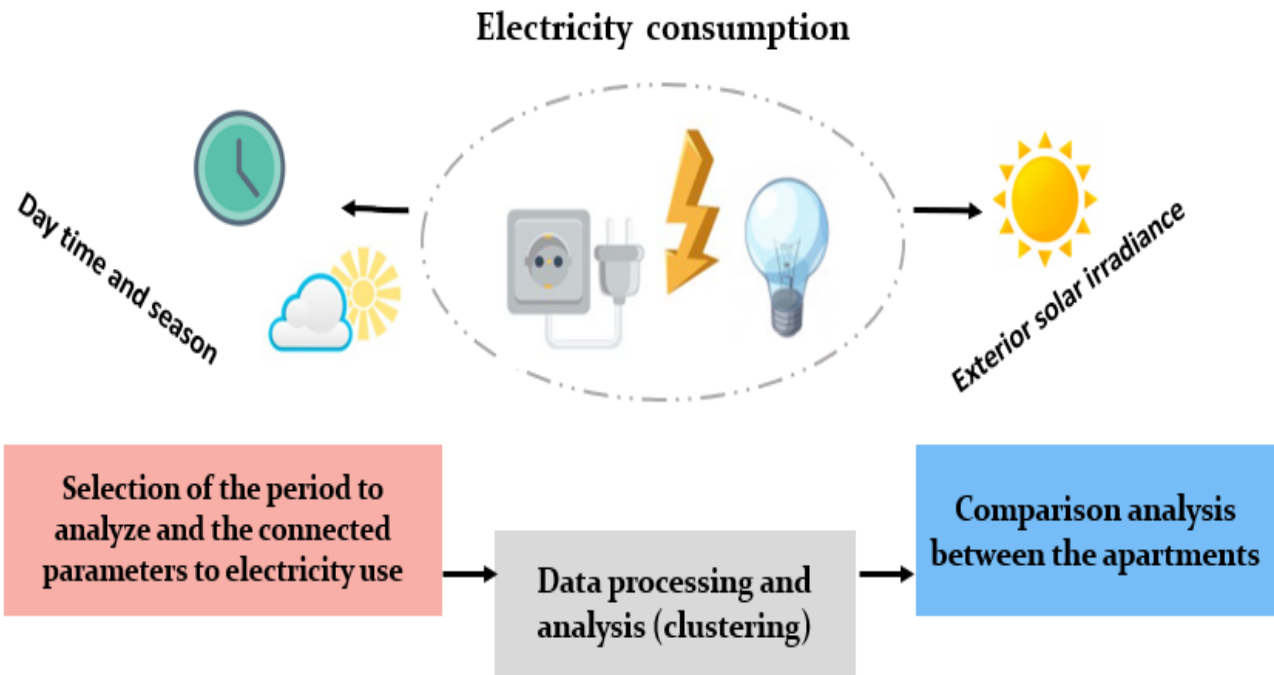


Figure 52: Technical framework of electricity use (AMPLIA case study).

IV.4.2 Electricity use in winter season

The clustering of electricity consumption in winter season according to exterior solar irradiance generates three clusters: 1) 0-90 W/m², 2) 90-250 W/m² and 250-650W/m². In the period when the exterior solar irradiance varies from 0 to 90 W/m², the peak of electricity consumption is detected for both apartments. The electricity use decreases significantly between 90-250 W/m² by 75% for apartment (A) and 80% for apartment B. Hence, the two apartments were characterized by a low electricity consumption for the values of solar irradiance superior to 250 W/m² (**Figure 53**).

The clustering analysis of apartment (A) and (B) according to exterior solar irradiance reveals that the electricity use is maximum when the values of this irradiance are inferior to 90 W/m². Considering that the exterior solar irradiance could only affect the conception of visual comfort and the lighting need, we can conclude that the exterior solar irradiance inferior to 90 W/m² is a major driver for lighting use for both apartments.

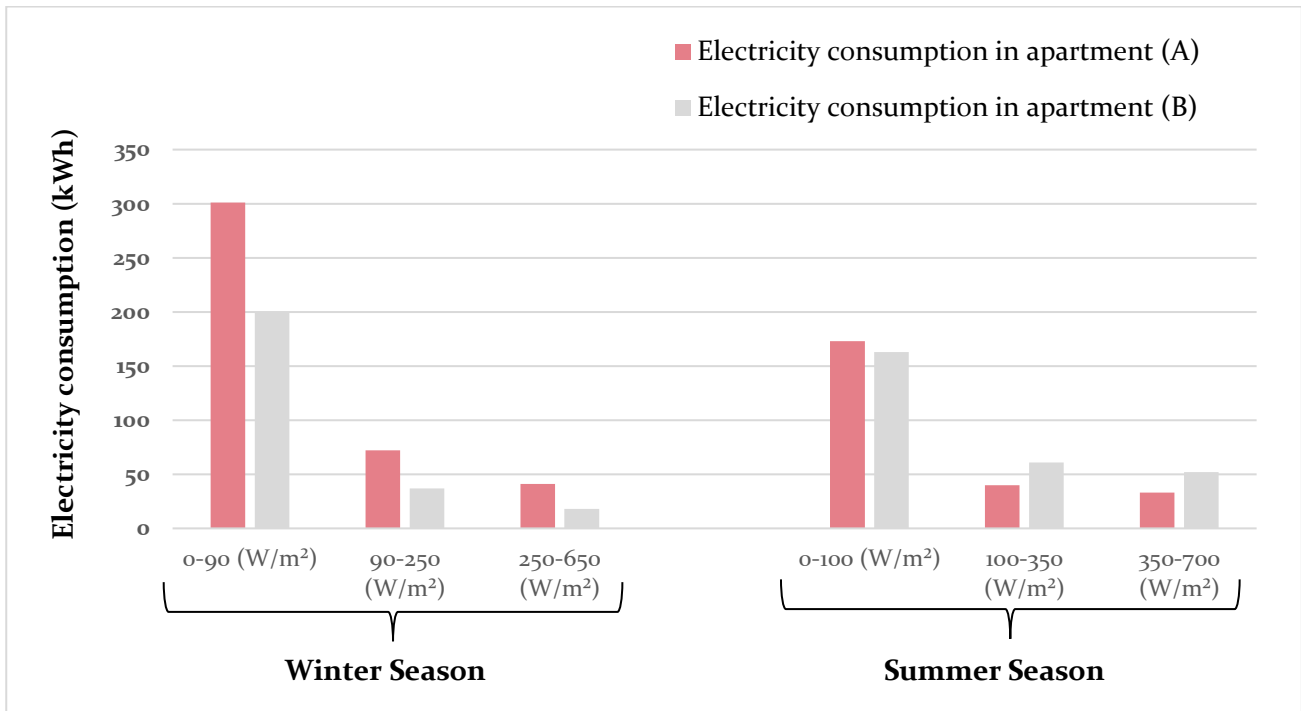


Figure 53: Clustering of electricity consumption according to exterior solar irradiance.

The use of K-means clustering was not adopted for the analysis of electricity consumption according to the time of day because the results of the algorithm show approximately similar clusters and do not reflect the level of accuracy required. For this reason, the methodology presented in section IV.2 will also be exploited in this part of the analysis. Accordingly, four time slots of the day have been selected (morning, evening, afternoon and night). Based on the electricity consumption evolution, a value threshold of 0.35 kWh was identified for peak's frequency investigation. All the peaks superior to 0.35 kWh will be evaluated in terms of frequency for each time slot as presented in **Figure 54**.

The results describe two different patterns of electricity use in apartments (A) and (B). **Apartment (A)** was characterized by an approximate frequency of peaks in the morning and evening. The distribution of the peaks is detected all day long, which reveals the presence of the occupants. However, the hourly analysis of peaks in this apartment (A) indicates that the major peaks are present around 9:00 a.m. and 10:00 a.m. in the morning, and between 8:00 p.m. and 9:00 p.m. in the evening. Regarding apartment (B), around 70% of the peaks are identified in the evening, principally between 9:00 p.m. and 10:00 p.m.

Another threshold was proposed to analyze the frequency of peaks superior to 1 kWh to better understand the electricity use behavior in the weekdays and weekend (**Figure 55**). Apartment (A) uses electricity intensively in weekdays at 1:00 p.m. and 8:00 p.m. Contrary to the weekend when the peaks superior to 1 kWh are detected mainly at 12:00 a.m. As for apartment (B) the explored peaks are mainly noticed at 10:00 p.m. and with less frequency at 2:00 p.m. for both weekdays and weekend.

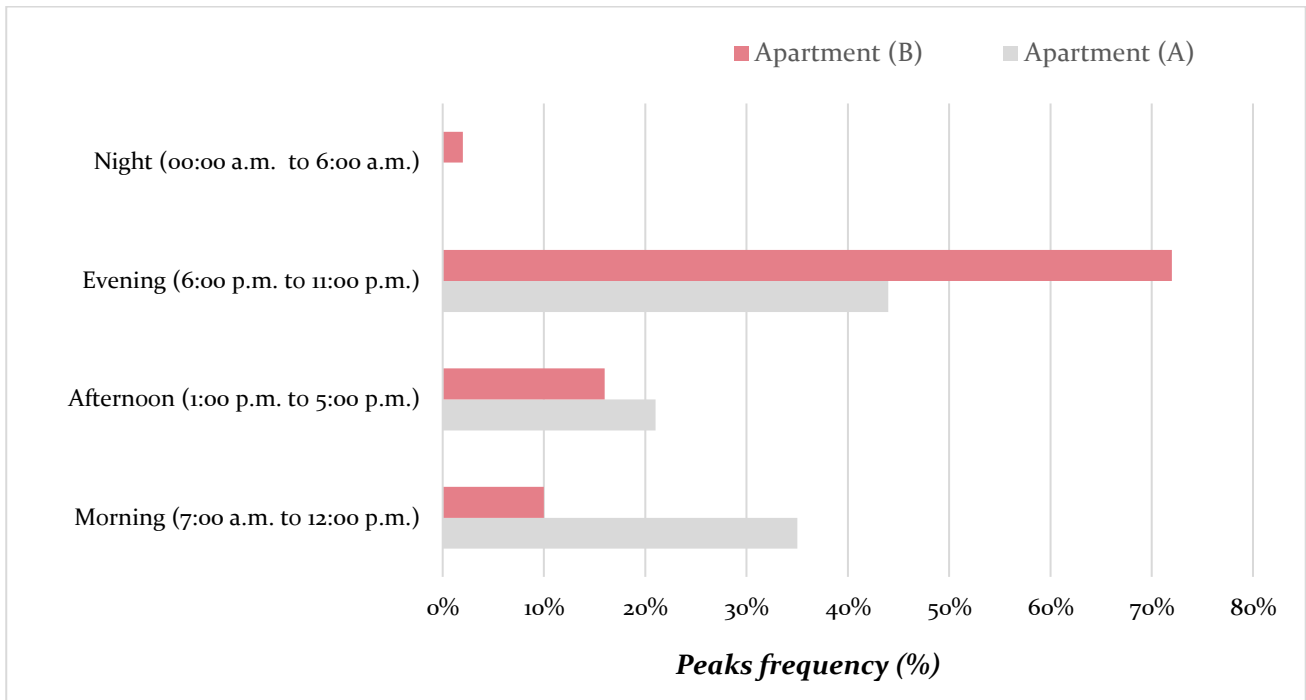


Figure 54: Peak's frequency of lighting use in winter according to time of day for apartment (A) and (B) (AMPLIA case study).

The electricity use reflects firstly the presence of occupants in the apartment and secondly the need of lighting, cooking or other activities that require electricity. The general electricity use in apartment (A) is affected by the routine pattern that was characterized by an intense need in the morning and evening during the weekdays (wake-up time, cooking time, the presence of all the occupants at these time slots). In the weekend, the peaks are randomly detected all day long.

Apartment B is characterized by a demanding need of electricity in the evening which could reflect a continuous absence during the day. The peak's frequency starts to be more important from 7:00 p.m. to 10:00 p.m. This time slot represents the time when all the occupants are back home (arrival and dinner time). The arrival time is considered as major factors affecting the general electricity use in apartment (B).

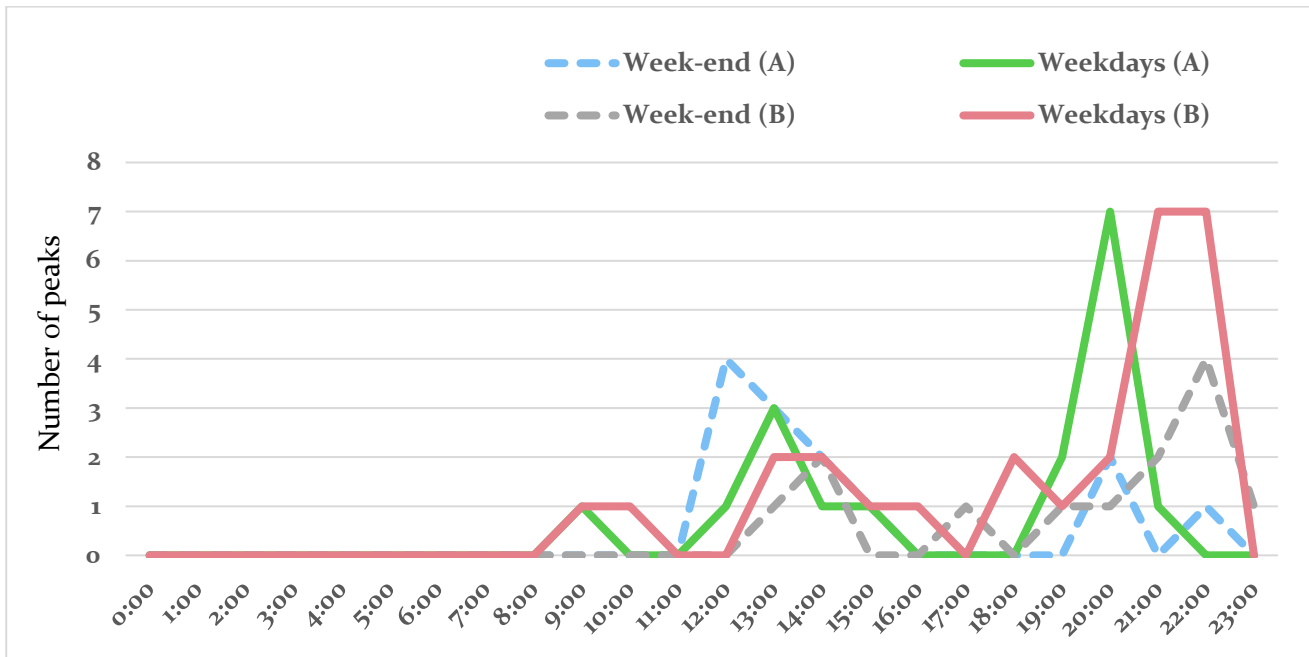


Figure 55: Peak's frequency (superior than 1 kWh) in apartment (A) and (B) during Winter season.

IV.4.3 Electricity use in summer season

The values of exterior solar irradiance are higher in summer season. For this reason, higher values are detected in following ranges of clusters: 1) 0-100 W/m², 2) 100-350 W/m² and 350-750 W/m². Similarly, to the winter season, the electricity is more consumed when the values of exterior solar irradiance are between 0 W/m² and 100 W/m². The results of summer season show that apartment (B) consumes more electricity in the second and the third cluster than apartment (A), contrary to winter season when the electricity consumption of apartment (A) was higher for all the clusters (Figure 53).

In parallel to the methodology proposed in the winter season analysis, the same time slots will be exploited for peak frequency analysis. The thresholds of 0.35 kWh will be investigated over again for the summer season. However, it was detected that the global electricity consumption in summer is lower than winter, for this reason the second threshold will be decreased from 1 kWh to 0.75 kWh.

The first peak's frequency analysis (peaks superior to 0.35 kWh) reveals that **apartment (A)** use more electricity in the evening and the peak's frequency at this time is around 40%. Electricity use after midnight was also detected with a peak frequency of 22%, and a frequency of 25% in the morning. Few peaks were detected in the afternoon. Regarding **apartment (B)**, the majority of electricity use was identified in the evening with a peak frequency of 45%, and 36% in the afternoon. The use of electricity after midnight in this apartment is negligible and, the peak's frequency in the morning is around 18%. The following Figure 56 clearly display the hourly peak frequency for the weekdays and weekend. It is deduced that the pattern of electricity use in the weekend converges with the pattern-use in the weekdays for both apartments. In addition, the analysis of the peak frequency of the peaks superior to 0.75 kWh provides similar pattern.

The routine of occupants in summer season could be completely different from the routine in winter season, which was clearly identified for both apartments. Apartments (A) and (B), in the weekdays and weekend were characterized by higher peak frequency in the evening around 9:0 p.m. Thus, apartment (A) represents also peaks after midnight contrary to apartment (B) where the electricity use at this time slot is inconsiderable. The higher electricity consumption in apartment (B) during the day reflects more presence of occupants in summer than in winter. It could give possibility of the presence of students or occupants working in an educational institution who have surely summer vacation, or the use of extra appliances such as cooling systems. In conclusion, the general electricity in summer is also affected by the routine of the occupants, their presence at home and the nature of their daily activities. The need of cooling system or ventilation is also considered. Regarding the lighting use, we can suppose that it is more important when the exterior solar irradiance is lower than 100 W/m^2 .

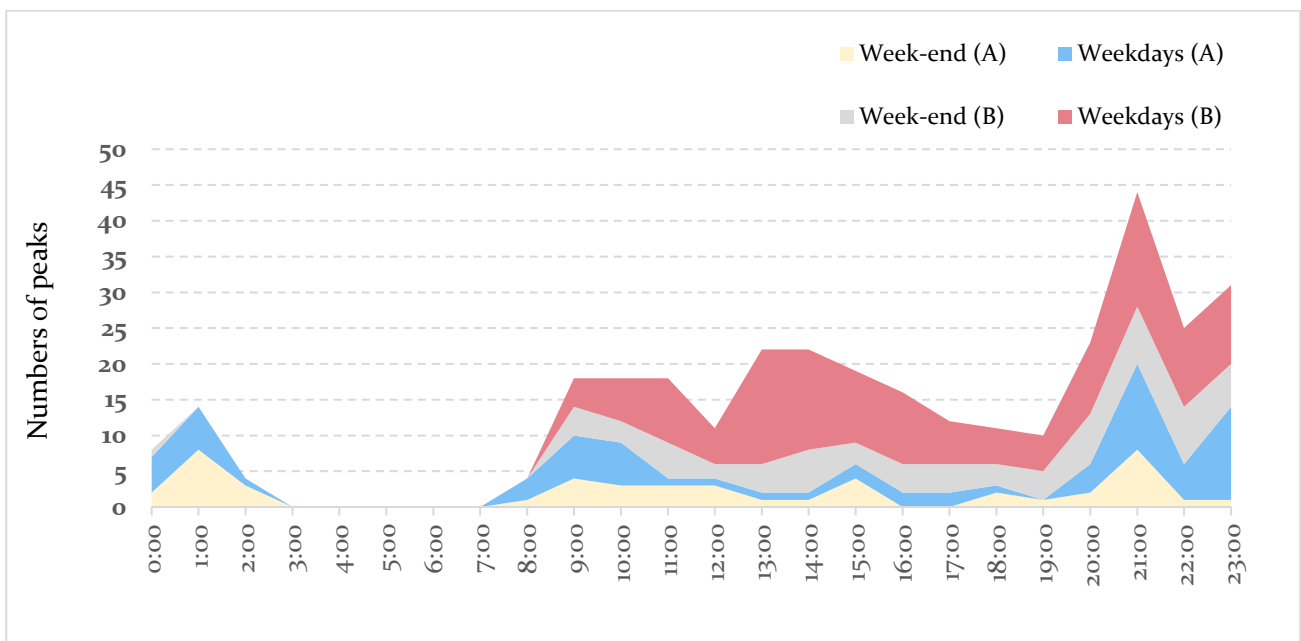


Figure 56: Peak's frequency (superior to 0.35 kWh) in apartment (A) and (B) during Summer season.

IV.4.4 Results and discussion

By analyzing the general electricity use that includes also the lighting use, two different patterns were identified. The first pattern concerns apartment (A) situated at the ground floor with a living area of 76 m^2 , and has two large windows facing North-West and South-West. This first pattern shows a continuous electricity use during the day in winter, which indicates the presence of occupants, and automatically a need for a visual comfort and other activities that require electricity. In summer, the need is more frequent in the evening around 9:00 p.m. and after midnight between 00:00 a.m. and 2:00 a.m. The second pattern regards apartment (B) situated at the first floor with a living area of 83 m^2 , and has windows oriented to the south-east, and another bay window oriented to the north-west. The electricity use in winter was mainly important in the evening between 8:00 p.m. and 10:00 p.m. Contrary to summer season where the electricity use is also important all day long.

The comparison of the general electricity consumption between the two apartments confirms that one of the major factors is the presence of occupants and day routine. Such factors conduct us to reconsider the importance of the occupant's profile that plays a major role in defining the day routine and the general needs in the apartments. Although the living area of apartment (A) is lower than apartment (B) the energy consumption is higher in winter season. Thus, the surface in this case is not considered as a driver. Conversely, it is important to explore the differences between the emplacement. Apartment (B) situated at the first floor could benefit more from the solar irradiance and the daylight, which decrease the need of lighting and the energy consumption. In addition to its south-east orientation that increases the benefit from the solar irradiance for heating and natural lighting, and consequently apartment B needs less energy in winter. It is essential to highlight that the connection between all these factors what gives a pertinent understanding of the energy use.

The clustering analysis of exterior solar irradiance reveals a strong correlation with the higher amount of electricity consumption, especially for the values inferior to 100 W/m^2 for winter and summer season. The exterior solar irradiance can only affect the lighting use (a part of the general electricity). In addition, the presence of large windows in both apartments allow a maximum benefit of the natural daylight and therefore decreases the lighting need.

IV.5 Occupant behavior in COVID19 confinement

The emergence of the virus COVID-19 around the world in late 2019 and the beginning of 2020 pushed the governments to take serious actions. In France, the government decided the first lockdown starting from March 17th 2020. This decision has changed completely the daily life of people (social impact), but more all the aspects in life, and has generated considerable impacts on the economy and the environment. The analysis impact of COVID-19 has been investigated by many researchers in different countries[117]. At European level, Bahmanyar et al. [118] analyzed different impact of COVID-19 on electricity consumption in European countries. The results showed that the countries which have adopted severe restrictions reveal a considerable reduction in electricity consumption. Similar results were proved by Sony Computer Science Laboratories [119] which confirm the remarkable load drop in most of Europe, except for Scandinavia and Switzerland where limited restrictions have been adopted.

Figure 57 represents the evolution of electricity consumption during 2020 in France, Germany, Italy, Spain, Great Britain and India. On one hand, the lockdowns generate a huge reduction in services and industry. On the other hand, the people were constrained to stay at home. Consequently, the energy consumption in the residential sector is increased.

Based on the measures monitored in 'HEART' project (presented in Chapter II), an evaluation of the energy consumption in residential building during the lockdown period, specifically in social housing has been performed. We choose the analysis of three occupant's interactions: 1) lighting use, 2) heating use, and 3) general electricity use.

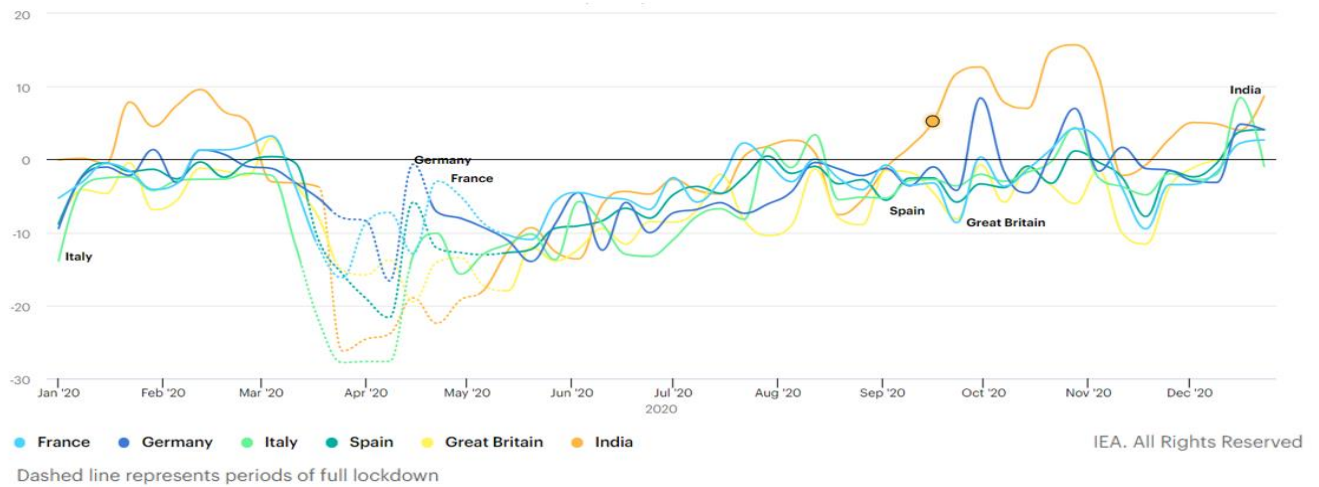


Figure 57: Evolution of electricity consumption in 2020 (France, Germany, Italy, Spain, Great Britain and India) [120].

IV.5.1 Methodology of analyzing the energy behavior in HEART case study

In this section, a specific attention has been paid to the energy behavior during the first lockdown in France by comparing it to the period before the lockdown. Accordingly, the analysis included in particular the month of March. The first fifteen days are considered the reference period where no lockdown was imposed, and the second fifteen days represent the period of lockdown analyzed. Other period was analyzed in order to better understand more the occupant behavior. Two apartments were studied for the investigation of the three interactions shown in **Figure 58**. The selection of the apartments was based on the availability of the data in the period targeted.

The opportunity of analyzing COVID-19 impact is due to HEART project within the framework of which we developed this monitoring activity.

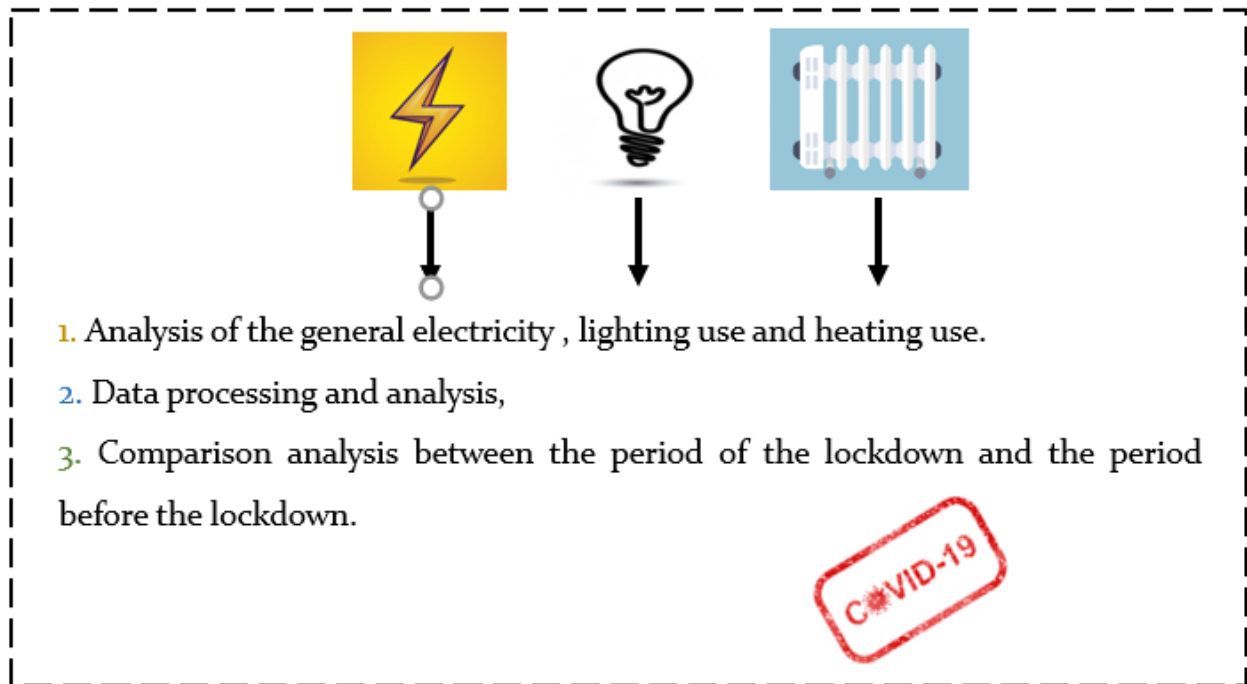


Figure 58: Technical framework of energy use analysis during and before the lockdown (HEART case study).

IV.5.2 Energy use analysis: HEART case study

As explained above, the main objective of this section is to analyze the energy use of lighting, heating and electricity use, and evaluate the impact of COVID 19 Lockdown in a case study in France. This section is divided into three subsections. Each one focus on and represents one occupant's interaction.

IV.5.2.1 Lighting use

The analysis of the occupant's interaction with lighting has been performed in an apartment situated on the first floor, and occupied by one-person, with a living area of 40 m². Based on the lighting use in this apartment, we selected a value of threshold of 0.25 kWh for peak's frequency analysis. The investigation of the lighting use in this apartment reveals a pattern characterized by low lighting use during the morning, afternoon and night, but with higher use from 7:00 p.m. to 10:00 p.m. in the evening. The arrival time in the period before the lockdown explains the peaks detected in this time slot. Regarding the lockdown period, the lighting use is affected mainly by the global illuminance that decreases at 6:00 p.m. (sunset time in March 2020 in the city of Lyon in France). **Figure 59** shows the evolution of the lighting use and the global illuminance in March 2020. The considerable peaks are principally detected when the global illuminance is equal to zero. The peaks are more present in the weekend for the first period, contrary to the period of lockdown where the peaks are present during the weekdays and over the weekend.

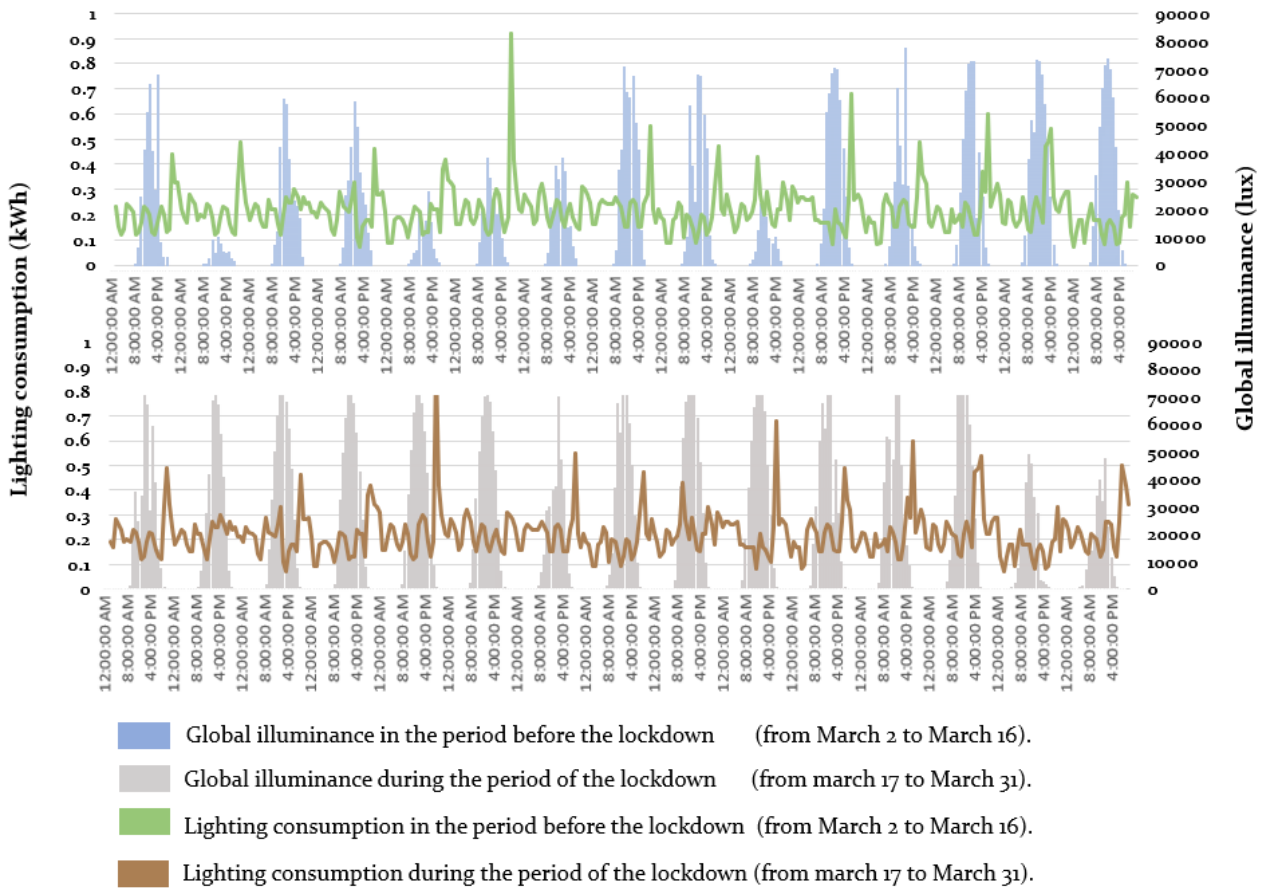


Figure 59: Evolution of the lighting use according to the global illuminance in March 2020.

By analyzing the difference in lighting consumption between the periods before and after the lockdown, we identify a 13% increase in total lighting use during the lockdown period. **Figure 60** represents a comparison of lighting consumption from March 2 to 16 (period before the lockdown), and from March 17 to 31 (first fifteen days of the lockdown in France).

The evolution of the lighting consumption in the periods studied (from March 2 to 31) converges and represents a similar pattern with important peaks in the evening. In conclusion, the need of visual comfort is still the same, which reflects the same pattern for the two periods before and after the lockdown which then imposes more presence at home, and a longer period of lighting use could be present which generates higher/ longer peaks.

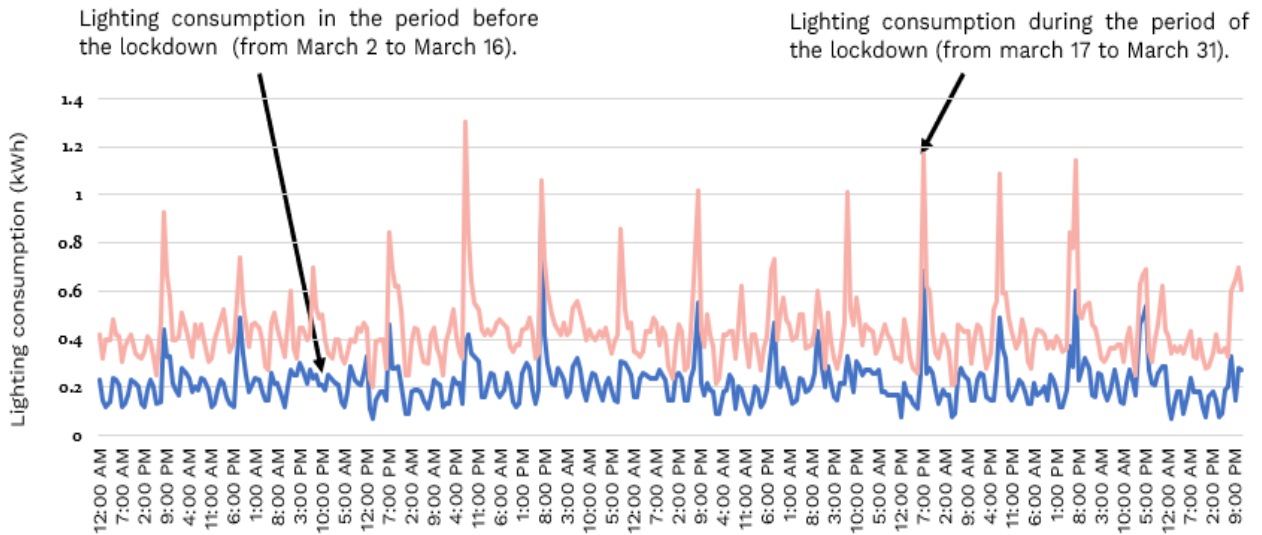


Figure 60: Comparison of the lighting consumption during and before the lockdown (March 2020).

IV.5.2.2 Electricity use (household appliances)

The analysis of occupant’s electricity use was performed in the same apartment of the previous section, and the same methodology of the peak’s frequency analysis was exploited. The period before the lockdown (from March 2 to March 16) was characterized by a higher electricity use from 6:00 p.m. to 10:00 p.m., and specifically the maximum peak was identified at 7:00 p.m. during the week. In the weekend, the higher electricity use starts later around 8:00 p.m. and decreases by 10:00 p.m. During the lockdown period in March, the time slot from 6:00 p.m. to 10:00 p.m. still represents the time with higher electricity use. In addition, the peaks were also important during the day from 11:00 a.m. to 01:00 p.m. Consequently, two different patterns are outlined:

- 1) **Before the lockdown:** a major use of electricity was determined in the evening from 6:00 p.m. to 10:00 p.m. This time slot represents the arrival time which means the presence of the occupant. Accordingly, the need of cooking, TV-on or other needs that require electricity is present.
- 2) **During the lockdown:** the electricity use is important in two time slots of the day as explained above due to the presence of the occupant in the apartment during the day in this period (when leaving home was very limited).

Figure 61 represents a comparison between the hourly peak’s frequency during and before the lockdown. A noticeable increase of the numbers of peaks during the period of the lockdown all day long is identified, except for the night where a decrease is detected compared to the period of the lockdown. By analyzing the electricity consumption between the two periods, an increase of 22% is identified in the period of the lockdown. In conclusion, the electricity consumption in this case study is only affected by the time of the day such as: arrival time and the routine of the day, and the lockdown that increases the occupant’s needs. The

measures of electricity in this apartment doesn't include the lighting consumption, and consequently no other factor is considered in the analysis.

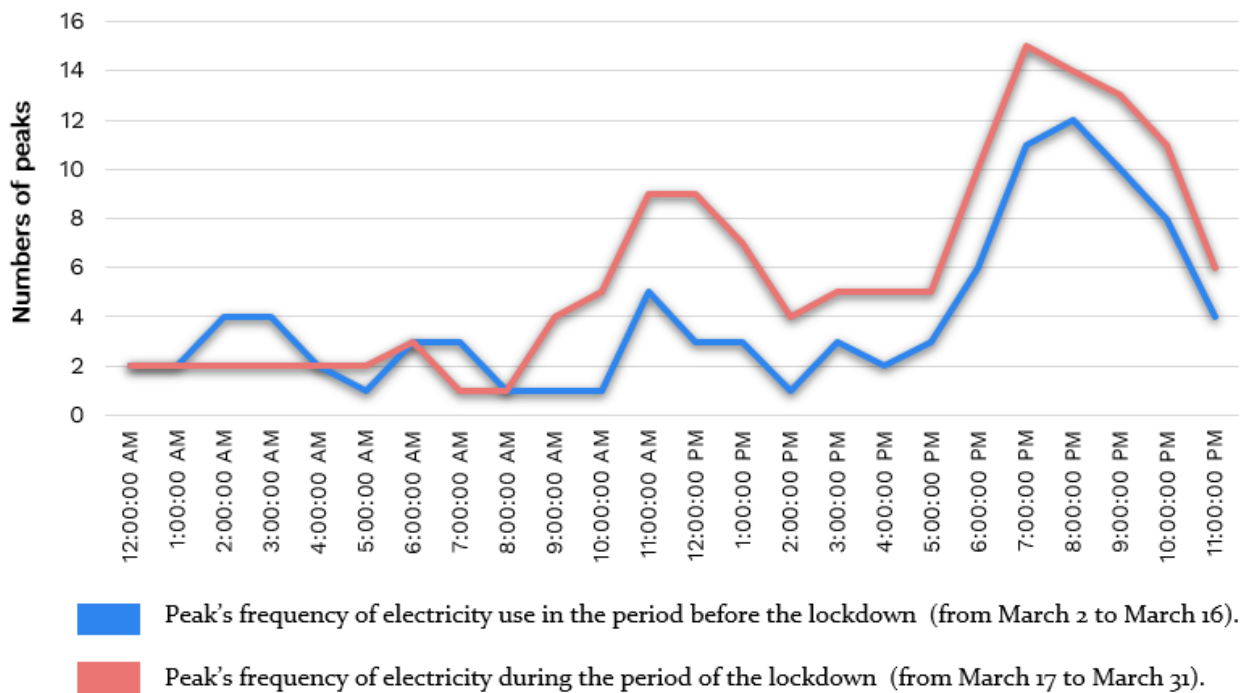


Figure 61: Hourly peak's frequency of electricity before and during the lockdown (March 2020).

IV.5.2.3 Heating use

The analysis of heating use concerns an apartment situated in the ground floor with a living area of 41 m², occupied by one person and situated in Saint-priest. By analyzing the data, it was identified that the sensor installed gives a value that varies from 0 to 1. The value equal to 1 kWh reflects the use of heating and the value equal to 0 indicates the non-use of heating. We choose to display a longer period to confirm that the heating use in the apartment studied is not obvious and was detected a few times. During the period of two months (February and March 2020), the heating was activated only 14 times in different days, around 25% of the total period targeted (**Figure 62**). By analyzing the heating use according to outdoor temperature, it is concluded that the heating is activated when the outdoor temperature varies from 2°C to 15 °C. Otherwise, the outdoor temperature at this period has dropped to 1 °C and during this decrease no heating consumption was identified. For this reason, the outdoor temperature is not considered as a driver for heating use during all the period studied, including the lockdown period.

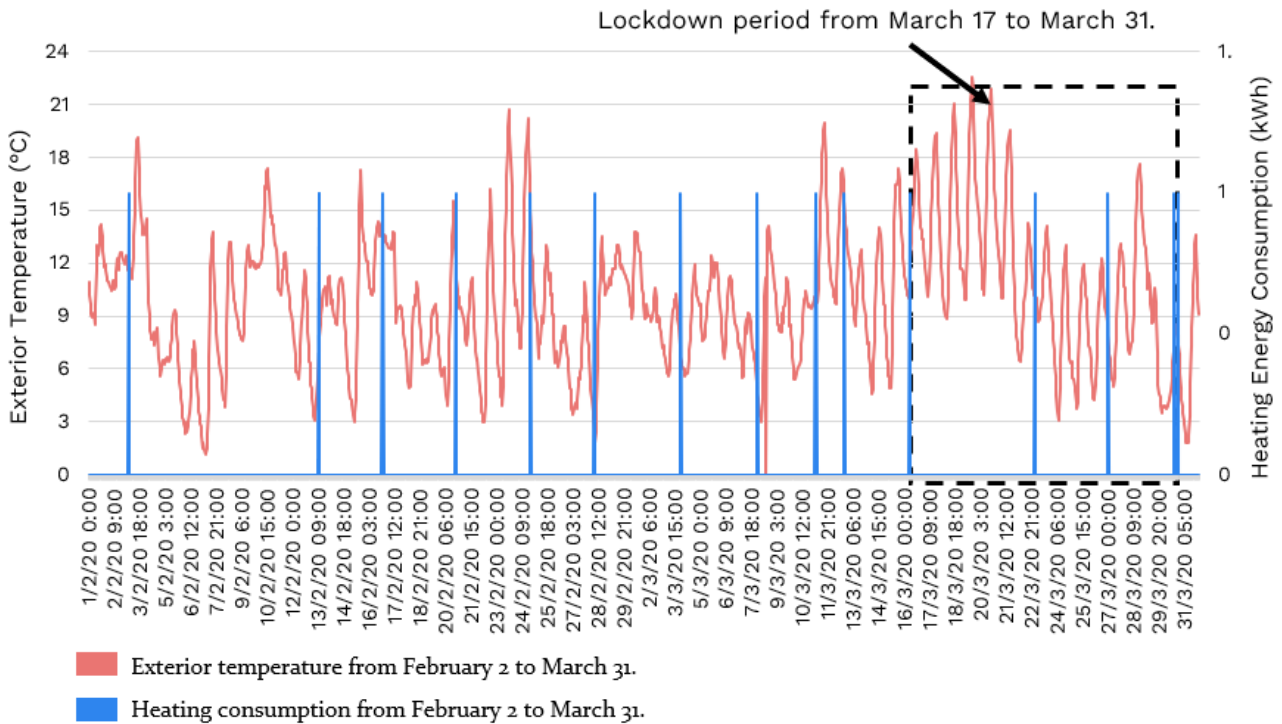


Figure 62: Heating use according to outdoor temperature during the months of February and March.

In addition, the building needs a renovation, which is the purpose of ‘HEART’ project, and the level of insulation is not sufficient for assuring a thermal comfort. Thus, the heating use is in general mandatory in this case. This situation was observed also for other apartments in the same building where indoor temperature is very low compared to that of the apartments using heating. The reason could be simply a cultural factor that reveals a heating as not an important equipment and other alternatives are exploited. The routine of the day and long absences could be also a factor for not using heating continuously. Furthermore, it is important to notice the impact of energy poverty that affects the occupant behavior, especially in social housing. The energy poverty could be a result of minimal systems efficiency, high energy prices, but also low occupants’ incomes [121]. In this respect, HEART project is considered as a contribution to the energy poverty alleviation in social housing which will provide an access to various energy sources and increase the systems efficiency and level of thermal comfort. No significant impact of COVID-19 is outlined in this case study.

IV.5.3 Results & discussion

The final section of this Chapter regards the investigation of energy use in social housing. Moreover, the impact of the first lockdown in France on energy consumption is evaluated. For that purpose, three interactions were selected for the analysis, and based on the database two apartments were identified for this study. The period of analysis is the month of March,

it was essential to keep the same dimension before and after the lockdown, and the objective is to provide an analysis methodology. Larger period will be explored in the future research. The results of the analysis show three levels of COVID-19 impact:

- 1- **Higher impact:** This first level is observed in the electricity use where 22% of increase was identified during the lockdown. The electricity use in general is affected only by the presence of occupants that creates a need of using systems and doing activities that require electricity. When this presence was more important in the lockdown period, the increase of electricity consumption was also greater.
- 2- **Medium impact:** The lighting use during and before the lockdown maintains the same pattern with a higher use in the evening. It is deduced that the need of visual comfort wasn't influenced or modified. Nevertheless, during the lockdown period, the presence is longer which could modify the duration of use of the lighting. Thus, an increase of 13% is estimated in this case.
- 3- **No impact:** The heating use in the apartment targeted reflects an important pattern to analyze. The heating was used only a couple of times and it is concluded that the outdoor temperature cannot be considered as a driver in this case. During the lockdown period, no modification of use was observed. Other drivers should be explored such as: cultural factor, energy poverty impact, and also the possibility of a long absence even during the lockdown period due to a specific type of work.

IV.6 Conclusion

The occupant's energy use analysis conducted in this Chapter aimed to provide a methodology of analysis for indirect measures, contrary to the Chapter III where direct measures about occupant's behavior were investigated. In this Chapter two different category of residential building have been presented: private building and social housing. And the measures analyzed in this Chapter are mainly energy consumption, exterior and interior conditions measured differently in each case study. Thus, the consumption of lighting, heating and electricity are the main interactions targeted for the analysis.

Several apartments were analyzed, for this reason, and in addition to the Knowledge Discovery in Databases methodology a clustering approach by using K-means algorithm was employed for facilitating the analysis. For each section, a synthesis of the technical framework is presented and a synthesis of the Chapter is represented in **Figure 63**.

In the case of **private building**, the analysis of the interactions mentioned was performed in two apartments for a comprehensive comparison. Regarding the use of lighting and electricity, the analysis has shown two patterns. One pattern represents a fixed schedule of presence and absence during the week, where the use of lighting and electricity are more frequent in the evening. The second pattern is characterized by a presence of one occupant or more all day long, and no fixed schedules could be estimated. The drivers are different and vary in the winter and summer seasons. The arrival and departure time, exterior solar

irradiance, emplacement and orientation, season, weekdays and weekend and personal preferences present all drivers for lighting and electricity use.

The investigation of the heating in private building reveals also two patterns. The first apartment where thermal comfort was ensured all the period was analyzed, and the second pattern where inferior temperature was detected. Accordingly, various factors should be taken into consideration for a complete analysis of the heating consumption such as: exterior conditions, windows opening, orientation, technical data about the apartment and the building.

The analysis of **social housing** includes the same interactions, but with additional analysis of COVID-19 impact. The results show that the COVID-19 affects significantly the electricity consumption which is affected mainly by the occupant's routine of the day which was changed completely during the lockdown. A considerable increase of lighting consumption was also identified. The analysis shows that the pattern of lighting use still the same but with longer peaks during the lockdown. In regard to heating consumption, no impact was detected, especially that the heating use in the apartment targeted wasn't a daily need. This specific heating behavior leads us to consider various factors as: long period of absence, cultural factor and the energy poverty impact.

In coherence with the conclusion of Chapter III, it is very recommended to consider the importance of a connected analysis between: technical, human and energy factors. By analyzing the energy consumption, only a time step of 1 hour was performed in the monitoring activity that aims to measure this consumption. The time step is evaluated sufficient in condition to have all the other information concerning the building and the apartments.

This research reveals the importance to consider the impact of the type of building and its current situation on the analysis of occupant's energy use. The objective is to gather the maximum of information for a better simulation of occupant behavior which will improve the accuracy of integrating of human behavior as an important factor in energy performance studies of building.

Occupant behavior in private and social residential building

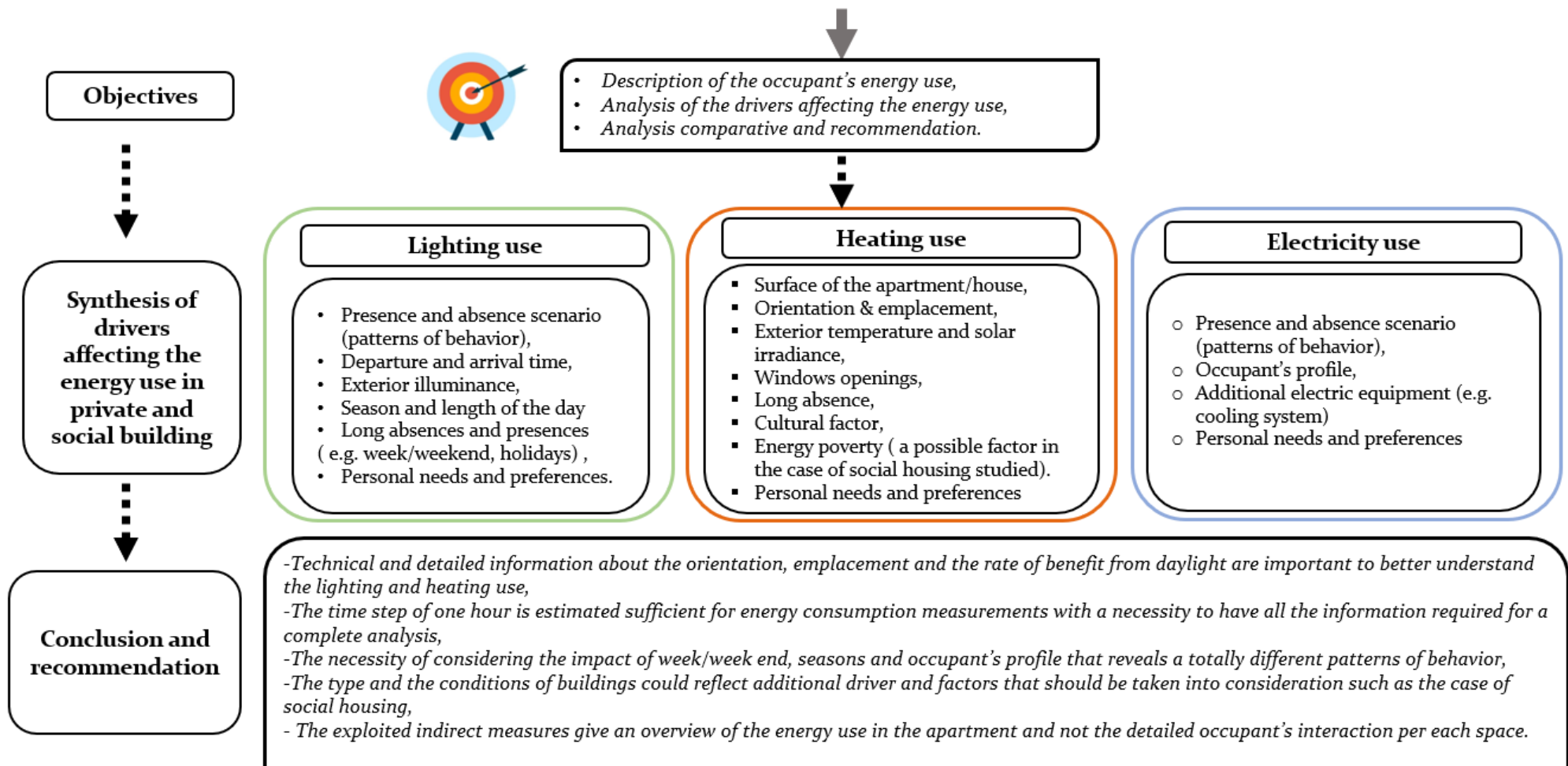


Figure 63: Synthesis of the occupant's energy use in private and social housing.

CHAPTER V

HOBIM

Holistic approach for Occupant Behavior assessment based on In-situ Monitoring



Chapter V

HOBIM: Holistic approach for Occupant Behavior assessment based on In-situ Monitoring

V.1 Introduction

In chapters III and IV a descriptive analysis of occupant behavior in residential buildings, and the evaluation of the drivers affecting the occupant's energy use were developed. By analyzing various parameters and types of data, the relevance of knowledge that we can obtain by developing a monitoring activity in residential building is of high importance for building energy performance analysis. The results of our analysis, and our experience of developing a monitoring activity will be exploited in this Chapter to propose a holistic methodology for occupant behavior assessment.

This Chapter comes to enrich the in-situ monitoring in residential buildings knowledge and methodology. Indeed, the monitoring activity is considered one of the most important approaches in occupant behavior assessment, and a suitable design and implementation of the activity could generate pertinent results[17]. However, many issues could impact the efficiency of the monitoring activity, which require a particular attention for all the process. Thus, the elaboration of a guideline that allows the organization, implementation and exploitation of the monitoring activity is proposed in this chapter.

The guideline is entitled HOBIM, and will be described in three main phases:

- 1) Advise the stakeholders in order to make the appropriate design of the monitoring activity, starting from the objectives' definition to the data collection,
- 2) Propose a methodology for data analysis,
- 3) Suggest the principal perspectives where the results of data analysis could be exploited.

This Chapter is composed of four main parts. The first section of the Chapter will present a general definition of the guideline. The second, third and fourth sections are dedicated to the development of the three phases of HOBIM guideline.

V.2 Definition of HOBIM tool

HOBIM tool is a guideline / manual that provides instructions to develop a monitoring activity in the context of occupant behavior analysis. The guideline regards the stakeholders interested in the assessment of occupant behavior in residential building performance. The Key-relevant stakeholders concerned with the development and implementation of a monitoring activity could be:

- i) Designers,
- ii) Researchers,

- iii) Building managers,
- iv) Energy managers and facilities.

The selection of the stakeholders was based on the stakeholder's map developed in the context of the European H2o2o HEART project. The maps permit the collection of the points of view of partners about the stakeholders interested in using the guideline [122]. After the analysis of the list collected from the partners, a final list of key-relevant stakeholders is proposed.

HOBIM guideline encourages the adoption of the monitoring approach by giving general instructions of the main phases and aspects to consider while developing it. Based on the previous analysis performed in the context of this research, it is designed that HOBIM tool will target three main phases:

1. ***Monitoring decision-making***: the first phase purposes the identification of the final objectives and the selection of the parameters to monitor. Moreover, it gives recommendations about the implementation of in-situ monitoring approach,
2. ***Data analysis***: the second phase regards the transformation of data to pertinent knowledge about the occupant's interactions/patterns in residential buildings (identification, assessment and interpretation of occupant behavior),
3. ***Valorization***: the last phase proposes the potential use of the gathered knowledge from data analysis. The perspectives contribute to increase the accuracy of occupant behavior in building energy performance evaluation and prediction.

The explanation of the phases will be represented in the following sections, and more details will be provided for each interaction studied in the context of this research: ***Lighting use, Heating and cooling use, Windows opening, Thermostat use, and Electricity use.***

V.3 Phase 1: Monitoring decision-making

The monitoring decision-making is represented as the first and principal phase of HOBIM tool. This phase will outline all the required elements for defining a set of directions for the next phases. The important and first element to define in phase 1 is the "OBJECTIVES". The stakeholder's/ users need to be aware of the final objective of developing a monitoring activity. Based on this response, the following steps for selecting the parameter to monitor and implementing monitoring are clearer and more precise. Accordingly, HOBIM proposes three stages of monitoring decision-making: **1) Definition of the final objectives, 2) Selection of the parameters to monitor, and 3) Implementation of the monitoring activity.** These stages will be detailed in the next sections.

V.3.1 Definition of the objectives

The existing methodologies for the development of in-situ monitoring for occupant behavior assessment in residential building assume a generic general objective. These methodologies don't reflect the real situation on the ground and doesn't meet what is really needed to be

developed from the monitoring activity and doesn't take the heterogeneity and final goals of different stakeholders. Based on that observation and facts, the originality of HOBIM guideline approach is to suggest a list of possible final objectives that will allow the stakeholders to better understand the various outputs of monitoring approach. The following **Figure 64** represents a list of final objectives suggested by HOBIM tool. The definition of one or more final objective permits the set-up of the next phases, and the focus on the output targeted. The objectives are connected, and the achievement of an objective could require the results of previous objectives.

After the identification of one objective or more, the tool will represent a recommendation of the parameters to monitor in order to achieve the objectives targeted (section V.3.2).

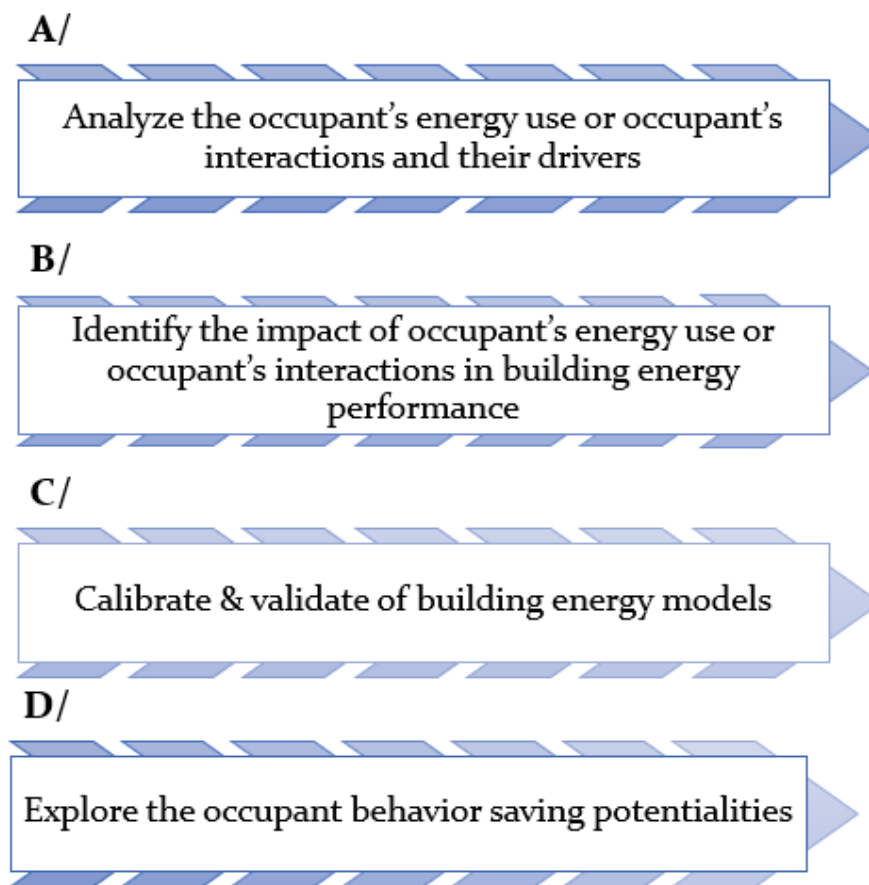


Figure 64: List of final objectives of monitoring approach applied to occupant behavior analysis (stage 1 of phase 1).

V.3.2 Selection of the parameters to monitor

The selection of the parameters to implement in the monitoring approach is proposed based on:

- 1) The final objective defined by the stakeholders,
- 2) The type of energy use or interactions targeted in the study.

The data targeted to occupant behavior assessment could be quantitative and qualitative [16]. In regard to quantitative data, two levels of measures are defined: **i)** direct, and **ii)** indirect. A

direct measure represents the sensors that provide a direct indication about the occupant's interaction with the systems in their environment, such as: windows opening, light on/off, blind on/off, shade on/off and thermostat use. While the indirect measures mainly concern the general consumption that reveals the occupant's energy patterns. The direct measures give an access to each space and system, for this reason they are considered more accurate and precise than the indirect ones. Nevertheless, the indirect measures could be sufficient for certain research and studies, and as explained above the choice will be based on the final objectives targeted. The aim of these measures is to describe the occupant behavior directly by direct measures, or indirectly by indirect measures. In addition to that, contextual environmental and technical data are required to ensure a complete analysis and explanation of the occupant's pattern, especially in the case of indirect measures.

The qualitative data collected from survey methods are essential to support the results of quantitative data analysis [16][17]. The combination between quantitative and qualitative data provide valuable answers to all the questions regarding the nature of occupant behavior and the reason behind. **Table 2** of Chapter I represents a synthesis of the parameters that could be exploited in the monitoring approach for occupant behavior assessment.

In order to provide a guide to the parameter's selection, flowcharts were developed according to the occupants' interactions/patterns studied in chapters III and IV. In this respect, three types of flowcharts were proposed and presented. The difference in the flowcharts remain mainly on the objective 1 where distinct levels of measures are proposed:

- 1) **Lighting use, heating/cooling use:** **Figure 65** and **Figure 66** represent the first two stages of monitoring decision-making phase for analyzing the lighting use and heating/cooling use. The selection of the parameters to monitor depends on the final objective of the study as indicated. These measures regard the identification of the lighting use and heating/cooling use that could be monitored directly or indirectly based on the stakeholder's choice.
- 2) **Windows opening, thermostat use:** If the objective is to explore the windows opening and the thermostat use, only direct measures that reflect the occupants' interactions with windows and thermostat are recommended. These measures are accurate, especially if all the windows and thermostats are monitored. Based on our research, no indirect measures could provide a considerable result comparing to direct measures (**Figure 67, Figure 68**).
- 3) **Electricity use:** the electricity use includes various needs and activities (cooking, TV, washing machine, etc.) which is difficult to monitor each need and interactions separately. Hence, the most important is to investigate the electricity use pattern. **Figure 69** shows that the electricity use could be monitored by implementing a sensor that measures the electricity consumption. This measure is appropriate to describe the electricity use pattern.

The indications developed for the identification of the drivers affecting the occupant behavior (objective 1) are identical for all the flowcharts. As explained above, it is very important to collect the several types of data for a complete and accurate analysis. Regarding the objective 2, two steps are recommended:

- 1) Identification of the occupant behavior based on the indication presented in the objective 1,
- 2) Selection of the Key Performance Indicators (KPIs) in order to define what are the category of impact investigated:
 - The energy consumption impact for each use (heating consumption, lighting consumption, electricity consumption),
 - The indoor comfort impact (thermal comfort, visual comfort and occupant well-being),
 - The environment impact,
 - The economic impact.

The parameters for validation and calibration of energy models (objective 3) should be defined according to the model or simulation tool exploited by the stakeholders. For example, if the simulation tool requires lighting consumption as input, then the lighting consumption must be monitored for the model validation. Therefore, the input of the models will provide the final parameters to monitor.

The achievement of objective 4 requires results and not measurements. If the parameters recommended for the objective 1 and 2 are installed and analyzed, the stakeholders could benefit from the pertinent knowledge identified for proposing strategies that allow the minimization of energy consumption while increasing occupant's comfort.

Lighting use

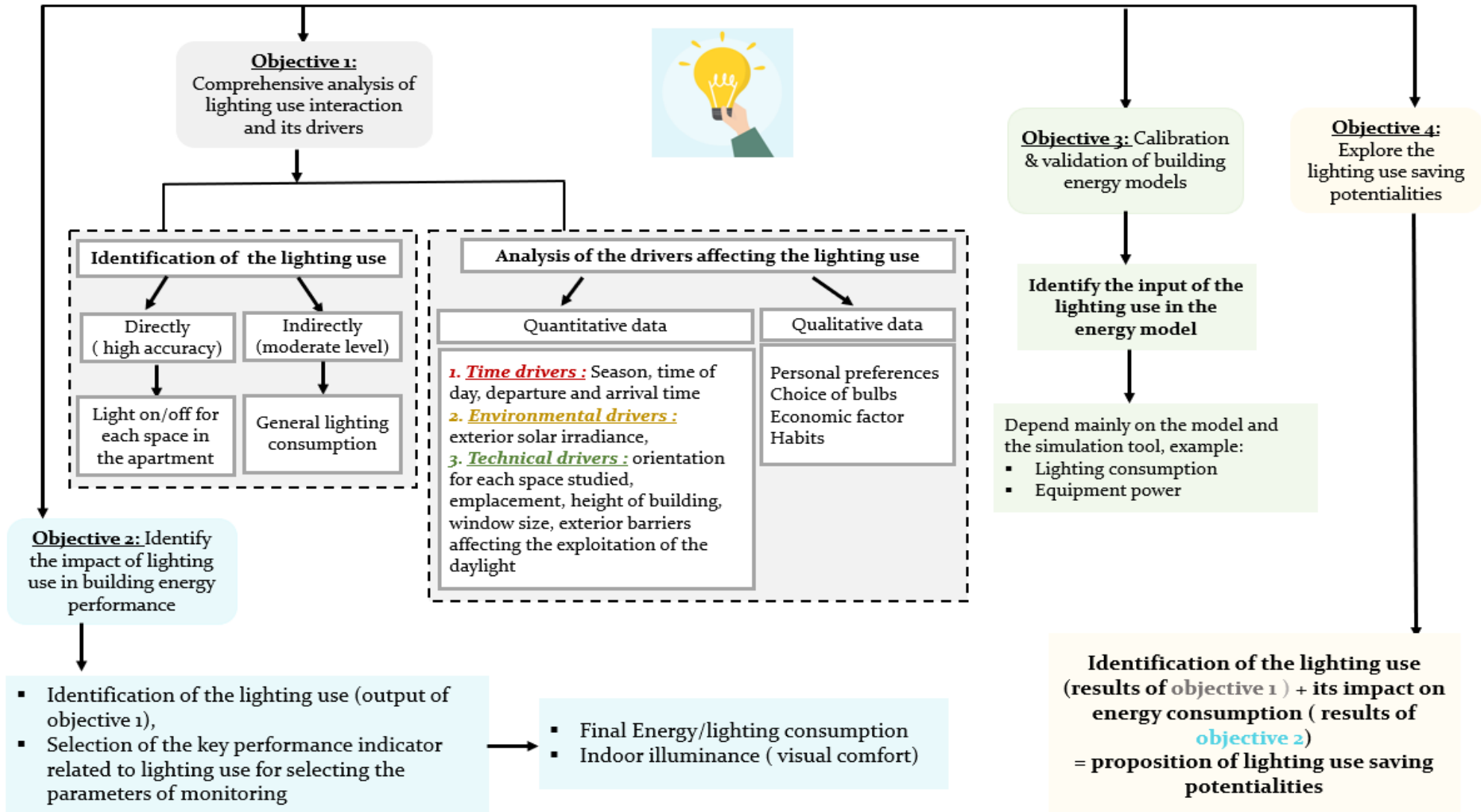


Figure 65: Flowchart of monitoring decision-making of lighting use (stage 1 and 2 of phase 1).

Heating/cooling use

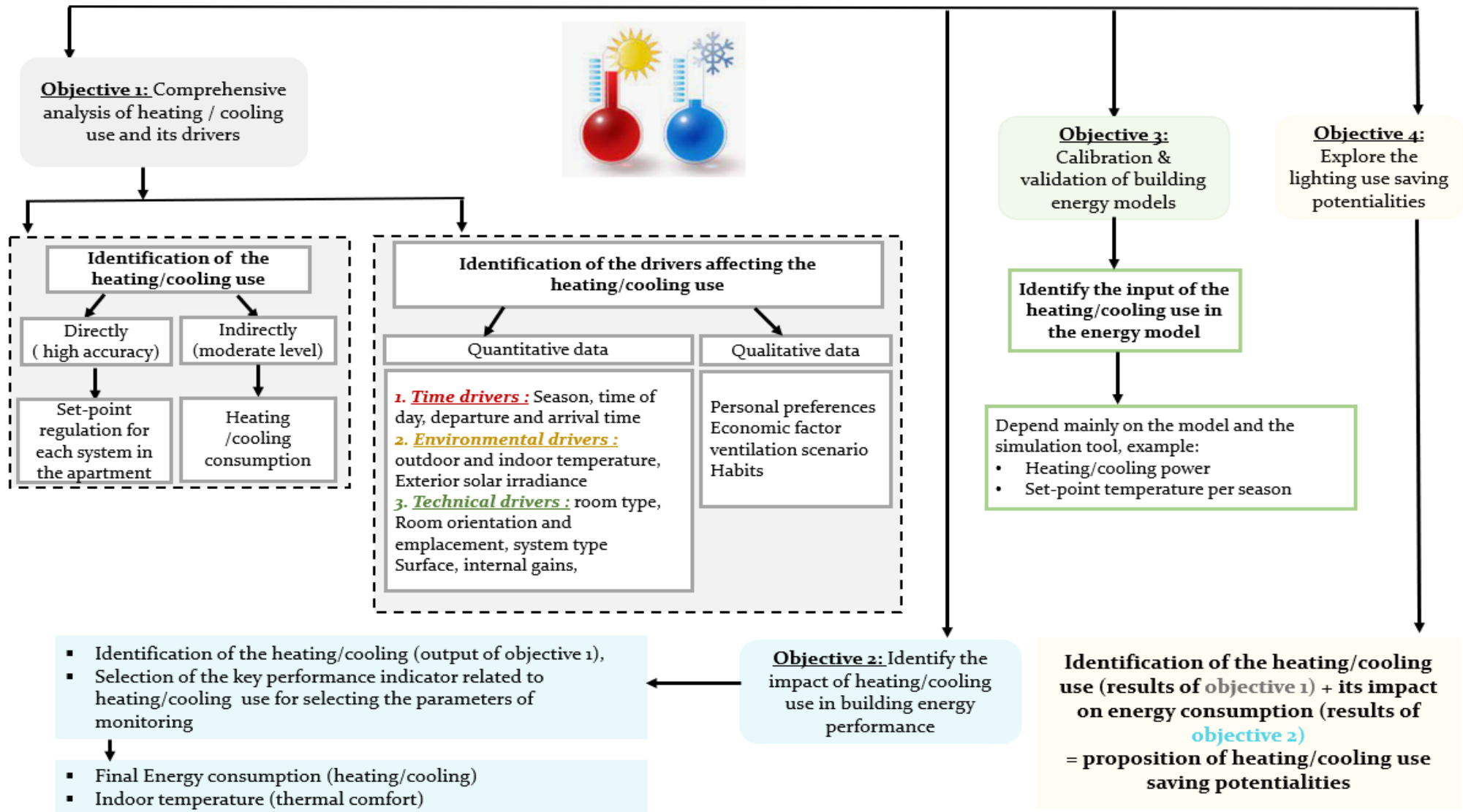


Figure 66: Flowchart of monitoring decision-making of heating/cooling use (stage 1 and 2 of phase 1).

Windows opening

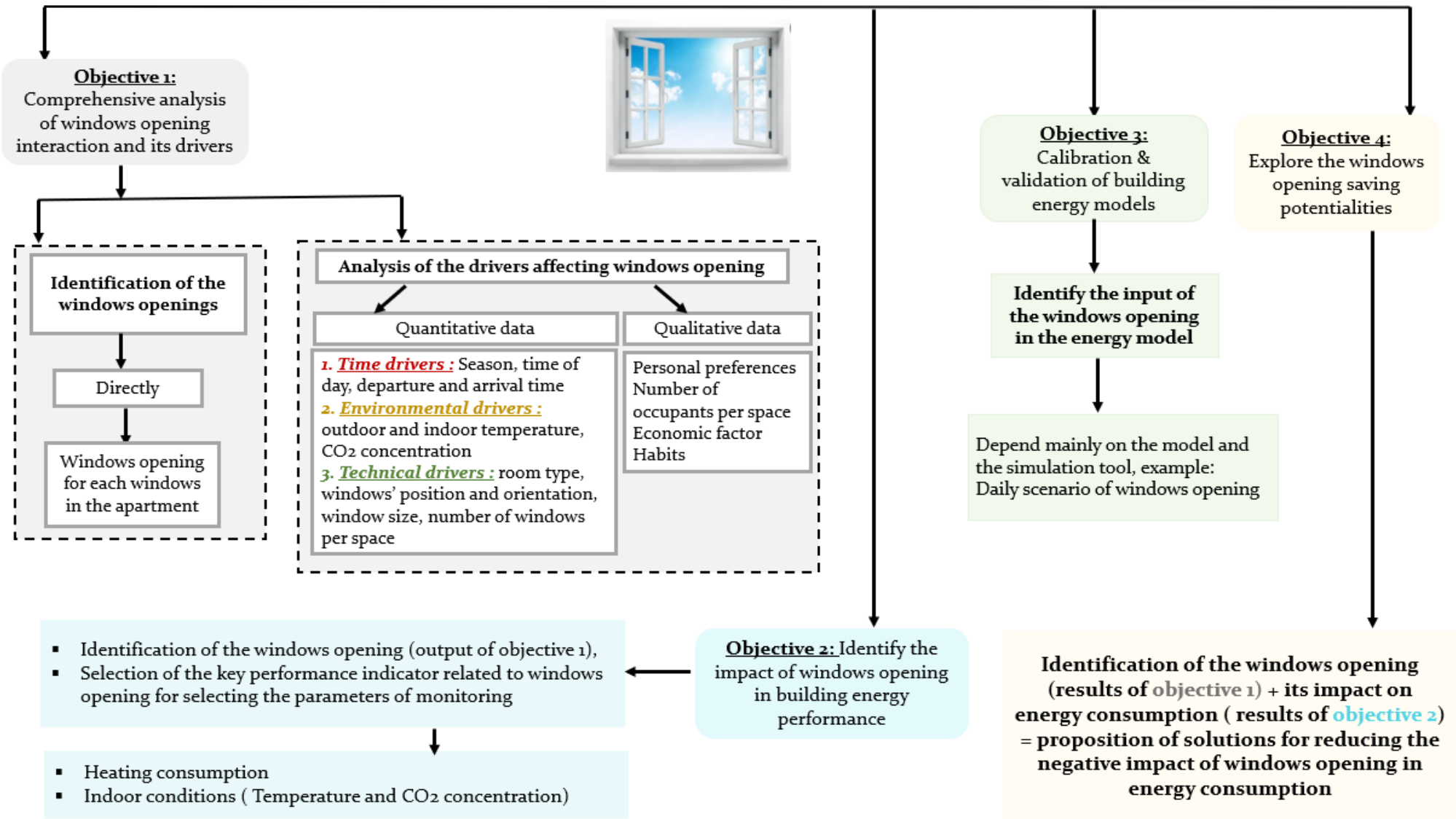


Figure 67: Flowchart of monitoring decision-making of windows opening (stage 1 and 2 of phase 1).

Thermostat use

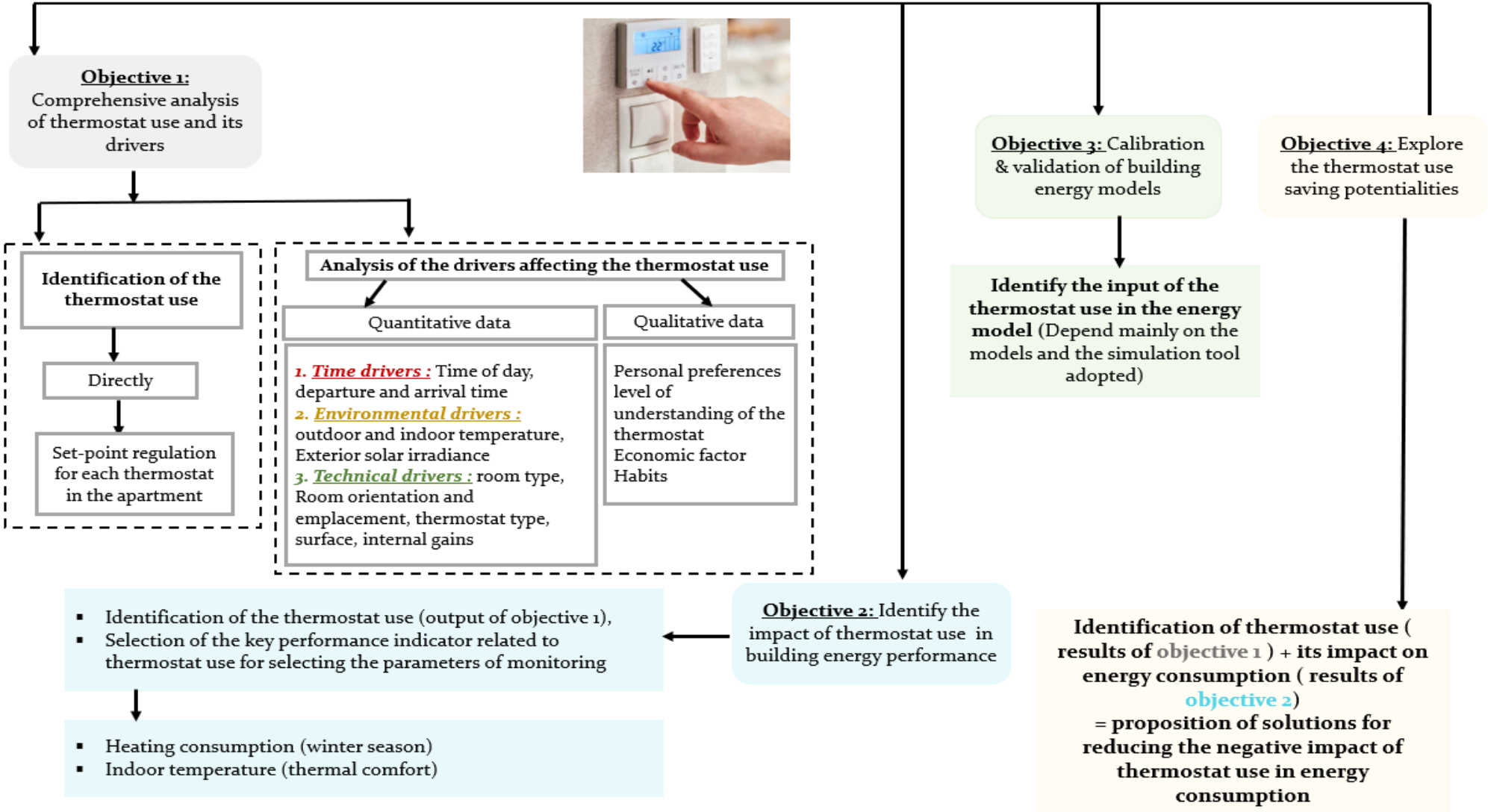


Figure 68: Flowchart of monitoring decision-making of thermostat use (stage 1 and 2 of phase 1).

Electricity use

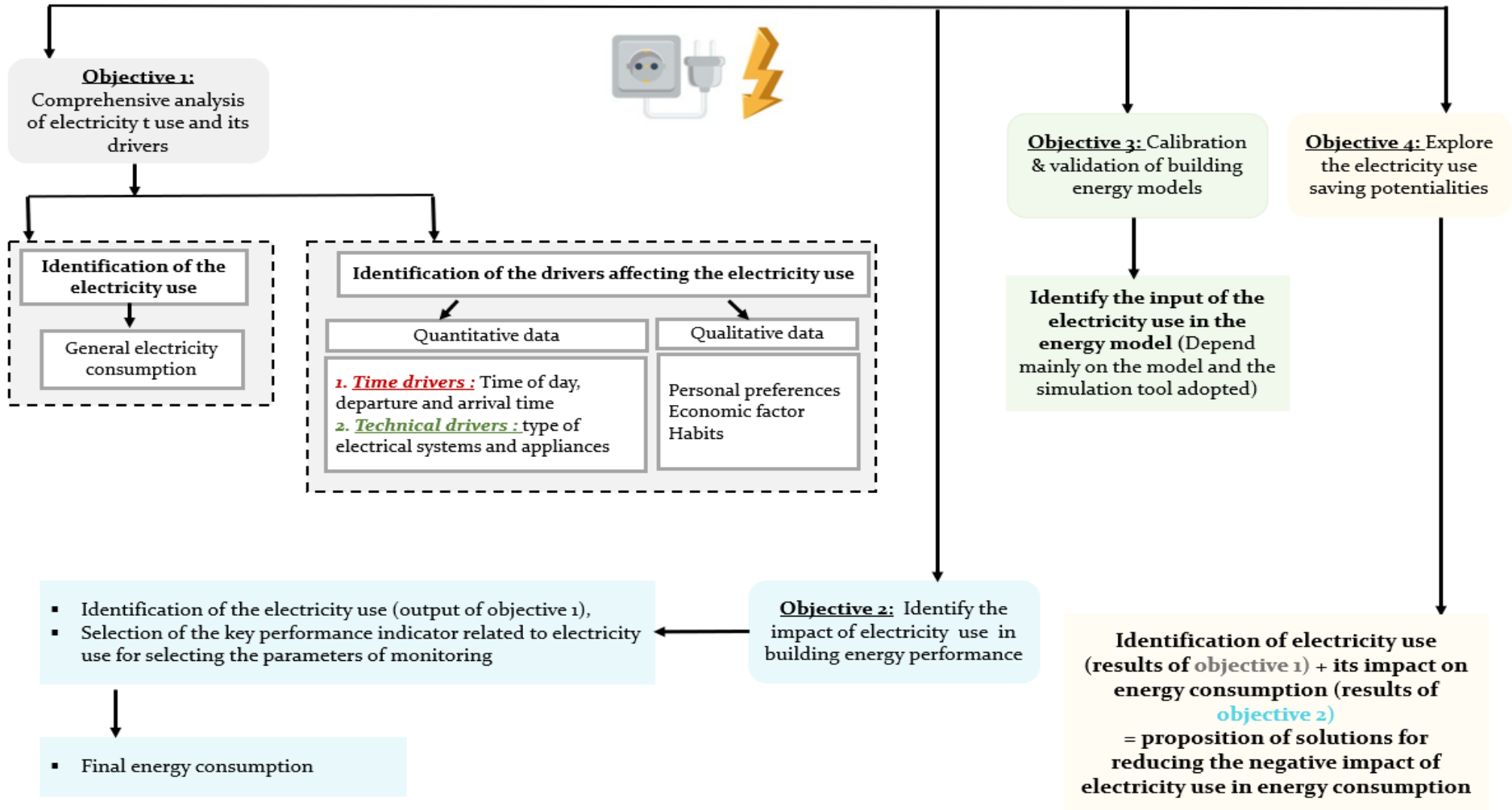


Figure 69: Flowchart of monitoring decision-making of electricity use (stage 1 and 2 of phase 1).

V.3.3 Implementation of monitoring activity and collecting data

After the identification of the parameters to monitor based on the final objective of the in-situ monitoring, six aspects were developed and proposed for the monitoring activity application. The first two aspects focus on the *sampling process*:

1. Definition of the application context and samples' criteria: This research regards the residential buildings; however, additional data are required to establish a final conception of the monitoring activity. Firstly, the definition of the general context: climate, type of building (e.g., social or private building). Secondly, the selection of the samples to monitor (individual house or apartment, the number of the samples, the size of the samples). The stakeholders need to consider the final objectives for the selection of appropriate samples for their study. A development of a list of samples' criteria that corresponds to the final objectives of the research would be helpful.

2. Selection of the participants and the elaboration of the collaboration process: The identification of samples doesn't ensure the acceptance of the occupant's collaboration in the monitoring activity. Consequently, a plan must be prepared in order to present the concept of the in-situ monitoring to the occupants and to convince them in participating in the experience. A complete monitoring can be achieved only if the occupants accept the collaboration, and believe that the measures won't affect their privacy by explaining the sensors functioning. Besides, ethical approval and review are important before the start of monitoring activity according to the procedure of each country and each structure. The objective is that the occupants feel secure and safe and don't doubt about a bad impact of the in-situ measures. The stakeholders must be sure that the occupants will collaborate and help them to finish the mission without constraints and interruption. A particular consideration should be accorded to this aspect that represents one of the reasons that makes the in-situ monitoring activity in residential buildings complicated.

The second two aspects concern the *measuring process*:

3. Identification of the sensors and the system of acquisition: it is important to set all the specifications about the sensors exploited in the monitoring activity: type of sensors, number of sensor and type of system acquisition. These specifications should be adapted to the application context and match with the final objectives. During the data collection period, various technical problems could be revealed, and for this purpose a sufficient level of understanding and operating the sensors and acquisition systems is mandatory. Similarly, for the storage and collection techniques, it is crucial to be aware of all the steps and functioning specifications in order to minimize all the constraints and delays possibilities.

4. Specification of the duration and time step of monitoring: This aspect is affected mainly by the objective of the research. Regarding the duration, it is very recommended to take into consideration the season impact as represented in this research. The longer the duration is, the more the interactions are monitored and the observations about the occupant behavior are intriguing. Concerning the time step, it is recommended to respect the same

time step of the building simulation is the objective is to validate an energy model. For the direct measures, the event-based logging is more privileged and efficient[14]. The indirect measures necessitate that the stakeholders be conscious of the parameter measured and its change frequency, so they can select an appropriate time interval that matches perfectly with their final objectives.

The third two aspects regard the *management process*:

5. Designation of a coordinator of the monitoring activity: the implementation of in-situ monitoring activity requires several skills and it is extremely time consuming. Building managers, sensors installers, technician and other person could be involved in the process of the implementation and data collection. In order to avoid all the unnecessary delays, communication lacks between these persons and other problems, it is recommended to design one person who is capable of coordinating successfully during all the period of the in-situ monitoring.

6. Final verification: at the end of all the steps mentioned above, a final check of the implementation process is an asset. It will help to verify the satisfaction of the objectives designed and the application’s success. A documentation and an explanation of all the performed steps should also be afforded.

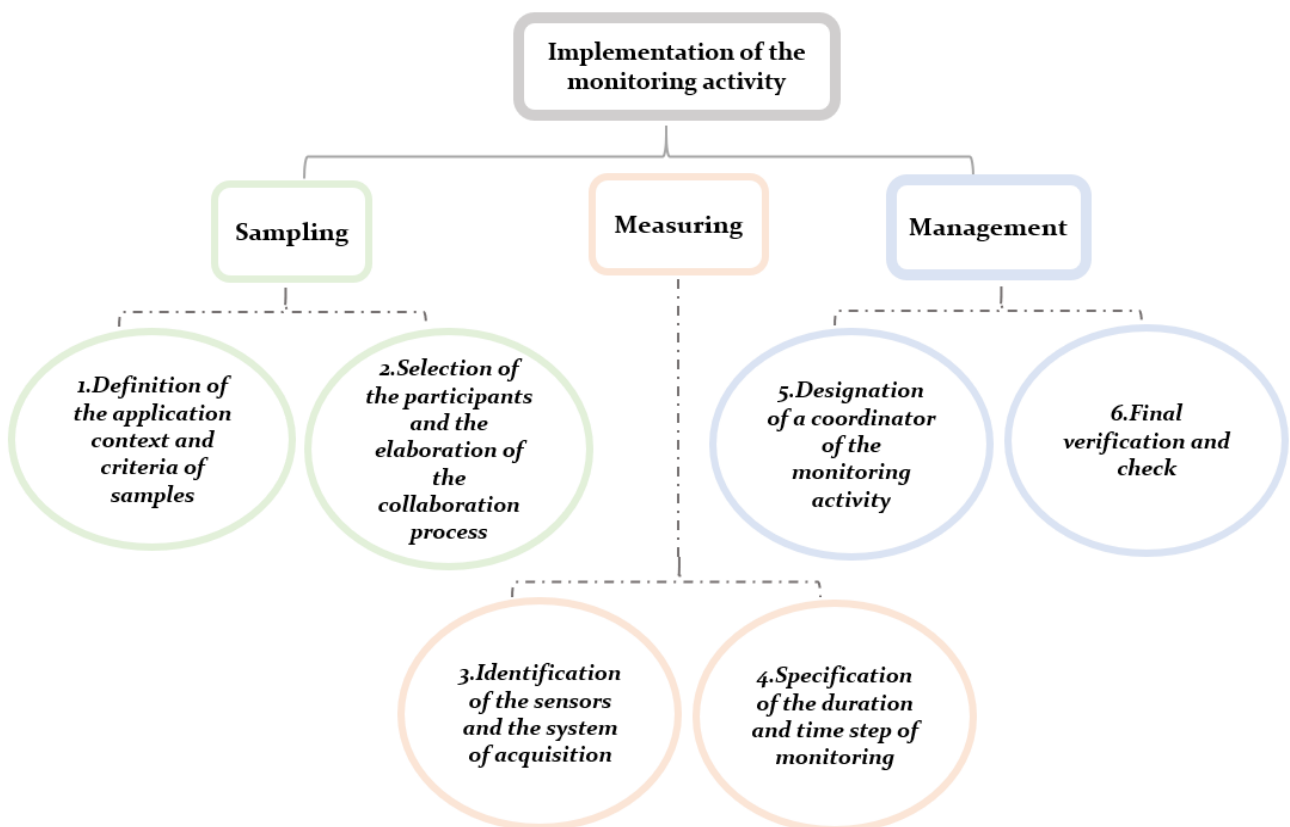


Figure 70: Synthesis of the monitoring activity implementation (stage 3 of phase 1).

V.4 Phase 2: Data analysis

The second phase that comes after implementing the monitoring and collecting the data is the data analysis. This phase represents the process of transforming data into knowledge, and it should correspond to the final objective of the monitoring activity developed. In the context of this research a methodology was presented in Chapter III and IV that reflects our perspective in describing and analyzing the occupant behavior and the drivers affecting it in residential buildings. In the literature, several technics were developed and represented by researchers for analyzing the data and for the model development of occupant behavior [14][16]. Thus, it is recommended to be open to any technique or tool that will help the stakeholders to achieve their final goals and the knowledge targeted.

The methodology adopted in this research was explained and detailed in each section for the different interactions and measures studied. Consequently, a chart synthesis of the general procedure is represented in **Figure 71**. The concept of the methodology proposed is to guide the stakeholders to the main steps of data analysis. The first thing to start with is the selection of the final data set to investigate. This final data set should consider the goal of the analysis which will impose some connected parameters to include in the data set (environmental, technical and qualitative data). In our perspective, it was necessary to select first the period and spaces targeted (if several sensors were installed in different spaces). Then, other parameters will be explored in order to better understand the interactions and the patterns described by the direct and indirect measures. It is deduced that the more the data is available and complete, the more the reflections and conclusions are accurate and precise (**Figure 71**). The table presented in **Figure 71** indicates that the direct measures about occupant behavior are more precise than the indirect measures. Additionally, the methodology developed in this thesis provide four types of data to analyze for a comprehensive analysis of the occupant behavior. The more the contextual, environmental, technical and qualitative data are available and accurate, the more the results of the analysis are considered reliable.

Due to the stochastic nature of occupant behavior and the various factors affecting it, it is very complicated to define a final characterization of the behavior in residential buildings. The accuracy of the results should be evaluated by performing a sensitivity analysis that takes into consideration the following aspects [123]:

- The accuracy and completeness of the measured data (sensors and the system of acquisition),
- Availability of all the data connected to the occupants' interactions (contextual, environmental, and qualitative data),
- Sample sizes, number of samples and time step,
- Approach of the analysis (methodology, technics and software adopted).

If we suppose that the quantitative data are accurate and complete, the results could show inexplicable behavior such as using the artificial light during the day when the exterior solar irradiance is at the maximum. In this respect, the qualitative data where occupants could

explain the nature of this behavior are necessary. Otherwise, the results are represented as suppositions and subjective reflections.

The analysis of occupants' interactions and patterns is a very rich experience. The combination between the technical and human factors is so interesting and reflects how it is important to consider the both aspects in analyzing the building energy performance. The analysis of occupant behavior must consider in parallel that the personal preferences and needs of occupants will play a major role in the interactions and the patterns. These factors are variable and depend on each occupant, and could not be predicted. The impact of these factors imposes a margin of uncertainty that must be considered in all the analysis and results process.

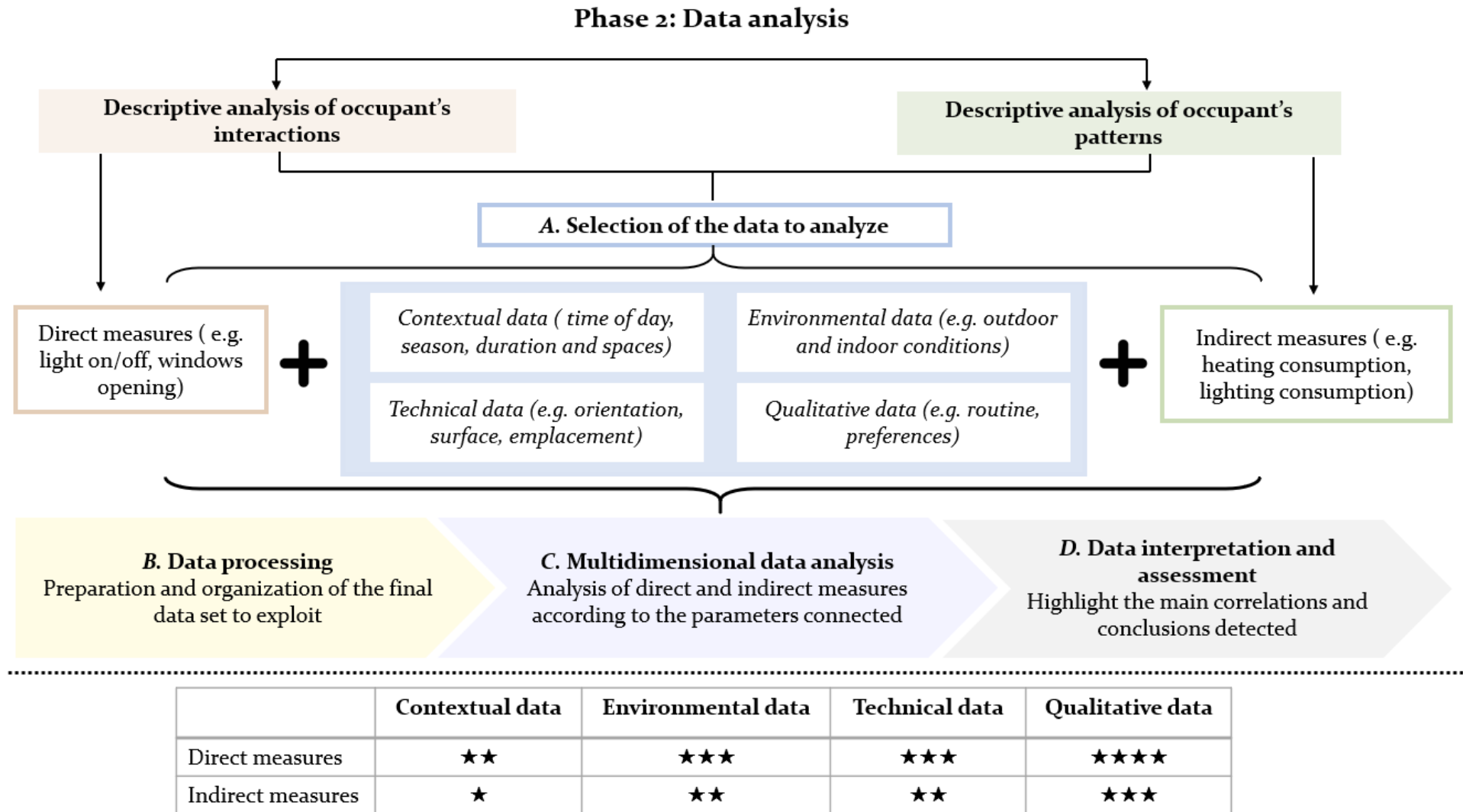


Figure 71: Synthesis of data analysis methodology developed in this research (phase 2).

V.5 Phase 3: valorization

The final phase of HOBIM process is the valorization of the knowledge developed in the second phase of data analysis. It represents the accomplishment of the objectives targeted in the first phase of monitoring decision-making, and it is what gives a real efficiency of the work performed above. For this purpose, it is very important to think about what and how the results of the previous phases will be exploited.

A descriptive analysis of the occupant's interactions/patterns, and the drivers affecting the occupant behavior is one of the primary achievements of the monitoring approach. It is confirmed based on the literature review (Chapter I) that the occupant behavior in residential building is an important factor in the building energy performance analysis. The analysis of occupant behavior in residential buildings is more challenging and complex. Thus, all the results from the descriptive analysis represent a significant contribution in this field. The goal is to collect the maximum possible of contributions in order to generate an occupant behavior model.

Another question could be answered by the knowledge gathered from the monitoring approach is: how the occupant behavior affects the building energy performance? A major issue to explore for increasing more and more the scientific awareness about the occupant behavior, and the involvement of this aspect in the conception phase of buildings.

The results of monitoring approach are pertinent input for energy models with a view to decrease the disparities between the results of simulation and the real building energy performance[124]. If the occupancy schedules and interactions are calibrated with accurate measures, a clear reflection of building operation is ensured. The parameters to calibrate depend on the tool of building energy simulation adopted for the modeling and simulations.

Based on the understanding of the several drivers affecting the occupant behavior, the perspective of investigating the energy saving potentialities is important. It could be developed by proposing or contributing to solutions that aims to engage the occupants in the process of building energy efficiency, or by including some modifications in the building design for saving energy.

V.6 Conclusion

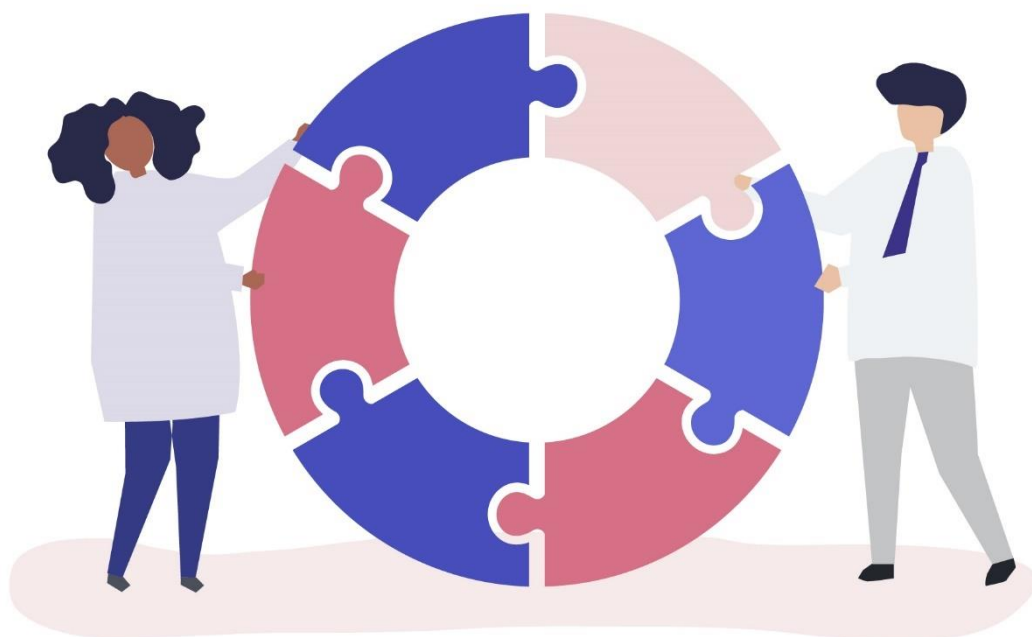
This Chapter represents the final results of this research. Based on the previous work presented in this thesis (Chapter I,II,III and IV) the development of HOBIM guideline was achieved. The main objective of this guideline is to provide a methodology that supports the assessment of occupant behavior in residential building by the monitoring approach. The first section represents the definition of the guideline and introduces the main three phases proposed. The phases indicate the order of the steps to follow for a successful implementation, analysis and the valorization of the monitoring approach.

The first phase of monitoring decision-making is considered an important step for the design definition of the monitoring approach. It includes three steps, starting by the definition of the final objectives from the approach that will guide the stakeholders to focus on the final output from the work, or developing other perspectives. In addition, it will help them to identify the appropriate parameter to monitor by giving indications about the types of data (quantitative and qualitative data), and the level of measures (direct and indirect). Finally, the phase 1 proposes instructions for implementation and collecting the data. The instructions regard the sampling, measuring and management process of monitoring approach.

The phase 2 of the guideline represents a synthesis of the methodology developed in this research for data analysis. Our methodology proposes to the classification of the data analysis based on the parameters monitored: analysis of occupants' interactions or occupants' patterns. The precision of the results in the occupant behavior research is a major issue, especially that the personal preferences and needs affect significantly the energy use. Finally, an overview of the valorization of data analysis results that corresponds to the final objectives is included in the phase 3 of the guideline.

The HOBIM guideline is a connected process of the three phases represented where it is recommended to carefully specify the final objective that will guide the stakeholders to take the appropriate decisions. A correct consideration of all the stages guarantees a successful in-situ monitoring, and considerable results of occupant behavior assessment in residential buildings.

Conclusion & perspectives



General Conclusion

The research developed in this thesis contributes to the occupant behavior analysis in residential buildings. The studies of building energy performance are assessed complete only if both technical and human factors are included. These factors play a major role in increasing or decreasing the building energy efficiency, however the occupant behavior has been neglected for a long time. Currently, the consideration of occupant behavior in the energy analysis of buildings becomes a necessity. Based on occupant behavior consideration and monitoring approach, this thesis focuses on the exploitation of in-situ monitoring approach in residential buildings for occupant behavior analysis. The goal of this research work is to develop a holistic methodology for the design, implementation of monitoring approach, and for the analysis of monitoring approach data toward a better understanding of the occupant behavior and its drivers in different types of residential buildings. Three types of buildings were investigated: smart, private and social housing and seven apartments were studied. In this research, two seasons were analyzed: winter and summer.

The selection of the case studies and the data to analyze was a crucial phase in this thesis. Firstly, an in-situ monitoring was developed for a **social housing** in order to understand completely all the phases, constraints and elements that should be prepared for the development of a monitoring activity. Secondly, the research of other data set that monitor the occupant behavior in residential building was carried out for covering the maximum of occupants' interactions. The variety of the context was also an important aspect to analyze in this research in order to define how the buildings' types could affect the occupant behavior, and whether the drivers are similar for all the buildings. In fact, the more the buildings are different, the more the monitoring activity could be implemented differently. This was the aim of Chapter II where all the details about the three targeted buildings were presented with a detailed comparative analysis.

A comprehensive analysis of occupant behavior in a **smart building** was represented in Chapter III. The goal is to propose a methodology for analyzing the occupants' interactions. In this case study, the measures were considered direct and with high accuracy. Different sensors were installed in each space of the apartment for monitoring the occupants' interactions with windows, light and thermostat. The proposed methodology aims to provide a description of the occupants' interactions targeted in winter and summer seasons, and to explore the various measures in the data set. Thus, the assessment of the occupant behavior and the identification of the drivers affecting it were performed.

Continuously, the occupant behavior was investigated in the case of **private buildings**. The data set of this case study provide indirect measures. Hence, these types of measures provide a description of occupants' patterns and don't give assessment for direct interactions. Similarly, a methodology was proposed for the identification of the occupants' patterns and its drivers. In the same Chapter IV, the occupant behavior was analyzed in the case of social housing with a comparative analysis between the occupant behavior before the first lockdown

and during it. The lighting use, heating use and electricity use were the targeted patterns studied in part of the research. The results show that the electricity use was increased by 22% during the period of the lockdown analyzed, and a percentage of 13% was detected for lighting use.

The employment of the knowledge discovery data base in the analysis process helped to determine the importance of analyzing each parameter and measure accurately. As a matter of fact, the analysis of occupant behavior could not be complete without the investigation of the contextual, technical, and environmental data. The results show that the drivers affecting the occupant behavior are different and depend on: 1) the context of the study (types of buildings and seasons), and 2) the types of the interactions or the energy use. Thus, the analysis conducted in this thesis reveals the necessity to establish a connection between the different types of parameters for a complete assessment of the occupant behavior. Furthermore, the qualitative data represent a significant input for the understanding of specific patterns, and for the confirmation of various suppositions performed in the analysis process.

In order to valorize all the important research work developed in Chapters 1,2,3 and4, Chapter V expands the knowledge identified from occupant behavior assessment based on the monitoring approach, in the different case studies into a guide. The concept of the guide is to support the building energy stakeholders in the adoption of in-situ monitoring for the occupant behavior analysis, especially in residential buildings. It is considered as a holistic methodology which provides all the phases for designing and implementing the monitoring activity. Furthermore, recommendations for data collection, analysis and valorization were developed.

Outlook and perspectives

A broad study of the occupant behavior assessment in the residential buildings was carried out towards the exploitation on in-situ monitoring approach. Several occupants' interactions and patterns were analyzed with the view of analyzing the occupant behavior in smart, private and social housing. The exploration of the drivers affecting the occupant behavior was performed by analyzing the contextual, technical and environmental data. Furthermore, a comprehensive methodology for supporting the application of the in-situ monitoring was developed in order to support the integration of the monitoring approach in residential buildings.

The results represented in this research work contribute to the assessment of occupant behavior in residential buildings to better understand the different energy use patterns and what really affect this use. It also increases the awareness about considering the types of buildings and types of measures to implement, and how the data should be connected to perform a complete analysis. Additionally, this thesis develops a detailed guide about the integration of monitoring approach in the further studies about the occupant behavior assessment in residential buildings.

The methodology developed in this research represents a potential approach to implement in Morocco residential buildings. A monitoring activity will be developed in an individual house localized in the south of Morocco to monitor the occupant behavior. The parameters monitored are:

- Temperature, humidity and CO₂ sensors,
- Windows opening/closing sensors,
- Shading device position (linear wire potentiometer),
- Temperature, humidity and air velocity at the entrance and at the exit of the ground heat exchanger,
- Energy meters for each usage,
- Hot water and cold-water consumption meter.

The modification of the analysis context will certainly generate different occupants' patterns. This research will allow us to better understand the impact of different weather conditions, cultural factors and also the different way of using energy sources.

Furthermore, subsequent research should analyze the blind/curtains interactions, and domestic hot water use for covering all the occupants' interactions in residential sector. The extension of the analysis to examine the autumn and spring season could be an important point to specify the impact of moderate outdoor temperature and solar irradiance on the energy use. The analysis of similar measures with a time step inferior or superior to the ones used in this research is also an important aspect to explore. It will help to provide an optimization of the accurate time steps to consider in the analysis of each interactions and patterns.

Moreover, the exploitation of the results developed in this research could be employed for the investigation of the occupant behavior impact on building energy performance. Also, the results could be used for exploring the energy saving potentialities by proposing some strategies for reducing the energy consumption.

The impact of the lockdown restrictions on occupant behavior should include further period of the year and other types of buildings for supporting the results developed in this research.

Finally, the investigation of the occupant behavior in other climate context, different cultural background and in various types of buildings is highly recommended to increase the understanding of this behavior.

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Appendix A



Figure 72: Evolution of the outdoor temperature according to windows opening in Kitchen and Stay (from 01/01 to 10/01).

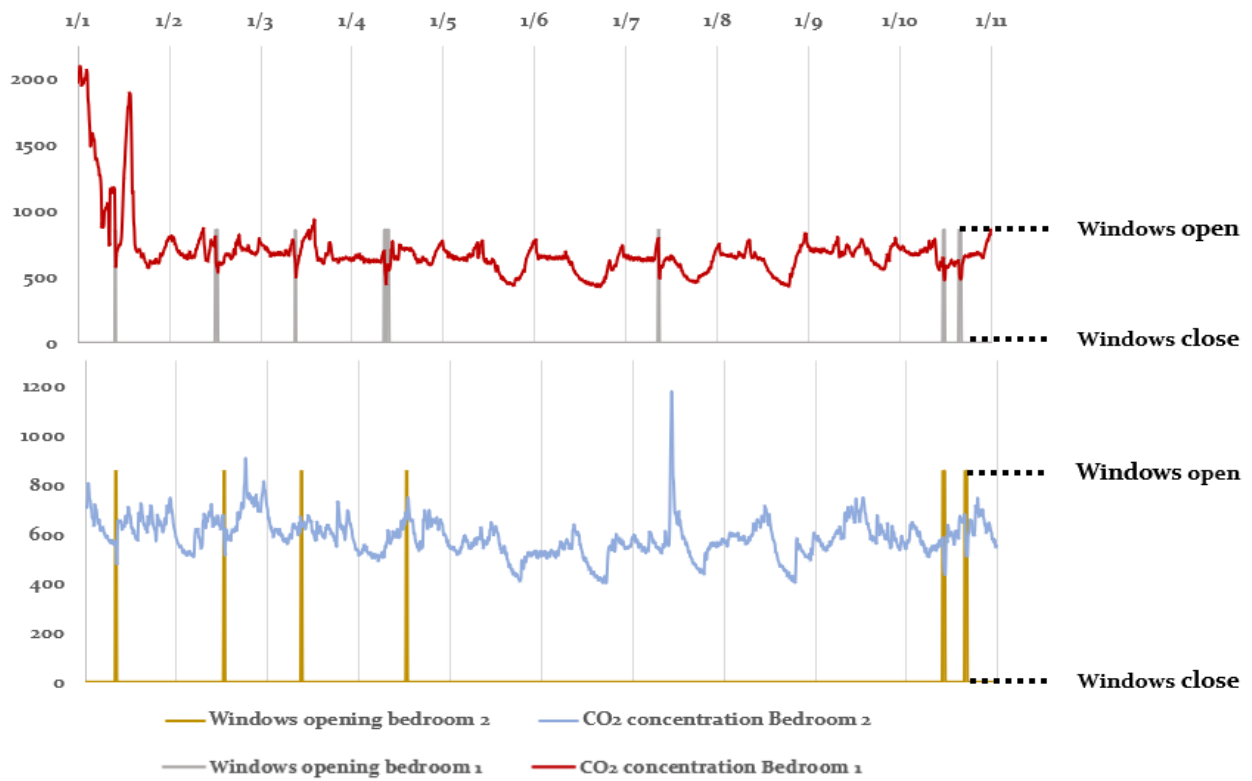


Figure 73: Evolution of CO₂ concentration according to windows opening in bedroom 1 & 2 in the period of 01/01 to 10/01.

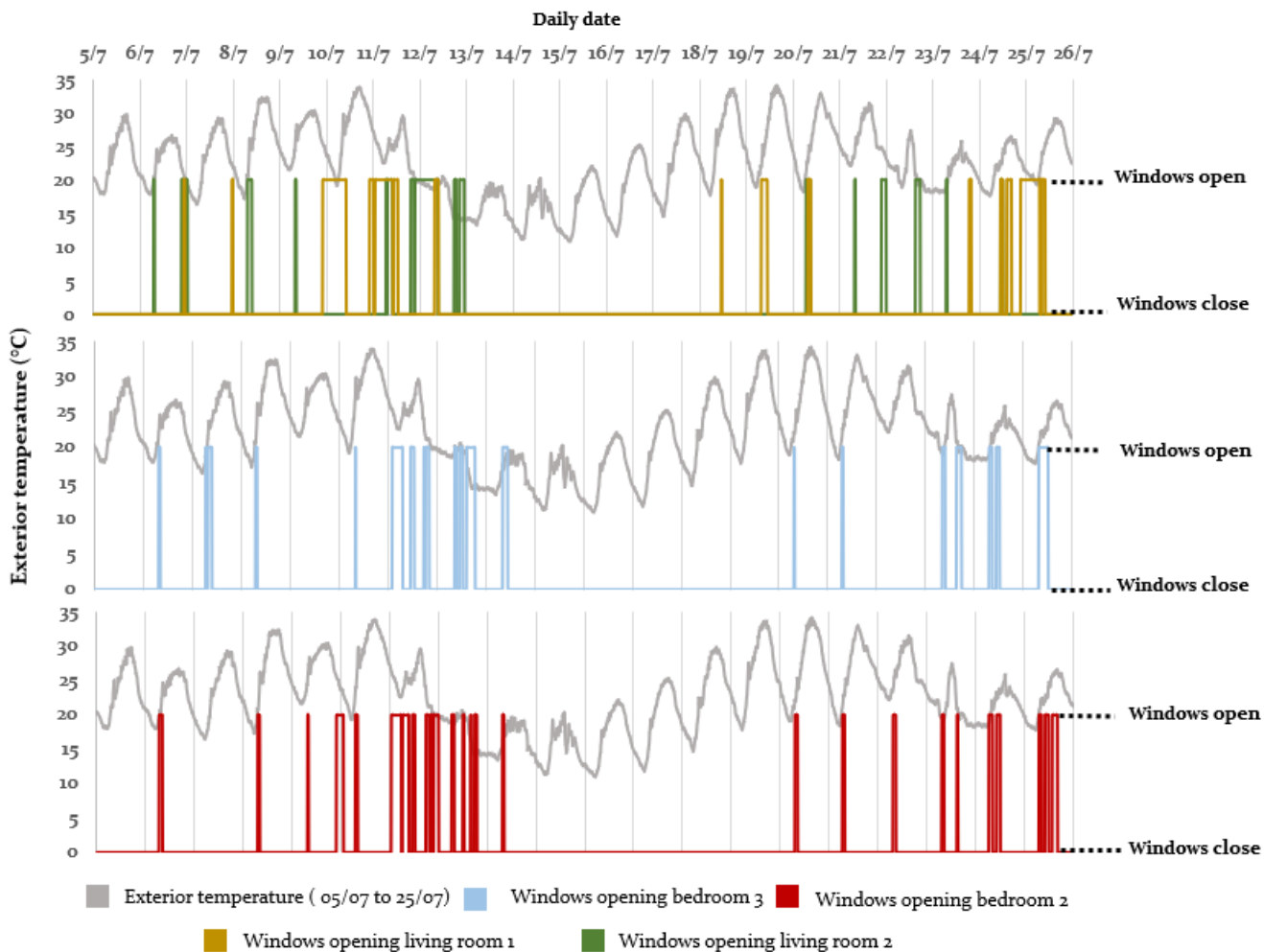


Figure 74: Evolution of outdoor temperature according to windows opening in bedroom 2,3 and living room from 05/07 to 25/07.

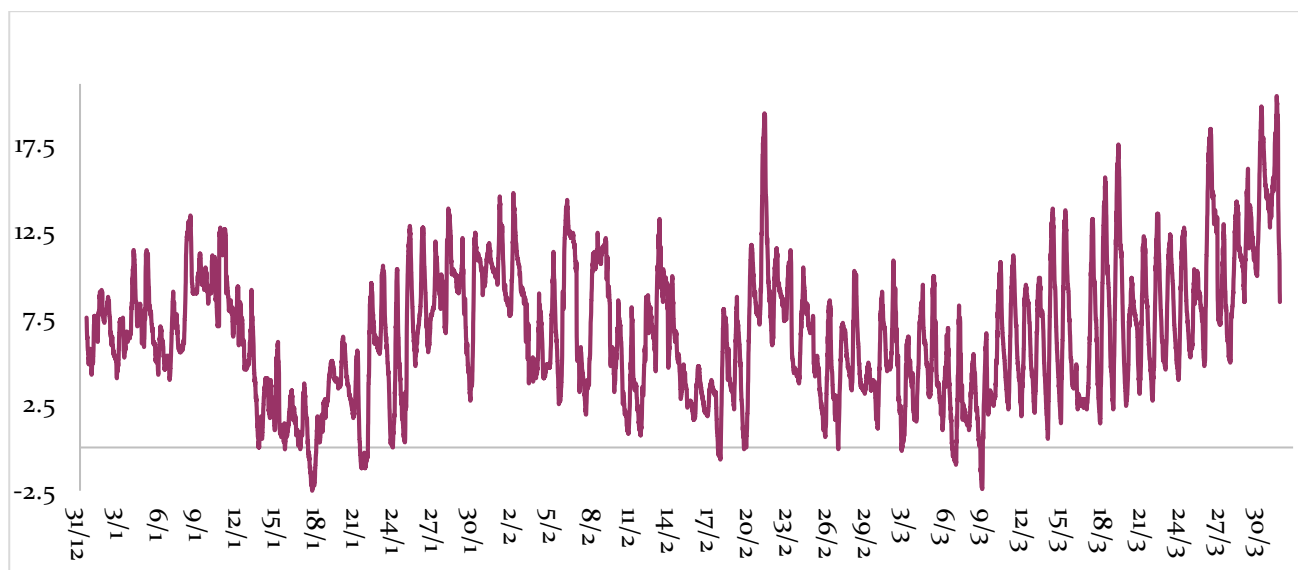


Figure 75: Evolution of outdoor temperature from January to March.

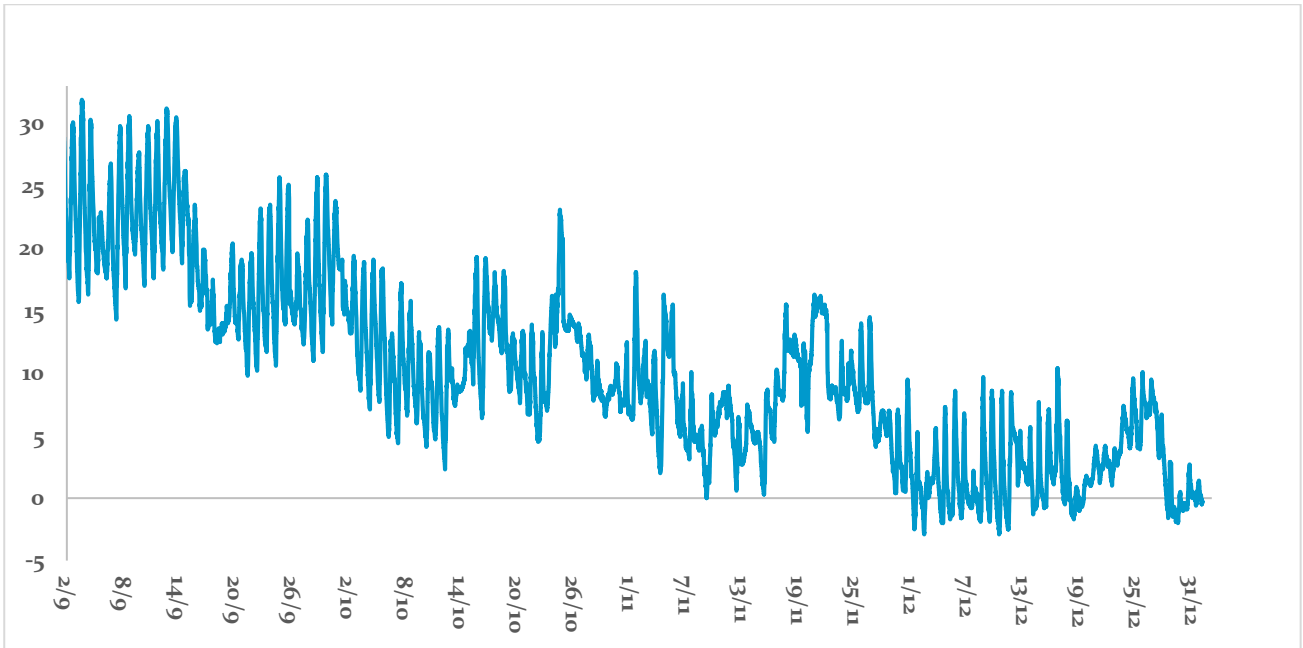


Figure 76: Evolution of outdoor temperature from September to December.

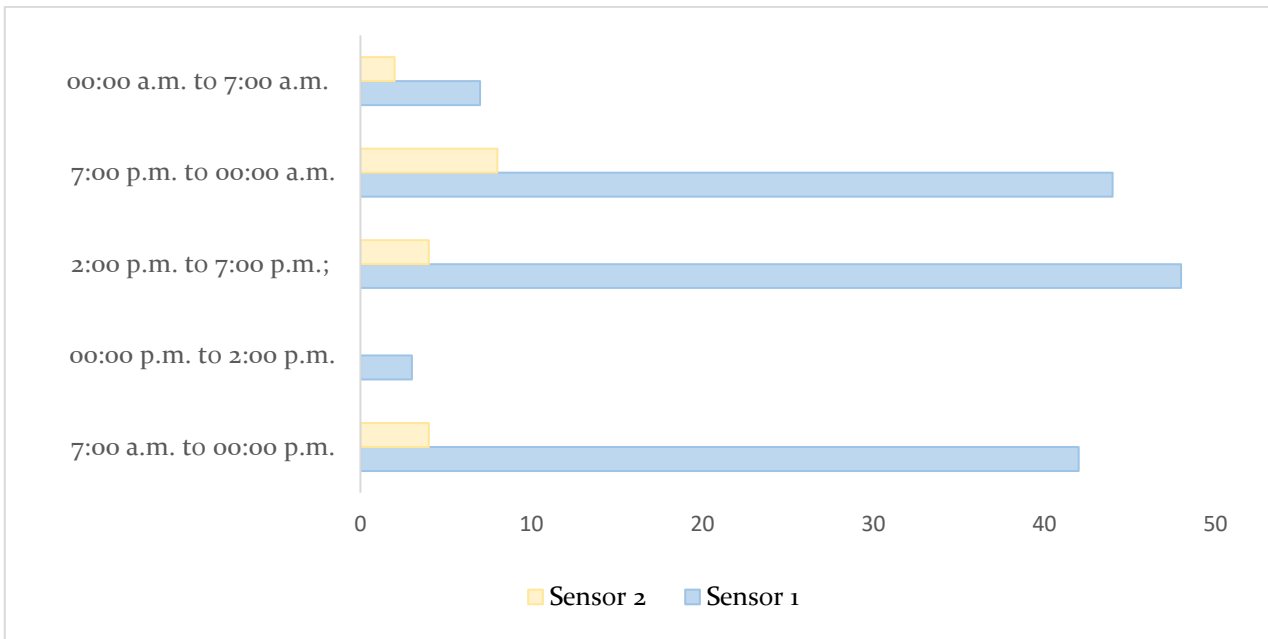


Figure 77: Artificial lighting use in the living-room according to each time slot for winter.

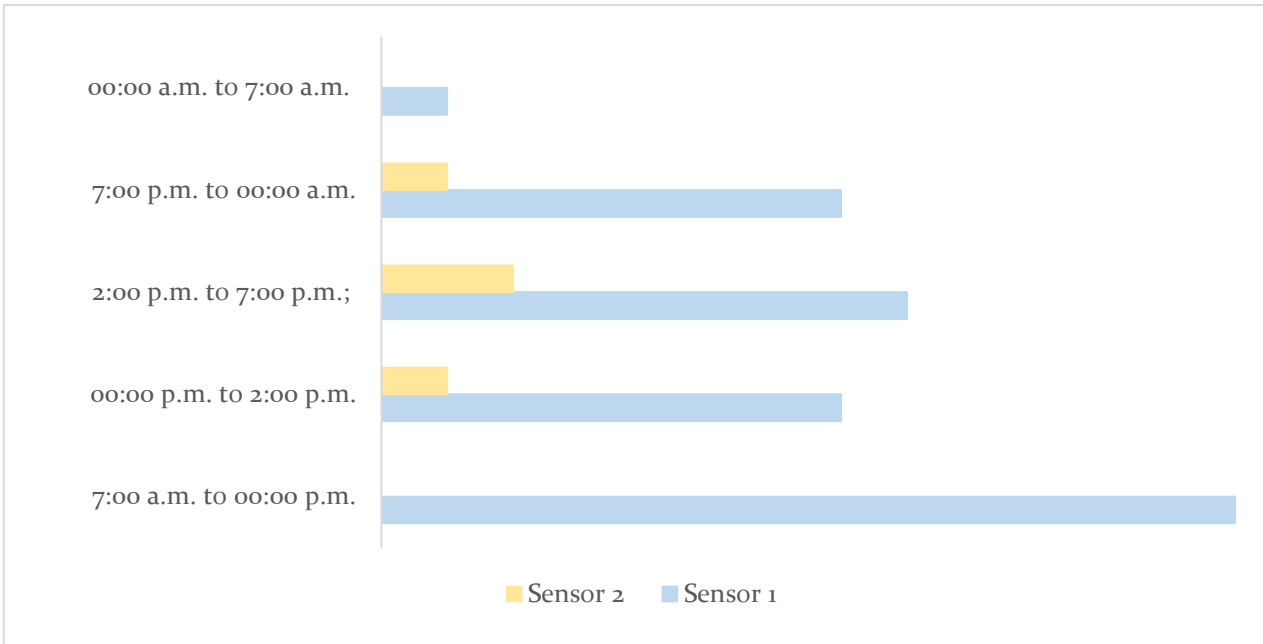


Figure 78: Lighting use in the living-room according to each timeslot for summer.

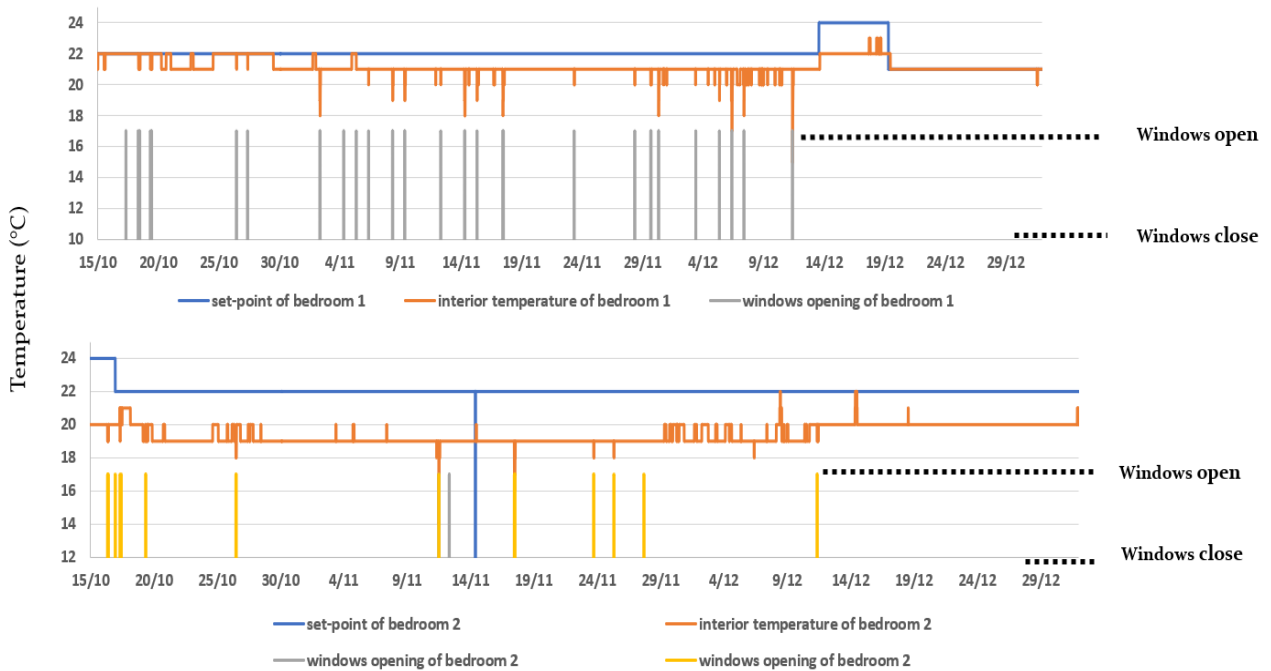


Figure 79: Evolution of indoor temperature, windows opening and set-point regulation for bedroom 1 & 2 in the period from October to December.

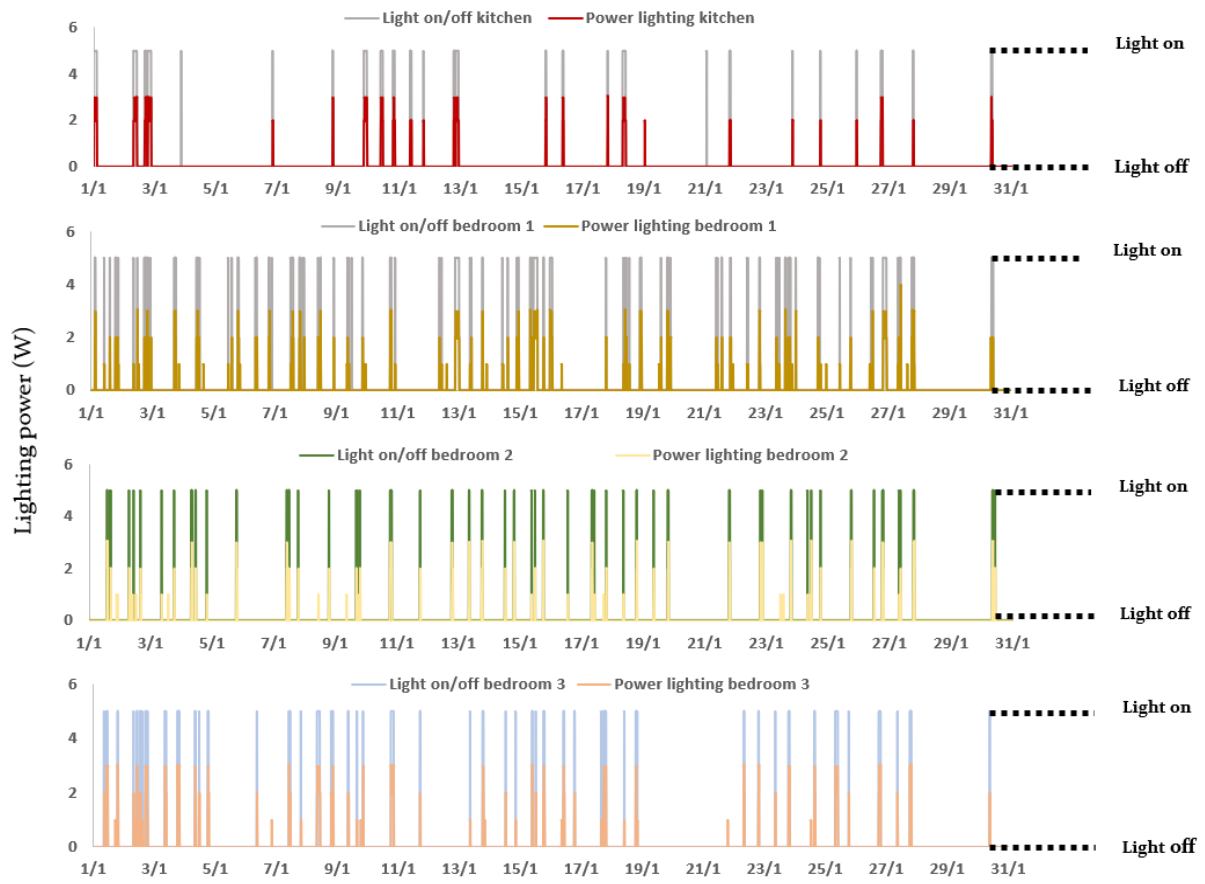


Figure 8o: comparison of the lighting power and light on data on January.

Appendix B

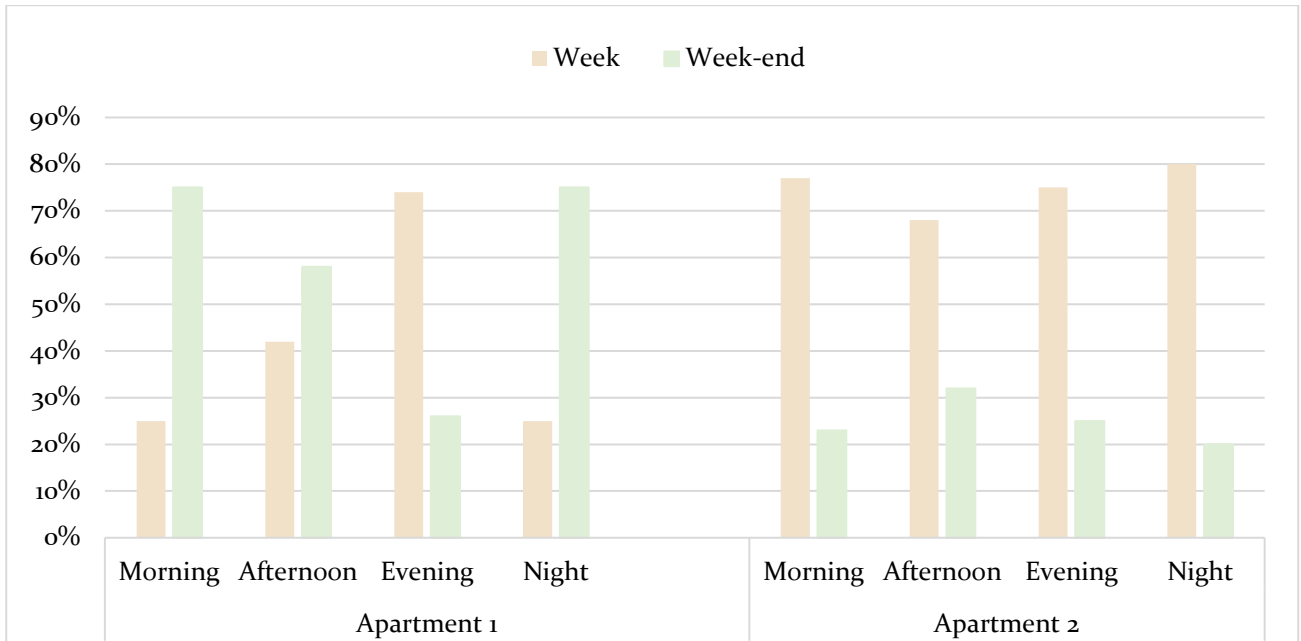


Figure 81: Analysis of peak's frequency of lighting use in winter according to the weekdays and weekend for apartment 1 and 2 (LES GENTIANES case study).

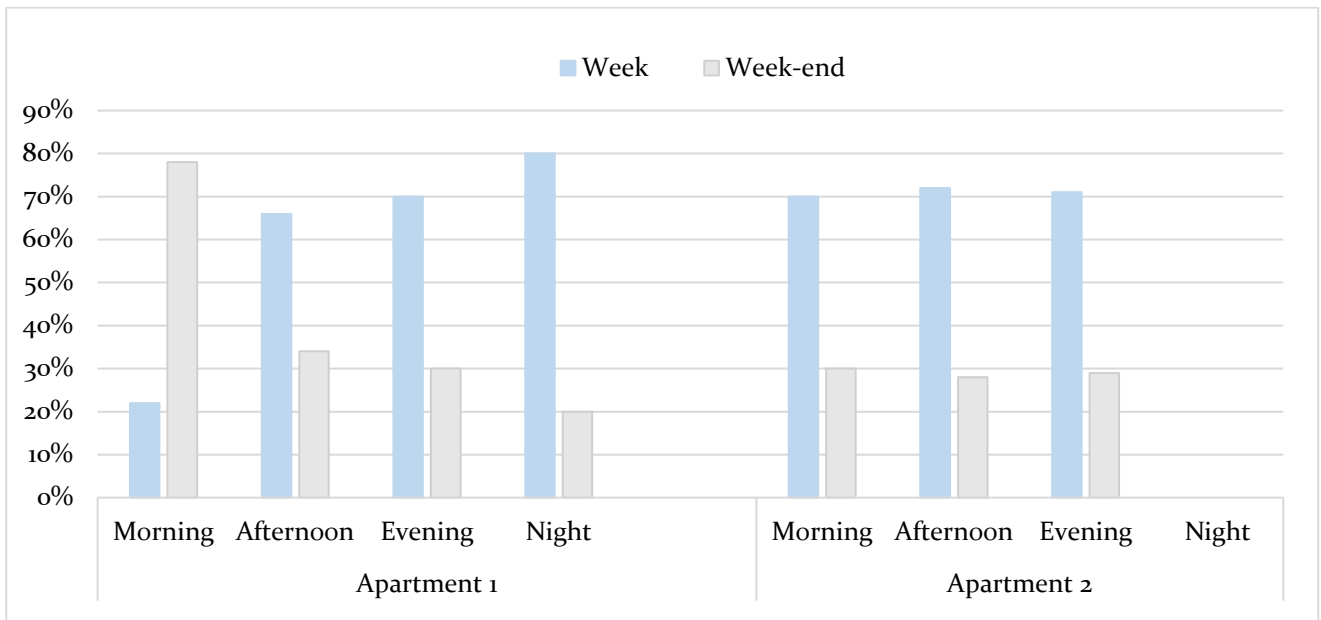


Figure 82: Analysis of peak's frequency of lighting use in summer according to the weekdays and weekend for apartment 1 and 2 (LES GENTIANES case study).

Table 17: Results of the heating consumption clustering according to interior and exterior conditions.

	Heating consumption / outdoor temperature		Heating consumption/ exterior solar irradiance		Heating consumption/ indoor temperature	
	Proposed segments	Observation percentage	Proposed segments	Observation percentage	Proposed segments	Observation percentage
Cluster 1	-5°C - 0°C	39 %	0-75 (W/m ²)	76 %	14°C - 19°C	46 %
Cluster 2	0°C - 9°C	41 %	75-250 (W/m ²)	16 %	19°C - 20°C	37 %
Cluster 3	9°C - 16°C	20 %	250-600 (W/m ²)	8 %	20°C - 22°C	18 %