# Multidisciplinary post-occupancy evaluation of a multifamily house: An example linking sociological, energy and LCA studies

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## Authors

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## Abstract

The way humans interact within buildings strongly affect building energy consumptions and environmental impacts. In addition, the building and its environment influence the human way of life. Human-building interactions are thus of interest in both engineering domains and social sciences. However, building engineering and social sciences are rarely suited by each other. In this article, a multidisciplinary post-occupancy evaluation of a new fully inhabited rental multifamily house is undertaken. A key feature is the contribution of a sociologist and engineers on the performance assessment of one building. Each actor performed separately: i) an immersive and co-

reflexive sociological study, based on in-situ discussions, with inhabitants; ii) a study of energy consumption and indoor environment through onsite measurements; iii) a life cycle assessment. Then, for the first time a sociologist and engineers cross-analysed their results and identified five convergence points studied from different perspectives in each discipline. They are related to people, health, outdoor conditions, use of systems and norms. The disciplinary and combined results are useful to improve the design of future buildings and the conditions of existing buildings. This article offers a baseline for a broader interdisciplinary analysis of building performances by issuing recommendations for future studies.

## Keywords

Human-Building interaction; Social sciences; Building Energy Performance; Life Cycle Assessment; Post-occupancy Evaluation

## Abbreviations[1]

DHW: Domestic Hot Water; LCA: Life Cycle Assessment.

# 1 Introduction

The building sector has a high potential in tackling today's energy and environmental challenges. In fact, more than the building itself, the largest energy consumers are people for which buildings are designed [1]. Still often neglected in current construction practices, the human dimension is a key topic in building energy research since more than a decade [2,3]. Reversely, the use of space and energy resources as well as the way a building design and its surrounding environment affect the human way of life was studied in social sciences [4–8]. Bridging the gaps between disciplines and moving towards more interdisciplinarity would be beneficial to reinforce each discipline [5,9,10]. However, building engineering and social sciences are rarely suited by each other. In this research,

[1] DHW: Domestic Hot Water; LCA: Life Cycle Assessment.

actors from several disciplines worked on the same research object, a new fully inhabited rental multifamily house, and performed for the first time a multidisciplinary study combining sociological, energy and life cycle assessment (LCA) results, as well as a cross-analysis of all disciplinary results.

## 1.1 The human dimension in building engineering

In building engineering, many studies highlighted the large influence of occupancy on real energy consumptions [11–15], especially in low-energy buildings [16–19]. Differences related to occupancy were observed between forecasted and real consumptions, leading to a performance gap [19]. Even nearly identical buildings could have different consumptions, differences being explained by the way of occupying buildings [20]. The building energy performance has also a strong impact on its environmental performance [21,22]. As a consequence, an increased attention is now paid to time-dependent factors, such as occupant behaviour, in dynamic LCA frameworks [23,24]. Occupancy should be described in a realistic manner in order to get more robust LCA results [25].

In order to refine the way humans are taken into account in building energy and environmental modelling, the research effort focussed on modelling the presence of occupants, their interaction with the building (operations on windows, shading devices [26], lighting, thermostat [27] or appliances [28]) and their activities. The effect of these behaviours on energy consumptions [3] and comfort [29–31] was also assessed.

## 1.2 Bridging gaps with social sciences

The two main methods used by engineers for gathering occupancy data were quantitative methods based on in-situ measurements, and qualitative methods, *i.e.* methods applied in social sciences and humanities [32]. In situ-monitoring is widely used to capture human activities in various context [33]. As human behaviour in building is affected by many factors, quantitative methods alone are not sufficient to understand the complexity of the human dimension [34] or occupants' preferences, e.g. regarding adaptive comfort [31]. Bavaresco *et al.* [32] pointed out that qualitative methods employed in social sciences and humanities are complementary to quantitative ones for a better

comprehension of the way human behave in buildings. Questionnaires and interviews were broadly used for that purpose. As examples, questionnaires were used in order to identify pro-environmental behaviour [35], to investigate the awareness of occupants living in eco-houses regarding their home performance [36] or to model thermal comfort [37]. In addition, interviews were exploited to understand habits [38] or building user values [39]. Time-use surveys have also been applied to identify occupancy and energy consumption patterns [40–42]. Beside these traditional qualitative methods, other social sciences approach can also be meaningful [32,43], even if less used in the frame of building energy. Among them, ethnographic studies combine open-ended interviews, participant observations and analysis of photographs and documents to learn implicit aspects of human's everyday life. As an example, Cerinsek *et al.* [44] applied an ethnographic approach combining semi-structured interviews, focus group discussions and observations of people in their home to identify behaviours influencing the renovation process of a residential building. An ethnographic study was also performed by Hampton [45] in order to understand practices related to energy use when people work from home

Despite the fact that the need for social sciences methods is recognised in building engineering, a few studies are effectively carried out by interdisciplinary groups [10], *i.e.* whose members have knowledge in different disciplines.

## 1.3 The building seen by social sciences

From a social sciences perspective, emphasis was given to the way a building and its surroundings affects inhabitant's lifestyles. Some research focussed on the way the space was occupied by inhabitants (moving, furnishing spaces) using an anthropological vision [46,47]. A large place was given to the use of all five senses in buildings [48]. Other researchers studied the emergence of an inhabitant-dwelling relationship based on activities, movements and practices experimented in the space [49–52], as well as on ballistic connections, *i.e.* connection depending on various signals from the outside [53]. The development of this relationship was called "architexture" by Lefèbvre [54].

In addition to the anthropology of space, the past and current practices regarding the use of energy resources was another research topic in social sciences [55,56]. Wolff *et al.* [6] showed that energy practices are linked to the material arrangement, available user interface, inhabitants' habits and preferences. However, despite the need of translating energy-related behaviours into environmental impacts [57,58], no LCA were performed in the frame of existing collaboration between building engineers and sociologists.

Overall, social sciences research on energy still have a little impact on policy-making [5,10]. Sociologist often lack of technical and physical knowledge [5,9,59] and quantitative methods were rarely employed in social sciences [60]. These problems could be solved in performing more interdisciplinary collaboration.

## 1.4 Previous collaboration in the building sector

The literature reports a few examples of collaborations between engineers and sociologists on building studies. Within the CaRB (Carbon Reduction in Buildings) project, building engineers, social scientists, mathematicians, environmental scientists, architects and psychologists worked together and performed modelling, monitoring and interviews [61]. As shown by Sibilla and Kurul [62], the context of energy retrofit requires more transdisciplinarity. In that sense, projects such as ReBo (Strategies for Integrated Sustainable Renovation) and SIRen (Sustainable Integrated Renovation) involved actors from engineering, architecture, social sciences as well as non-academic partners, exchanging through meetings, seminars and workshops and implementing their methods on living labs [63,64]. During a workshop of the Healthy Indoor Environments project, researchers from technical, behavioural and medical disciplines identified factors having impacts on health and well-being, that should be considered from a holistic perspective [65]. In these previous projects, disciplinary studies were not always performed on the same building. Sociological studies were performed using traditional questionnaires or interviews. Although the CO2 emissions of buildings were sometimes investigated, the LCA methodology was not applied.

Several barriers were identified to explain the lack of interdisciplinarity in existing building studies. Among them, communication difficulties were often reported as disciplines do not share the same vocabulary and concepts [59,9,10]. Different modus operandi and methods were followed in each discipline [9]. Pellegrino and Musy [10] thus suggested to first take the time of sharing concepts and discussing methods before analysing interdisciplinary results.

## 1.5 Aim of the article

As observed in the literature, building engineering and social sciences can reinforce each other and provide useful information on the human-building interactions when performed during the post-occupancy phase. However, a few study however put together research from these different fields [10]. To the best of our knowledge, no article brought together sociologists and engineers in order to conduct on the same building sociological, energy and LCA studies. In addition, immersive qualitative methods such as ethnography were less frequently applied to understand the effect of occupancy in building energy. Finally, the communication and comprehension between disciplines can be difficult [59], while languages and knowledge should be mutually shared and understood [10] for a successful collaboration. In existing literature, communication problems between sociologist and engineers have not been studied in the context of building performance.

In order to fill these gaps, this study involves for the first time researchers from social sciences, building energy and building LCA in a multidisciplinary work performed on a rental multifamily house after it has been occupied for some time. The aim of this article is firstly to have a broader understanding of the global performance of one building through three disciplinary analyses. Secondly, it intends to follow an immersive and co-reflexive qualitative strategy, based on in-situ discussion with inhabitants, to understand how inhabitants are doing in order to feel well at home. Thirdly, this work aims to facilitate the understanding among different disciplinary fields, tackling communication problems. Fourthly, recommendations are set and area for improvement are identified to be applied in future multidisciplinary building studies.

We refer to multidisciplinarity [10] instead of interdisciplinarity, pluridisciplinarity or transdisciplinarity, as the three disciplinary studies are first conducted separately before performing a cross-analysis of all gathered results. Common concepts and terminologies are then identified before results are discussed and points of improvement highlighted.

The methodologies followed for each disciplinary study as well as for the cross-disciplinary study are presented in section 2. After describing the case study in section 3, results of the post-occupancy mono-disciplinary and cross-disciplinary evaluations are reported in section 4 and discussed in section 5. Last conclusions are drawn in section 6.

# 2 Methodology

This article aims at presenting the results of a multi-disciplinary work performed on a residential building during the post-occupancy phase. A key point is that building design and construction are representative of the current construction standards and practices, while novelty is in the multi-disciplinary post-occupancy studies undertaken. Figure 1 shows an overview of the methodology and the methodology applied in each step is described in the next paragraphs.

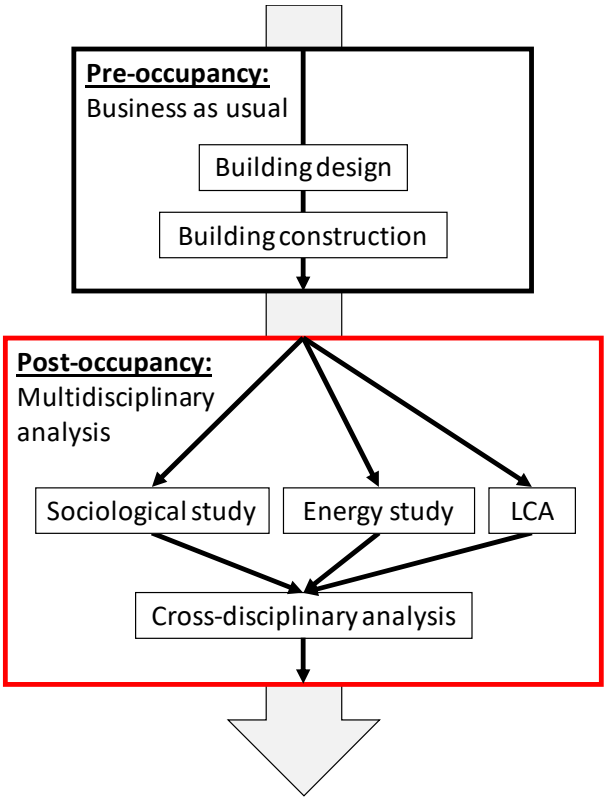


**Figure 1: Schematic overview of the methodology**

## 2.1 Pre-occupancy phase

A traditional building design process is followed for the building. No multidisciplinary study is performed at this stage, as this is the case for most of the current constructions. Before constructing the building, the compliance with several regulations (e.g. the French thermal regulation RT 2012 [66,67]) has to be checked. The regulatory calculation method for the energy consumption provides specific assumptions regarding the occupancy of the future building (heating temperature, occupancy scenarios, amount of domestic hot water consumed, etc.), that may differ from the real one. Therefore, the calculated theoretical consumptions do not correspond to the real consumption during the use phase.

At the construction stage, specific data are collected on the building site. This aims at determining the quantities of materials employed to build the residence. This information is required in order to assess as precisely as possible the environmental impacts of the construction phase with the LCA methodology.

## 2.2 Post-occupancy evaluation

### 2.2.1 Human-building interactions

Ways of life and interactions between humans and their dwellings are studied shortly after inhabitants moved into the new building. Information is extracted from discussions between the sociologist and the family willing to participate. This kind of immersive and co-reflexive study shares some aspects with ethnographic studies as data from various types are collected and the sociologist meet families individually, in their home, in order to experience their everyday practices in real-life context. However, the main different with ethnographical studies is that in this study, the sociologist does not maintain the distance with inhabitant, but rather the sociologist intends to become a member of the family. Thus time is required to build the trusty climate necessary to get reliable data.

The sociological study intends to understand how inhabitants are doing in order to feel well at home. In a preliminary brief meeting (meeting 0), the sociologist explains the demarche, the way the investigation will be performed in the next meetings and answers all inhabitants' questions. No recording device is operated during this preliminary meeting in order to be less intrusive. During the first long meeting (meeting 1), the weaving process between inhabitants and their new home is studied based on recorded discussions than can last several hours. Instead of using a list of predefined questions, subject related to well-being, use of the living space and energy emerge through the discussions and walkthroughs in the home. Without fixed questionnaires, inhabitants have more opportunities to express their own points of view. The sociologist observes and practices with the inhabitants. Based on observations and discussions the sociologist asks inhabitants on their habits. A cooperation or a "co-reflexion" [68] is developed on the way they live in their dwelling. Ideally, inhabitants are met at least a second time (meeting 2). Sometimes three or four meetings are organised. Between meetings, the sociologist summarises points for which precisions are required. In the same time, inhabitants generally continue thinking on their habits related to energy. In the next meetings, the co-construction continues. The sociologist is then able to validate his hypothesis

related to the conditions of use and inhabitants continue to mature their thinking and share their daily experiences.

### 2.2.2 Energy and comfort

Energy consumption and comfort indicators are recorded using a set of sensors and results are analysed by an energy engineer. The objectives are to determine the building real energy performance and to understand how energy is consumed.

The instrumentation enables to monitor the apartments heating and electricity consumptions and the volumes of domestic hot water (DHW) and cold water used. Among the sensors installed, some record comfort indicators (temperature, humidity, air quality, brightness). Wireless technology is favoured in order to be flexible and less intrusive. Sensors locations in the apartments should receive a specific attention and good practices of metrology must be followed [69–71] to ensure the quality of measurement. Sensors record data every ten minutes in order to allow both to go deep in the analysis or to aggregate data to have more global values.

In addition to measured data, inhabitants' bills are analysed to collect the building gas consumptions for heating and for domestic hot water, as for the electricity consumptions of common areas and technical equipment.

### 2.2.3 Environmental assessment

The third study, performed by an engineer, aims at quantifying environmental impacts using the life cycle assessment methodology [72,73] and intends to a better understanding whence the most significant impacts originate.

The assessment is done with the building LCA tool *Pléiades* ACV [74,75]. It is linked to the dynamic building energy simulation tool *Pléiades*+COMFIE [76] for a more precise evaluation of the energy performance. Impact related to electricity consumptions are evaluated at an hourly time step with the French hourly electricity mix provided in the tool and the hourly electricity consumption calculated by COMFIE. Environmental data for building materials and equipment, as well as processes

used in the building life cycle are based on the ecoinvent database [77] and a set of twelve fluxes and environmental indicators are calculated (Table 1).

**Table 1 : Environmental indicators and fluxes calculated in *Pléiades* ACV**

| Indicator or flux | Legend | Unit | Reference |
|---|---|---|---|
| Climate change (with GWP 100) | CC | kg $CO_{2\,eq}$ | [78] |
| Cumulative energy demand | CED | MJ | [77] |
| Water consumption | Water | l | [77] |
| Non-radioactive waste creation | Waste | kg $_{eq}$ | [77] |
| Radioactive waste creation | Rad | $m^3$ | [77] |
| Abiotic depletion potential | ADP | kg Sb $_{eq}$ | [79] |
| Acidification potential | AP | kg $SO_{2\,eq}$ | [79] |
| Eutrophication potential | EP | kg $PO_4^{3-}{}_{eq}$ | [79] |
| Photochemical oxidant formation | POP | kg $C_2H_{4\,eq}$ | [79] |
| Odour | Odour | $m^3$ air | [79] |
| Damage caused to ecosystems | Biodiv | PDF.$m^2$.yr | [80] |
| Damage to human health | Health | DALY | [80] |

The LCA is performed over 50 years. The following framework is chosen for the environmental assessment. First, for materials and equipment production as well as building construction (module A of the EN 15804 / EN 15978 framework [81,82]), quantities implemented in the model are based on observations made onsite during the construction work. Second, the use phase (module B of the framework) is characterised by (i) the energy consumption for heating and DHW preparation, (ii) the electricity consumption for using domestic devices, ventilating, lighting and supplying heat and DHW, (iii) the drinkable water preparation and the waste water treatment. The underlying occupancy scenarios for building use are based on scenarios from the French energy regulation, except for the indoor temperature setpoint and the number of occupants that are obtained from measurement and discussions. Occupants daily commuting and household waste are excluded from the scope as these aspects of the use phase are not intended to be monitored nor discussed with occupants. Impact assessment of replacements are only based on assumptions: during the life cycle, doors and windows are assumed to be replaced every 30 years, buildings' finishes every 10 years and energy systems every 20 years. Last, at the end-of-life (module C of the framework) all materials are assumed to be landfilled, except wooden materials that are incinerated with energy recovery.

### 2.2.4 Cross-disciplinary analysis

Once the three disciplinary studies are performed, the next step consists in cross-discussions between actors of all disciplinary fields. It aims at learning from all disciplines and at understanding how disciplines enhance and reinforce each other. Two main steps are followed in the cross-disciplinary analysis.

Firstly, concepts occurring in all disciplinary fields (but using different terminologies) are identified. Therefore, each actor explains the aim of its study with discipline specific terminologies. Actions performed to reach the goals are also described and summarised in mind maps. Then, aims and actions are rephrased by actors of the two other disciplines, under the control of the third actor. This first step brings an initial level of comprehension between disciplines.

In a second step, the main results of each study are presented and cross-analysed. When results stand out from several disciplines or express previously identified concepts, they are further discussed. In that way, complementary conclusions are drawn regarding this concept. Furthermore, actors jointly issued recommendations for the design of future buildings.

# 3 Case study

## 3.1 Building description

The methodology was applied to a French rental multifamily house. This building belongs to a complex of three multifamily houses called the Three Besants (Figure 2), that was built in 2015 by the Pelletier Group in the town of Le Bourget-du-Lac (Auvergne Rhone Alps region, France). The studied multifamily house consists in twelve apartments, with one to four main rooms, spread over three storeys.

**Figure 2: The Three Besants (architect's sketch)**

The building has a concrete structure with concrete slab walls and is externally insulated with 15 cm of polystyrene and internally insulated with 5 cm of polystyrene, allowing to reach a wall performance of 0.2 W/m²/K. A 65 kW gas boiler is used for heating and water radiators are placed in each flat. The temperature setpoint is controlled using thermostats. DHW is mainly provided by a solar system consisting in 18.4 m² of solar panels placed on the concrete roof terrace and a 1,500 l storage tank. The gas boiler complements the DHW system when the solar gains are not sufficient. A simple flow mechanical ventilation system is operated to exhaust stale air. This building can be considered as a typical new French building, as its technique and design are representative of what is currently performed in France.

The building of about 890 m² complies with the French thermal regulation. The regulatory primary yearly energy consumption for heating, cooling, lighting, DHW, and auxiliaries (fans and pumps) reaches 51.5 kWh/m². This value remains lower the maximal value authorised of 60 kWh/m² for this building type and location. According to the regulatory study, heating is the main contributor to the primary consumption with almost half of the consumption (Figure 3). It is followed by DHW (about 30 %), lighting and last auxiliary consumption.

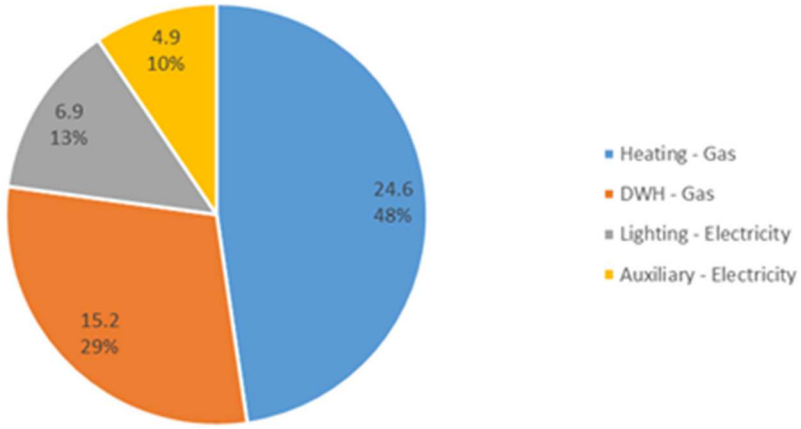


**Figure 3: Distribution of the primary energy consumptions obtained with the regulatory calculation**

## 3.2 Discussions with inhabitants

The multifamily house is fully inhabited. An immersive and co-reflexive sociological study was performed from mid-November 2015 until mid-May 2016. Each family was contacted individually through a letter followed by a call to introduce the demarche and fix a meeting. Among the twelve families, eleven agreed to participate. Depending on the family, the meeting 1 was more or less complex and a trusting relationship needed to be built. It was sometimes difficult for inhabitants to speak about their home because it's something private. Furthermore, talking with people about their relation with energy can lead to shaming and they had to understand that no judgment would be made. Four families received the sociologist many times (sometime informally) and three families met her twice, while other families met her only once as they were not interested to go further in the reflexive demarche on their habits, the way they lived in their home and their relation with energy uses. In total, 21 discussions were conducted. Most of them lasted more than two hours. Some of them continued with a shared meal and lasted much longer (seven hours for the longest one).

## 3.3 Building monitoring

The studied building was instrumented with sensors, whose locations are shown in Figure 4 for one storey. Half of the apartments were fully instrumented with sensors allowing to record heating consumption using calorie counter, electricity consumption using electrical switchboards, DHW and

cold water consumption using impulse meters, and rooms comfort using temperature, humidity, illuminance and indoor air quality sensors. The monitored apartments and their characteristics are listed in Table 2.

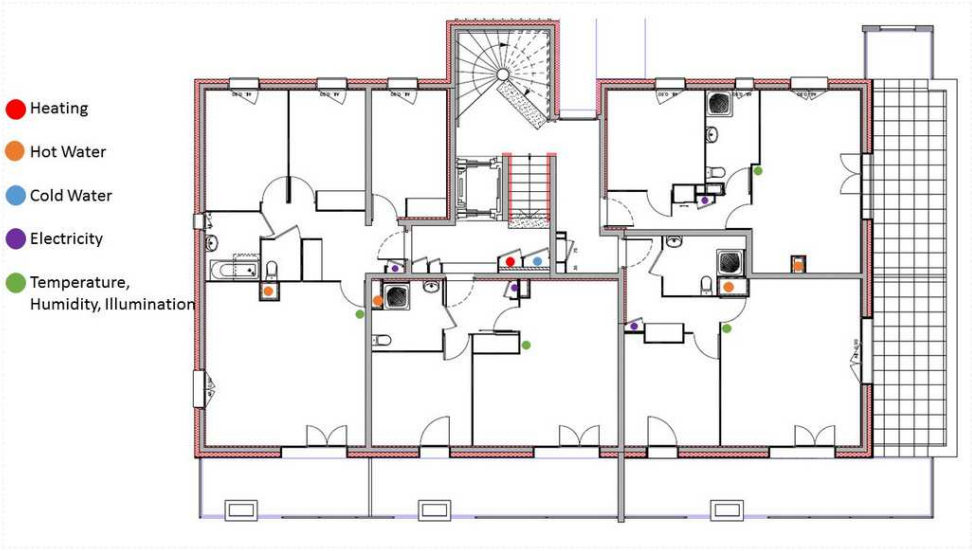


**Figure 4: Sensors position in a four apartment storey**

**Table 2 : Apartments' characteristics**

| Apartments | Dwelling Type | Area ($m^2$) | Number of Occupants | | Family type | Main orientation |
|---|---|---|---|---|---|---|
| | | | Week | Week-end | | |
| **C003** | T2 | 45.7 | 1 | 0 | Single person: worker | South |
| **C004** | T4 | 77.8 | 3 | 6 (max) | Couple with child: worker | South West |
| **C102** | T2 | 50.0 | 2 | 2 | Childless couple: worker | South East |
| **C103** | T2 | 45.7 | 1 | 1 | Single person: retired | South |
| **C201** | T2 | 44.9 | 2 | 2 | Childless couple: worker | East |
| **C204** | T4 | 77.8 | 2 | 3 | Single-parent family: worker | South West |

All these meters communicate with a radio gateway to extract data from the building and return them via a man-machine interface (Figure 5). Radio communication is employed to trace the building data. This technology was however not the most efficient regarding the building structure. This concrete building has a large reinforcement which disturbed the communication system of the sensors. Relay antennas had to be installed to minimise losses.

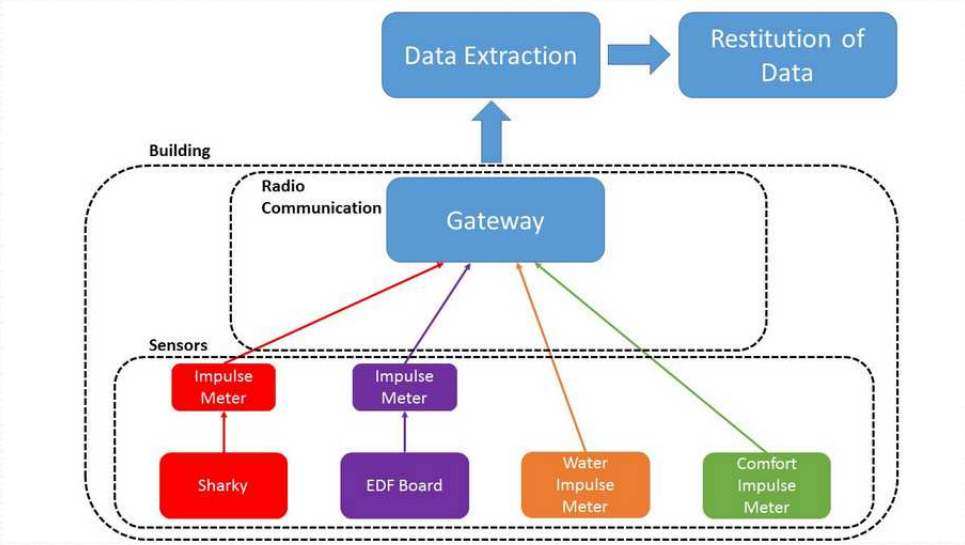


**Figure 5: Data extraction process**

In parallel to the instrumentation, the energy bills (gas and electricity) of the building were collected. These invoices help determining the total consumption of gas (for heating and DHW) and electricity (for common and technical equipment).

# 4 Post-occupancy evaluation results

## 4.1 Sociological study

When possible, the sociological study followed an iterative process. Families that agreed to meet the sociologist at least twice continued thinking on their habits related to energy between meetings. While most of the inhabitants first got the impression they had nothing to say about their use of their living place during meeting 1, then they realised that this subject calls for further reflexions, as it was not as usual as they might have intended to explain their habits. As an example, an inhabitant firstly told he lived “normally” and heated his home between 19 and 20 °C. Then, he realized that he forgot to mention a special habit regarding his use of energy and at the beginning of meeting 2 he took the lead of the discussion to explain that he was always opening the windows for five min before bedtime, without switching-off the radiator. This habit was so well anchored in his daily habits that

he did not though about it during meeting 1. The study was therefore co-reflexive: inhabitants and sociologist were all “on the same boat”: the reflection was enriched and hypothesis of the sociologist were validated through all discussions.

### 4.1.1 Inhabitant relation with their new dwelling

Several subject were alternatively discussed regarding the inhabitant-dwelling relationship: the reason for choosing the residence, the space appropriation, the furniture arrangement and the adaption of novel habits. Learnings from the weaving process are summarized in Table 3.

The results showed that most inhabitants had chosen to live in this residence because of the district life quality: proximity of the mountain, forest, lake, presence of small shops, easy access to public transportation, and human-size of the town (almost 4,500 inhabitants). None of them were aware of the building performance labeling at first glance. At the most, after they moved in their new dwelling, this information was regarded as a “good mark” for the tenants. When the sociologist told inhabitants that a solar system was mounted on the roof for the DHW, they had a very positive reaction although they did not know how such system works and in which matter it could change their habits.

After moving-in a building, a relationship has to be “woven” between inhabitants and their dwelling, so that inhabitants can say they live somewhere or feel "at home". For one resident, the space appropriation happened after a first night in the dwelling. She talked about “the apartment” before this time and about “my apartment” from the moment she was finally able to sleep in it, *i.e.* once her move was completed. Her first experience of space as an inhabitant allowed her to integrate space as an integral part of her life.

In addition, anchor points arise from this inhabitant-dwelling interpenetration. A resident explained, as an example, to have "his" place on the couch, a place that took a new meaning for him after experiencing others with which he did not feel the same comfort. This place allowed him, like a conductor, to compose with what is offered around him (sockets, armrest, direct access to the

balcony, the kitchen, view on the outside, television set facing) and to make it a harmonious experience for him.

Ballistic connections operate while “weaving” of one’s home. Thus, the weather, the perceived landscape or the brightness do not remain outside the home but are welcomed by inhabitants. For instance, they may cook differently in winter and in summer, as highlighted by one resident who said that she preferred cooking crepes in a rainy and cold February’s day than in a hot and sunny June’s day. Furthermore, they may choose their furniture arrangement depending on landscape considerations, as this resident who after several attempts finally positioned her bed so as to have a breath-taking view of the outside. She explained: *"the morning I get up, because I close just a little bit the shutter, it's amazing this view out on nature, and then this perspective especially, […] And the neighbours I do not see them”.* It should be noticed that this resident was brought to place her bed in a place that was not that thought by the designers who suggest the location of the bed by installing two plugs for possible bedside lamps.

The “weaving of the home” is the result of the inhabitant-dwelling interpenetration, making the inhabitant a real designer of everyday life. The delivery of a building does not mark the end, as it is usually thought, of its edification; rather, the opposite is true. Inhabitants begin their own building with the architectural and technical bases that were conceived without them. This weaving will be meaningful and will be lived daily by inhabitants who are constantly brought to “knit”[2] their home beyond what had been thought upstream. A building is delivered with its batch of expected "uses", suggested, recommended or even imposed (the television plug will for example act as a prescription to residents who, if they want to watch TV, do not have other choice than to connect it to this specific location). However, as described hereafter, the conditions of use do not necessarily fit with the usual uses of the designers.

[2] Term used by an inhabitant.

People who usually utilise a freezer were very embarrassed when, once home, they realized they had nowhere to plug their device. They first wanted to connect it in their cellar, which was denied, the outlets being connected to the collective electrical circuit. As they did not wish to abandon their equipment, they dealt with a standard: the handicap standard. Thanks to, or because of, this standard, the toilets of their home were spacious enough (to enable access for a wheelchair) and they could install their freezer inside.

**Table 3: Summary of learnings regarding the weaving between inhabitants and their new dwelling**

| Dimension of the inhabitant-dwelling relation | Examples cited | Drivers | Consequences |
|---|---|---|---|
| Accommodation choice | Building location | Quality of life: surrounding area, access to shops, public transportation, city size | Building performance is not a criteria |
| Space appropriation | Feeling at home | First night in the building | Integration of the space as a part of inhabitants life |
| Furniture arrangement | Bed | View: outside, unoverlooked place | Bed was not installed to the location planed by designers |
| | Freezer | No place designed to plug a freezer in the apartment | Freezer were plugged in the spacious toilets |
| New habits adoption | Place on the couch | Convenience: sockets, armrest<br>Access: balcony, kitchen<br>View: outside, TV | Anchor points are developed |

### 4.1.2 Inhabitants relation with energy uses

Discussion topics were turned by the sociologist to the way inhabitants consumed energy in their daily life. As energy systems are not directly reachable to inhabitants, discussions mainly focused on interface of energy systems inside the dwelling. Learnings from the way inhabitants used energy are summarized in Table 4.

Inhabitants had a quite complicated relation with the ambiance thermostat. None of the residents knew exactly how to make this device work and it has even become a source of fears for many (ten of the twelve flats in the building). While the thermostat offered a multitude of options, no inhabitant could exploit all potentialities of this device (lowering the temperature in case of absence...) during the time of investigation. For a minority of inhabitants, the programming of such a

tool seemed more or less intuitive. But for the majority, the use of it seemed too complicated and made no sense in their daily lives. They preferred turning the thermostatic valves of the radiators rather than venturing into direct contact with their thermostat.

The windows of the apartments were opened at any time of the day. Sometimes inhabitants explained that they “turned radiators on zero" (nobody had noticed the "on-off" button of the thermostat). But not all of them did it as they argued that the apartments are so well insulated that the heat can go up quickly after the windows closing.

Some inhabitants do have reflexes regarding external conditions. One of them explained he increased the heating temperature (using the thermostatic valve of the radiator) on the evening after he saw in the weather report forecasting a drop down in temperature for the next morning. He did not know that the heating control is performed according to the internal and external temperatures.

Several residents explained that they had to plug in their own lights because of the wrong position of the light spots scattered on the ceiling. Often the new lighting system did not replace the other and all the bright spots in the apartment were lit.

The role of the ventilation system remained poorly understood by most residents. Air inlets are seen as an acoustic discomfort and one inhabitant even plugged them. Furthermore, the sociologist pointed out to all inhabitants the thin cord in their kitchen. Once actuated it increases the exhaust air flow. Six inhabitants did not notice this cord before. Others had not dared to pull it for fear of breaking it or of not being able to stop the increased flow afterwards. Some took advantage of the sociologist presence to pull it and test the consequences of this action, thus sweating their fear. Finally, the hoods installed in the kitchen were almost never started (only one couple operated it every time they cooked) because they found them too noisy. It is particularly interesting that the hoods were perceived (for six of the inhabitants met) only as a way to exhaust cooking odours. Then, they preferred to open the windows to remove odours rather than turning their hood on, since it is considered too noisy.

**Table 4: Summary of learnings from the inhabitant relation with energy uses**

| Energy use | Equipment | Issue | Consequence |
|---|---|---|---|
| Heating | Thermostat | Unintuitive use | Use thermostatic valves instead of thermostat |
| | | | Open windows to avoid overheating |
| | Radiator thermostatic valves | Manual adjustment before a cold snap | Double heating control adjustment (building scale + room scale) |
| Lighting | Light spots | Unsatisfactory position | Plug additional lamps |
| Ventilation | Air inlet | Acoustic unhappiness | Plugged air inlet |
| | Cord hanging from the kitchen air extract unit | Not noticed<br>Fear of using it | Open windows instead of using ventilation unit |
| | Hood | Acoustic unhappiness | Open windows instead of using the hood |

## 4.2 Energy and comfort study

The real building consumption is analysed from measurements and energy bills. At the building level, gas and electricity bills were analysed for the one-year period mid-june 2017 to mid-june 2018. A final gas energy consumption of 56,166 kWh of gas was required to cover heating and DHW. In addition, an electricity final energy consumption of 14,651 kWh was necessary in order to provide electricity to common areas of the building and to auxiliaries. Taking into account the building area and the conversion factor between final and primary energy of the French thermal regulation (1.11 for gas and 2.58 for electricity), primary energy consumptions of 63.3 kWh/m² for gas and 16.5 kWh/m² for electricity were observed from the bills.

The real building consumption was different from that of the regulatory calculation. The performance gap reaches 59 % of the gas consumption. The over-consumption is mainly due to heating as the measured heating setpoint (Figure 8 for December) are mostly higher than conventional ones considered in the regulatory calculation: 19 °C when occupants are present and 16 °C when they are absent during the day. As previously mentioned, conventional scenarios of the regulation are not intended to be representative of reality but are rather used for comparison purpose.

Figure 6 and Figure 7 show the real energy consumptions at the apartment level. Data plotted were collected between 15/12/2017 and 14/06/2018. Many parameters can influence the consumption: orientation, storey, number of occupants, socio-professional category, user sensitivity... Linking the influence of these parameters to the consumption may be a difficult task. For instance, apartments in the last storey have more heat losses than the ones in intermediate stories. But this is not reflected in energy consumption due to the various parameters aforementioned.

Uses are studied through different indicators and are discussed with a particular attention to two apartments (C003 and C103), that are identical in geometry and orientation but occupied by different family type (respectively one worker and one retired person as shown in Table 2).

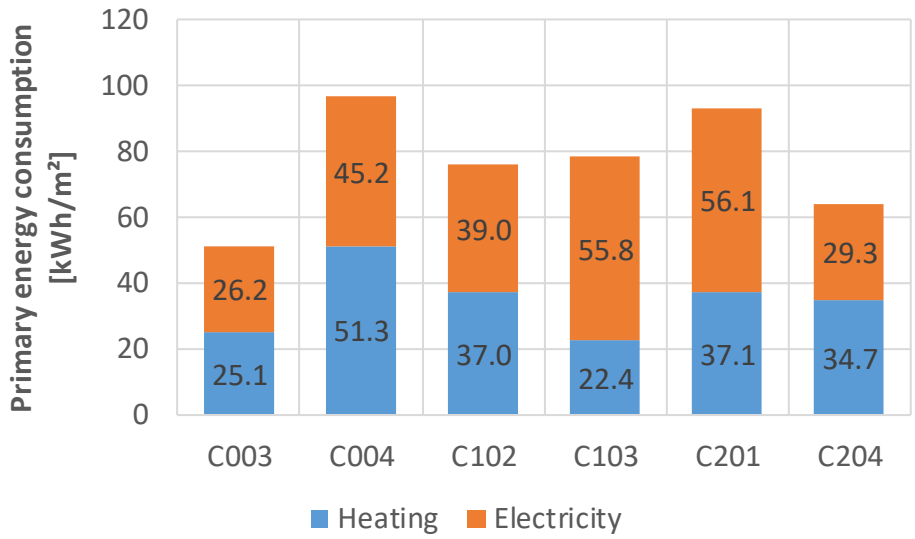


**Figure 6 : Primary heating and electricity consumption in the six monitored apartments**

Heating consumption (Figure 6) was higher in apartment C003 while the worker was less often present than the retired person. This can be explained by a non-optimal regulation for the flat C003 (no setback mode in case of absence). Electricity consumptions was twice as high in apartment C103 than the C003. This result was directly related to the presence of the inhabitant in his dwelling. The retired person was much more present and consumed more electricity (lighting, television, computer, cooking ...). The same phenomenon was observed for cold water (Figure 7).

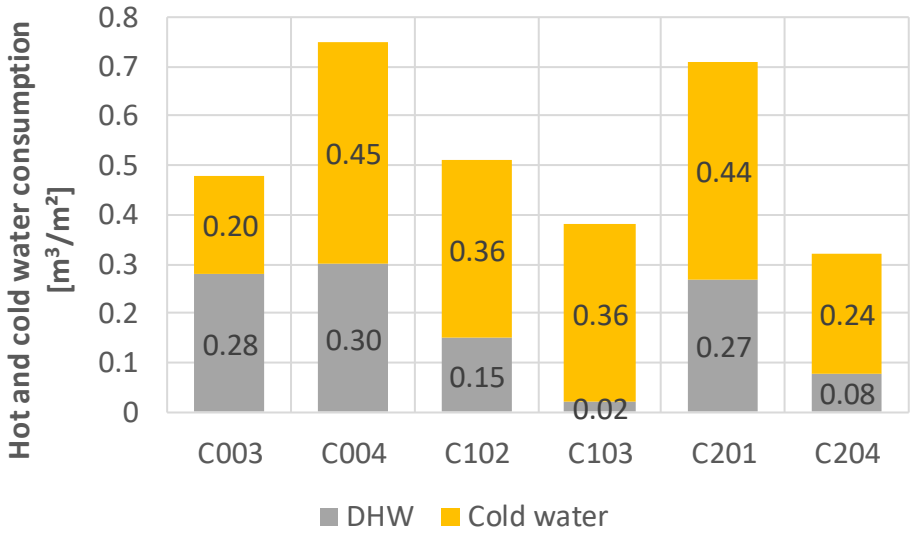


**Figure 7: Water consumption in the six monitored apartments**

DHW consumption (Figure 7) was much higher for apartment C003 (0.28 m3/m²) than for C103 (0.02 m3/m²), unlike cold water consumption. At first sight such a big difference could have suggest a measurement error but after investigation it turned out that this retired person almost never used hot water.

For comfort indicators, trends were easier to highlight. These trends were essentially related to the season. Temperature, humidity and $CO_2$ rated in six apartments are presented in Figure 8 to Figure 10 for the months of December 2017, April and June 2018. These months were chosen as they represent different periods of the year (heating season, mid-season, summer).

The temperature (Figure 8) increased in summer months, which is quite normal as the outside temperature also increases. In winter, a high variability is observed for the median temperature in the apartments, which ranged from 17 °C to 22.5 °C in December 2017. All families did not have the same thermal comfort requirements in winter conditions. Furthermore, the observed median temperature did not reflect the heating setpoint consider in the thermal regulation (19 °C in case of presence and 16 °C in case of absence during the day).

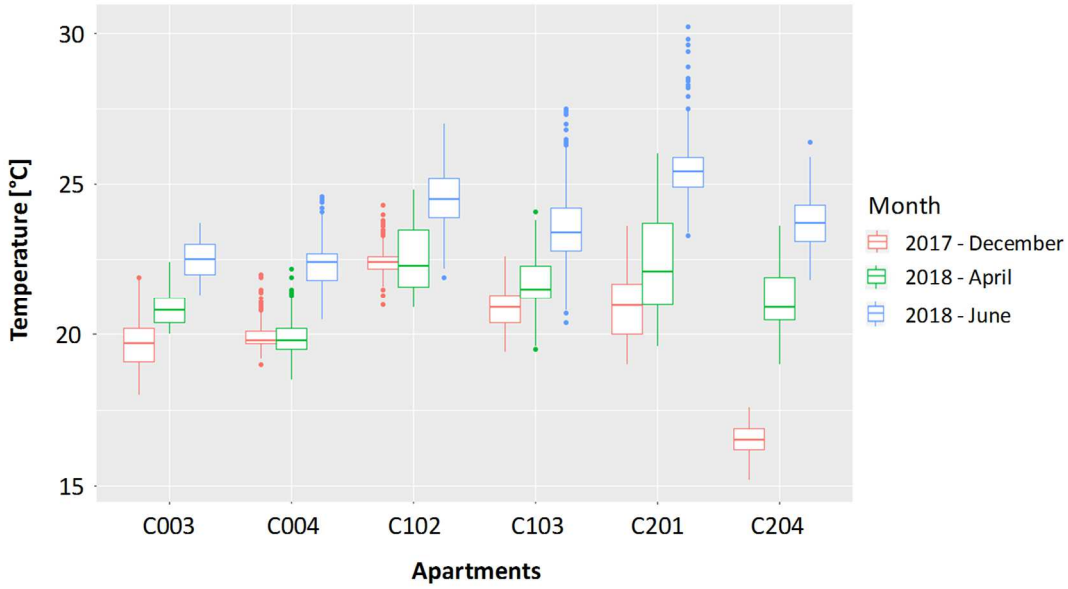


**Figure 8 : Evolution of temperature in the six monitored apartments**

The same trend was observed for humidity (Figure 9): humidity rates are higher in summer than in winter. This can be explained by the geographical location and the associated climate. In Savoy, winters are generally cold and dry, while in summer humidity and temperature increase. Furthermore, in winter, air becomes dryer due to heating.

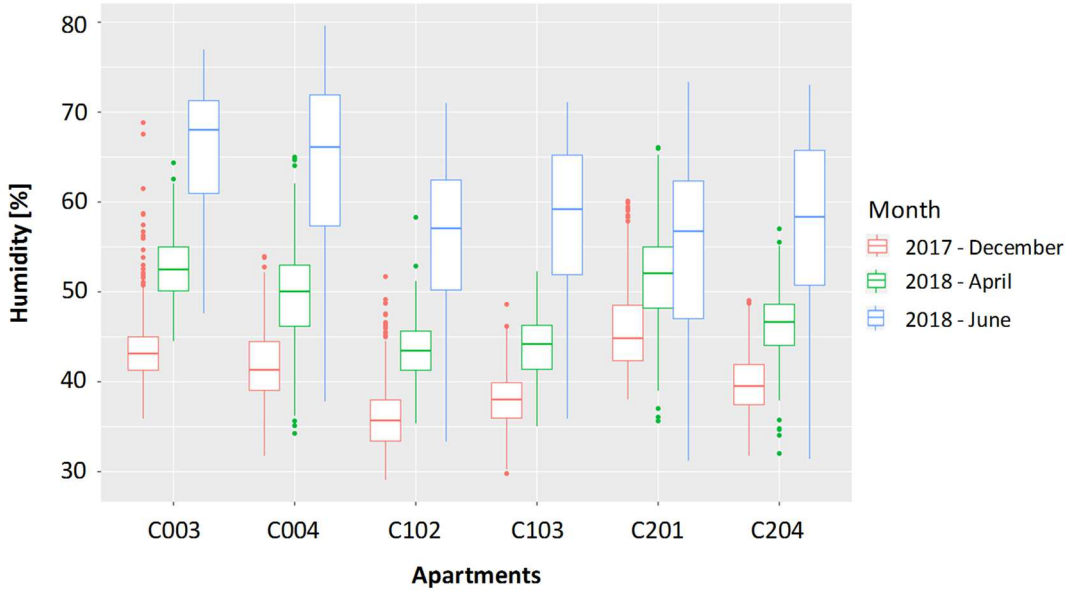


**Figure 9 : Evolution of humidity in the six monitored apartments**

For indoor air quality (Figure 10), the trend was linked to the choice of ventilation system. The system is a simple humidity-controlled flow ventilation. This means that the air change rate increases

with the humidity. As the humidity is more important in summer than in winter, the air quality is better during the summer period. Moreover, this period was more conducive to windows opening and therefore to lower $CO_2$-concentration. In winter, the $CO_2$-concentration in some apartments exceeded 1,500 ppm, leading to a poor air quality.

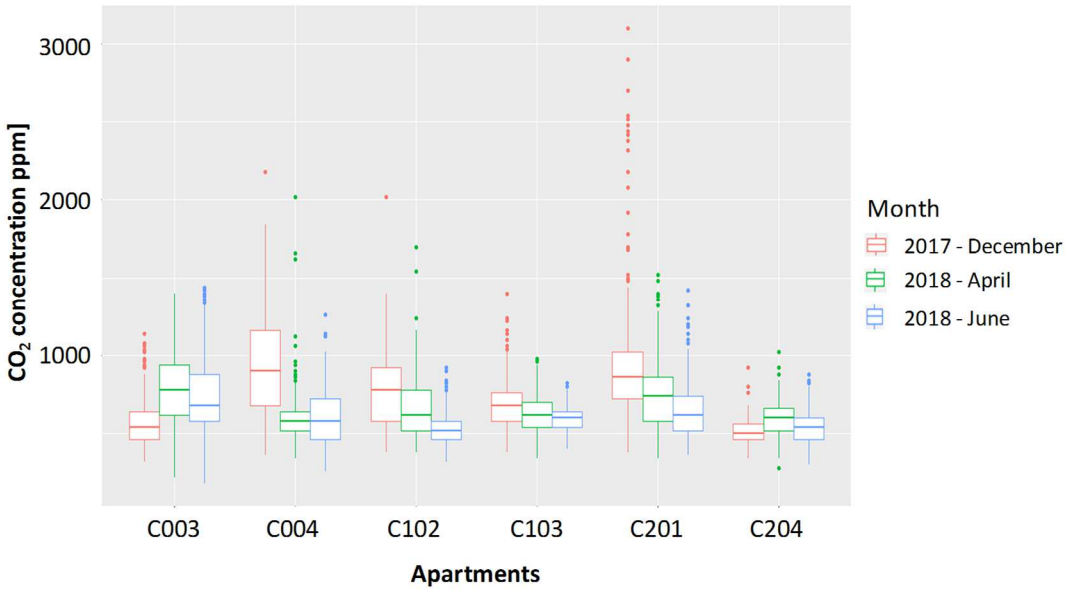


**Figure 10 : Evolution of $CO_2$ concentration in the six monitored apartments**

These few examples highlight that consumption patterns were very varied and complex to analyse. Even though monitoring provides information, data remain crude and may be difficult to interpret. Additional information must be gathered to allow a more detailed consumption analysis.

## 4.3 Life cycle assessment

The results of the LCA are presented in the contribution analyses in Figure 11 and Figure 12. The use phase is a major contributor for most of the studied environmental indicators (Figure 11). For instance, the use phase represents more than three quarters of the impacts for the cumulative energy demand and contributes to more than 60 % to the climate change impact. For the acidification potential, the photochemical ozone formation and the human health, the construction phase contributes as much as the use phase to the impacts for the chosen building lifetime. Furthermore, the construction phase is the major contributor for the biodiversity indicator. The high

impacts of the construction phase are mostly linked to materials like metals (*e.g.* for concrete reinforcement), concrete and waterproofing or damp proofing layers. The major contributor for the waste production is obviously the end-of-life.

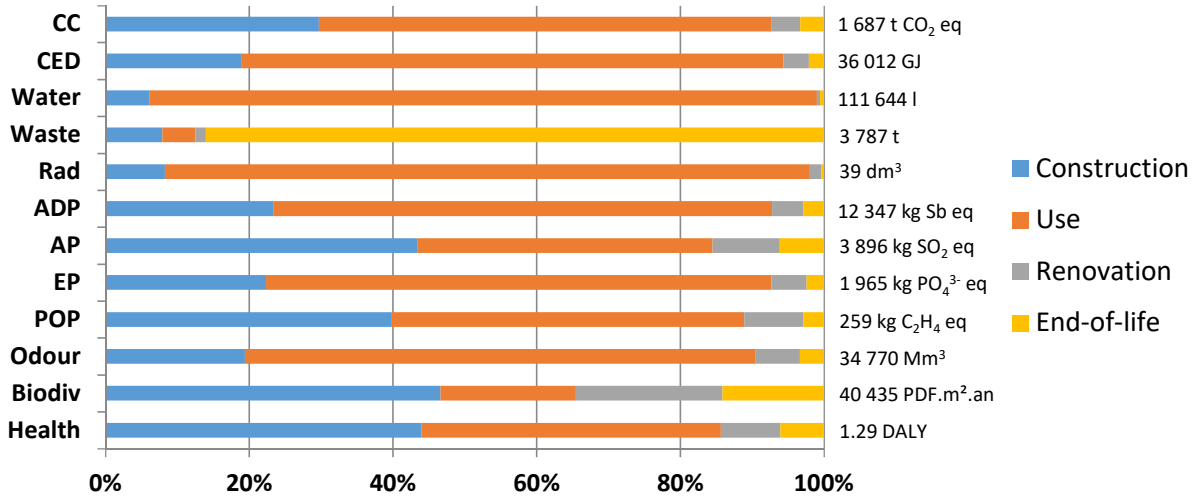


**Figure 11: Contribution of the building life phases to the impacts for a building 50 years lifetime**

Contributions of the building operations to the use phase are detailed in Figure 12, as this phase is subject to a particular attention in this study. Due to the use of gas as an energy carrier, heating and DHW are major contributors for some indicators: climate change, abiotic depletion potential, photochemical ozone formation and odours. The water consumption significantly affects other indicators. While the water consumption is obviously driven by the tap water preparation, the treatment of waste water is responsible for significant impacts for the waste production, acidification, eutrophication and the loss of biodiversity. Electricity is consumed in the building to operate pumps and fans, for lighting and for domestic appliances. As the share of nuclear power is high in the French electricity mix, the electricity consumption largely contributes to the radioactive waste production.

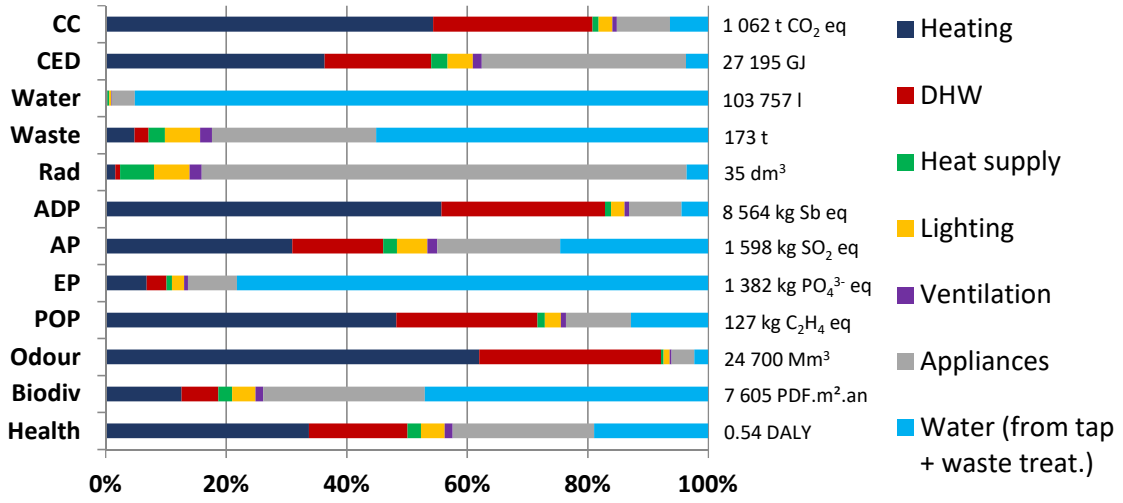


**Figure 12: Contribution of the building energy and water uses during the use phase**

## 4.4 Cross-disciplinary analysis

The cross-disciplinary analysis followed two main steps. First, points of convergence, *i.e.* concepts that are of importance in several disciplines, were highlighted. Second, results of each study were cross-analysed and points of improvement were issued in order to progress towards more integrated multidisciplinary studies during design and use phases. Results of each steps are described in the next paragraphs.

### 4.4.1 Identification of points of convergence

In this step, each actor explained the aim of his study and actions he performed to reach the goals using discipline specific terminologies. Then, aims and actions were rephrased by actors of the two other disciplines. It resulted in three mind-maps[3] presented in Figure 13, Figure 14 and Figure 15, on which inputs or contexts are displayed left and outputs are shown right. The mind-maps development is not further explained in this section as it reflects the methodology followed in each study. In the three mind-maps, five points of convergence, that are important in two or in the three disciplines, were highlighted. Each of these concepts is framed in the mind-maps by box with a coloured frame. The terminology describing each of these five concepts may differ in each disciplinary field as shown in the next paragraphs.

[3] The tool coogle.it has been used to draw the mind-maps.

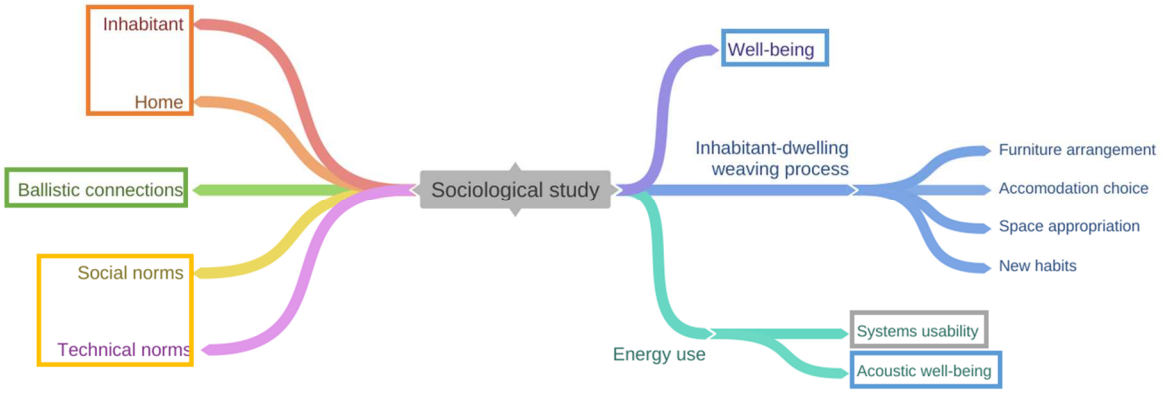


**Figure 13: Sociological study mind-map**

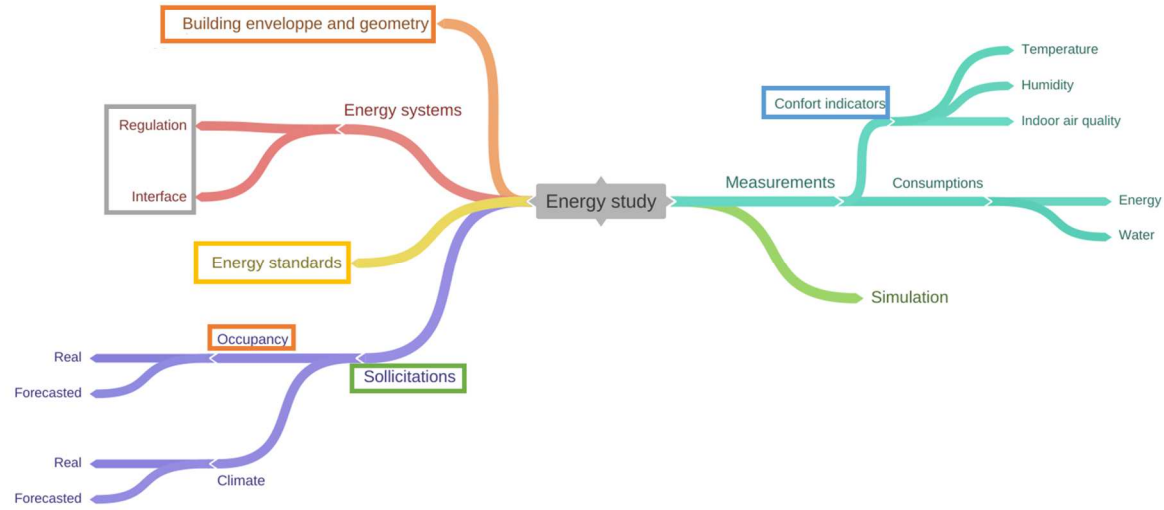


**Figure 14: Energy study mind-map**

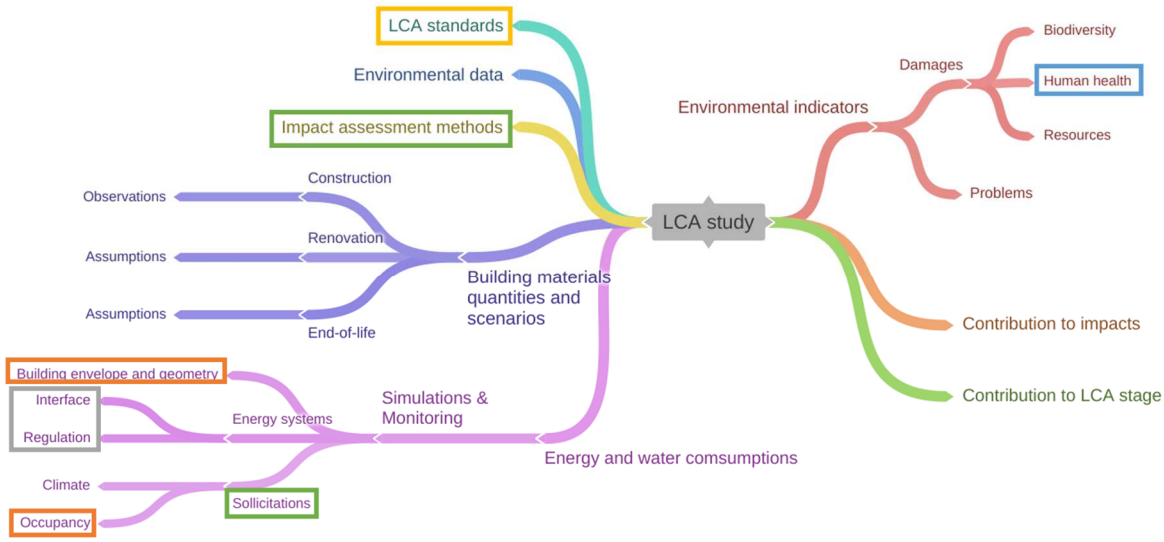


**Figure 15: LCA study mind-map**

First, people residing in the multifamily house and the way they act in their house are key points in all disciplines (boxes with orange frame on the mind-maps). These points are at the heart of concerns in the sociological study and they strongly influence the energy consumption and related environmental impacts. In energy and LCA studies the terms “occupant”, “housing” or “behaviour” are widely employed when referring to these aspects. Social sciences refer instead to “inhabitants”, “home”, or “conditions of use” to get more information on how humans interact with their building. As highlighted in Cole *et al.* [83] the term “occupant” is linked to passivity, whereas when using the term “inhabitant” we recognise that people are active in their homes. The “occupant” is rational, adapts itself to a context and reacts mechanically. The “inhabitant” on the other side interacts with all five senses with his home. For instance, he is able to detect a problem (for instance regarding the ventilation system) if the noise inside the building changes. Furthermore, a housing is a measured and normed space, with an architecture and engineering framework, sometimes complying with strict rules. Thinking in terms of a “housing” limits the living place to be seen only as a receptacle, which is designed to be occupied by families with more or less people having expected, or unexpected behaviours. In the same way, behaviours are thought by designers as preconceived or expected uses and they may differ from real ones.

A second point of convergence (boxes with blue frame) is related to the ambiance in the dwelling that should be healthy and pleasant. In sociological studies, this concept refers to “well-being”. For energy engineer, this concept is more related to “hygrothermal comfort” and “indoor air quality”. In this domain, comfortable conditions should be guaranteed by good sizing and settings of heating and ventilation equipment. In LCA, “damages caused to human-health” are investigated. However, they do not refer to conditions inside buildings, but rather to the global impact on human-health of a building along its entire life cycle.

Thirdly, environmental conditions outside the building are identified as a cornerstone in all three disciplines (boxes with green frame). Among them, “solicitations” coming from the outside are a

central point in building energy as for instance weather conditions influence heating, cooling and lighting consumptions. For sociologists, inhabitants act depending on connection of a “ballistic nature” [53] and react to different outdoor temperature or luminosity. In LCA, environmental conditions are also considered when designing impact assessment method as it is necessary to understand how environmental compartments (air, water, soil) or bodies “react to pollutants”.

The fourth point of convergence is linked to the use of energy systems and to man-machine interfaces of energy systems (boxes with grey frame). For engineers, such interfaces are “tools” helping in the energy demand management and in the reduction on energy related environmental impacts. For sociologists, the main concerns are on the “usability” and on the way inhabitants interact with interfaces.

The last point of convergence concerns norms (boxes with yellow frame). In building engineering, the compliance with regulations and standards has to be checked. Before it can be built, a building has to comply with several regulations such as the current “thermal regulation”. Furthermore, when performing a LCA study, “standardised steps” have to be followed. In a social sciences perspective, norms are seen differently and refers to “social norms or subjective norms” that people tacitly respect as well as to “technical norms” that affect the way of life.

### 4.4.2 Cross-analysis of disciplinary results

In a second step, a cross-analysis of all disciplinary results is performed in order to draw conclusions regarding the use of the building under investigation and to highlight the complementarity of each study. The cross-analysis showed that several results can be put in perspective, mainly in connection with a central aspect: heating. The way inhabitants interact with interfaces of energy systems can strongly affect the heating consumption. Furthermore, this contributor is a major energy consumer, leading the highest environmental impacts in the use phase for most environmental indicators.

The main man-machine interfaces related to heating were radiators thermostatic valves. Inhabitants preferred using valves instead of room thermostats in order to adjust their home temperature. It

turns out that the use of thermostat was not intuitive at all and inhabitants were sometimes afraid of operating this engineering device. On the contrary, thermostats are seen by engineers as convenient tools that facilitate the home heating system control. Thermostats may be less user-friendly than intended, making its use complex, as also pointed out in Peffer *et al.* [84]. Developments in home automation could help progressing towards more user-friendly man-machine interfaces. In this study, detailed thermostat operating manuals were provided to occupants after the cross-disciplinary discussions. In that way, they could lessen their fears and exploit the heating system more efficiently.

The sociological study also reports the case of an inhabitant, who manually adjust radiators thermostatic valves before a forecasted cold snap, as he did not know that the building heating regulation was performed according to internal and external temperatures. As the sociologist did not know it either, the occupant could not be informed of it. Therefore, it seems very important that all disciplinary contributions happened simultaneously and early in the design process. In this case, an effective inhabitants' accompaniment would have been useful: the sociologist could have thus exchanged with the engineer in charge of the study almost in real time. They would have been able, with the inhabitants, to enter into a reflexive dynamic in order to improve the well-being and to guarantee a lower energy consumption and less environmental impacts.

An approach, bringing together several disciplines highlights the necessity of considering at the same time, design and operation of energy systems, since they are perceived differently by all building actors. Consequently, understanding and answering questions related to the inhabitants-equipment relations is necessary, since they are central in order to reduce energy consumptions and environmental impacts.

Not only the operation of heating system but also the role of ventilation remained poorly understood by most residents. Air inlets were sometimes plugged and air extraction units were not exploited as expected by designer because of noise or for fear of breaking them. It is difficult to conclude from the measured data which consequences these behaviours had more globally on the energy

performance, as occupants' activities were not collected on a small time-step basis. However, this avoids an optimal air renewal and can lead to a poor air quality (increase of humidity and $CO_2$-concentrations). In this context, the study highlights the necessity of carrying out correlation analyses between measurements and uses. The observed activities were different from the expected ones and inhabitants had sometimes to deploy "tactics" [50,52] to ensure their well-being, and these tactics are not necessarily intended when the question of comfort is studied only in one disciplinary perspective.

Another important result underlined by the energy study is a significant variation of energy and water consumptions found in similar housings (same surface, room layout and orientation but different floors): *e.g.* apartments C003 and C103. Disparities can be explained by differences in the occupancy: a retired person was present during daytime in one dwelling, while the other one was rented by a worker leaving in the morning and returning in the evening. Echoing of energy monitoring and sociological approaches can provide an explanation for such measurements disparities. Situations and habits inherent to various ways of living must be taken into account when comparing the real performance of similar housing.

Finally, the sociological study has shown that residents had chosen to live in that residence because of the district life quality. However, the building performance was not a criterion in the decision to move-into their new rental house. For engineers on the contrary, energy and environmental performances are highly important aspects in a building. Furthermore, inhabitants did not know which energy systems were installed in the building, nor in which matter to deal with some specific user-interface that were not present in their previous dwelling. For designer however these interfaces are intuitive to operate and play a full-part in developed energy-management strategies. A further communication on the building characteristics from the design phase, as well as an "instructions manual" on energy systems could thus allow inhabitants to have a more conscious view of their use, in relation to their expected quality of life. Some research in this direction, conducted on

energy-efficient office buildings [85], showed that occupants who received training on the building use were more satisfied and felt better in their office environment. However, beside such manual of recommended practices, a personal guidance, or a co-reflexion with the inhabitants would be relevant in order to explain how to operate systems appropriately based on the individual habits.

# 5 Discussion

The proposed methodology was applied to a French rental multifamily-house complying with French standards. However, the methodology, *i.e.* performing disciplinary studies and then a cross-analysis, can easily be transposed to other buildings. While some disciplinary results remain specific to the case study context, knowledge from the cross-disciplinary analysis, and especially the identified points of convergence will be helpful to carry out further multidisciplinary studies in various building applications.

## 5.1 Discussion on the disciplinary studies

### 5.1.1 Sociological study

The sociological study investigated the way inhabitants are doing in order to feel well in their new home. In this article, the findings were synthesised and focussed on the human-building interaction and the interaction between inhabitants and their energy systems. The methodology for this study was not based on surveys nor on interviews as frequently performed [86,87]. Information was rather extracted following an immersive and co-reflexive approach, based on in-situ discussions with inhabitants. Such iterative discussion meetings were preferred because they allow more flexibility in the collection of information, they stimulate conversation and they fully involve inhabitants. Using in-situ observations, without preconceived ideas from the sociologist, a co-reflexion is achieved: inhabitants progress with the sociologist in the understanding of the conditions of use in their homes. Although more flexible, the chosen approach has some drawback. It may be more burdensome as the sociologist has to spend a lot of time into the inhabitants' apartments. The sociologist should be very involved and conscientious in its work to analyse all the collected

information and extract reliable data. Iterations (*i.e.* meeting 2, 3, …) are therefore necessary to validate with the inhabitants the hypothesis regarding their real-life practices at home. In addition, the findings of this study are hardly generalizable as they are very specific to the context and inhabitants' habits.

### 5.1.2 Energy and comfort study

Building C was monitored with energy counters and sensors in order to get energy and water consumptions and to gather information on indoor environmental conditions. The building monitoring highlighted disparities in the consumptions and comfort conditions of similar flats. In average, the yearly energy consumption of the building (63.3 kWh/m² for gas and 16.5 kWh/m² for electricity) was representative of what was built in the French Auvergne Rhone Alps region. This was confirmed by a report of the French Environment & Energy Management Agency which had monitored six multifamily houses built between 2006 and 2011 in this region [88]. Out of the six buildings, four were equipped with a gas boiler serving as a backup to a solar thermal DHW system. Of these four, the measured primary consumptions ranged between 42 and 64 kWh/m² for heating, between 18 and 26 kWh/m² for DHW and between 60 and 90 kWh/m² for both contributors.

Comfort related sensors were installed in the building in order to understand what indoor temperature setpoint is chosen by occupants in winter, if overheating occurred in summer, if the ventilation system worked properly and when lightings were required. These sensors were installed for technical reasons and to have insight regarding the comfort of occupants, as measured data could be compared to comfort requirement standards. In this article, only the results linked to hygrothermal comfort and indoor air quality have been presented. These indicators may not be sufficient in order to represent the indoor environmental comfort of occupants in a user-centric perspective. The illuminance sensors installed may give additional data regarding the visual comfort. Furthermore, this study could be extended by adding sensors to record the acoustic comfort.

The aim of this energy study was not to monitor all occupants activities nor to develop occupant behaviour and thermal comfort model, as performed in other works [3,33], but rather to better understand the performance of the building under investigation. Therefore, energy and comfort indicators were not analysed in a shorter time-step or spatial-scale (*e.g.* per room). Based on this first analysis, the studies could be extended in order to predict and optimise future energy consumptions while keeping the indoor environment comfortable and healthy as performed in Fan *et al.* [89] or in Reynolds *et al.* [90].

### 5.1.3 LCA study

Environmental impacts found in this study may be difficult to interpret as no variant comparison is performed. The work of Lavagna *et al.* [91] can be used in order to compare the LCA results of the Three Besants to those of average European multifamily houses. They studied the environmental impacts of building archetypes in Europe and found that a multifamily houses built for 100 years in moderate climate (as in France) between 1990 and 2010 (most recent period available) emitted 2.47 t $CO_2$ eq. per dwelling and per year[4]. In our study, 2.29 t $CO_2$ eq. per dwelling and per year are emitted when recalculating the LCA results with a building lifetime of 100 years[5]. The results from Lavagna *et al.* [91] and our study are in the same order of magnitude and the lower value in this study can be explained by the higher energy performance of the Three Besants building compared to the performance of an average multifamily house built between1990 and 2010 in a moderate European climate.

As highlighted in other studies [92,21,22,91], the use phase still has a strong influence on the LCA results. The processes operated during this phase should therefore be described precisely. It involves a better knowledge on the occupant behaviour and emphasises usefulness of refining occupancy scenarios.

[4] 2.47 t $CO_2$ eq. per dwelling and per year are obtained by multiplying the 41.2 kg $CO_2$ eq. emitted per square meter and per year for a multifamily house in moderate climate that was built between 1990 and 2010 (see table 8 of Lavagna *et al.* [91]), by the average floor area of this archetype which is 59.97 m².

[5] The climate change indicator is chosen for the comparison as it is calculated with the same life cycle impact assessment methodology in both studies.

No uncertainty analysis has been performed on these results. However, LCA results strongly depend on all assumptions taken and occupant behaviours is not the only source of variability. The building lifetime and the building components lifetime significantly impacts the results as discussed in several studies [93–96]. Buildings having a long lifetime, processes linked with the use phase as well as the building context could change a lot over the lifetime. Therefore, there are high uncertainties on long-term scenarios [97–99].

## 5.2 Discussion on the cross-analysis

During the cross-analysis, actors of the three disciplinary fields met around a table to share their experiences. In-depth discussions on each actor practices made it possible to identify aspects that could be neglected in a mono-disciplinary research. Tweed and Zapata-Lancaster [7] highlighted that humanities-based approaches may enrich building performance evaluation. In this study, the same conclusion was drawn: conclusion of the sociological study provides a better insight into energy consumptions and environmental impacts. Additionally, it turns out that the reverse is also true. Engineering approaches also enriched the human-building interaction study: interaction between inhabitant and energy systems can be better depicted when the sociologist has some knowledge on building energy. All in all, transversal concepts were found and disciplinary results could be put in perspective.

The points of convergence found may be described with different terminologies in each discipline. In this article, these common concepts were identified using one mind-map for each discipline as well as extensive discussions on each methodological steps. The identification of points of convergence could be extended and improved carrying out lexicological studies to recognise the semantic relations between disciplinary concepts more systematically.

The first point of convergence was related to the people living in a building. Each study has its own terminology regarding these concepts: “inhabitants” vs. “occupants”. This point of convergence was easily identified as the words seemed to be synonyms. However, it turned out that these words were

rather complementary: inhabitants are occupants that developed a special relationship with their dwelling. Considering this distinction, the two words can be used more appropriately in future studies.

The second point of convergence linked well-being, comfort and health. All three words are echoing the notions of positive or negative feelings regarding a context. They were thus clustered behind one concept. Well-being is related to internal feelings and perceptions from all five sense. It comprises comfort and health. In order to improve the correlations between sociological and engineering approaches and to get better insights regarding adaptive comfort in future studies, information linked to all five sense should be monitored.

Regarding the third point of convergence, terms used by engineers and sociologist are very different. A link between “ballistic connections” and “solicitations” was not directly established. After each actor explained the aim of his study and the two other actors rephrased it, this common concept was identified. It is mainly related to variable signals coming from outside the dwelling (*e.g.* response from and to the environment). This concept should be further cross-analysed in future multi-disciplinary studies in order to better understand the effect that each signal coming from the outside has on each disciplinary results.

The fourth point of convergence was identified as it refers in all cases to the “usability” of “engineering tools” for acting on energy systems. Several words are used to describe man-machine interfaces, which are perceived very differently by designer and inhabitants. More than offering "instructions manual" on energy systems to inhabitants, we rather suggest a personal accompaniment on the way to operate systems, based on inhabitants’ previous experiences.

The last point of convergence was easily identified as synonyms are used in the three disciplines. “Standards” and “norms” refer to rules that are followed but they have different connotations in each discipline. While engineers comply with standards, in sociology, norms affect inhabitants that

have to cope with what was designed without them. More integration and interdisciplinarity is required so that technical norms are not seen as constraints by inhabitants.

## 5.3 Recommendations for future studies

From the cross-analysis results, two levels of recommendations are issued. For future studies involving sociological, energy and LCA studies, we suggest to involve actors from all disciplines as well as future inhabitants (or at least future owners) from the early design stage of a construction or renovation project. This is necessary so that all participants express their expectations and habits, understand the norms to be observed and receive information on how systems will work. We recommend that all three post-occupancy evaluations have to be performed during the same time period. Actors of each discipline can thus interact with each other and share some research objects such as well-being, comfort and health on the one side, or ballistic connections and solicitations on the other side. An accompaniment of inhabitants is also advised, especially for rental buildings, regarding the use of energy and the environmental impacts of the use phase. A personal guidance, based on discussions on the inhabitant habits and previous experiences, seems more appropriate than providing a building user manual or training, as the inhabitant is invited to reflect upon its own habits. Finally, we propose to apply the immersive and co-reflexive sociological approach to other studies when a knowledge of context specific conditions of use is required.

In addition, for efficient collaborations between disciplinary fields in future studies, we first suggest to continue the identification of points of convergence using lexicological studies. This work can be extended by cross-analysing other building projects (*e.g.* housing, office, …), during several projects stages (*e.g.* design, construction, operation, refurbishment, …), and involving actors from other disciplines (*e.g.* architects, economists, urban planners, …). In that way, a more exhaustive view of the common concepts shared by at least two disciplines will be achieved, reducing the communication problems in transdisciplinary projects.

# 6 Conclusion

In this paper, the post-occupancy phase of a multifamily house was investigated using sociological, energy and LCA studies followed by a cross-disciplinary analysis. The general approach and the studies presented were fed by the idea of deploying various views and disciplinary analyses at the scale of one building. Design and building techniques applied on this building are representative of the current practices in France. Experiments carried out on this building bring therefore knowledge transposable to other common buildings. This research aimed to demonstrate and measure the heuristic added value of a multidisciplinary approach combining three disciplinary approaches all indexed to a "standard building". More specifically, our objective was to mirror three different approaches in order to identify and bring light to points of convergence allowing: i) to provide a broader lighting on one building; ii) to ensure that each of the disciplinary experiments can enhance and reinforce each other; and iii) to put into perspective forms of complementarity potentially useful in any analysis of the *in vivo* operation of a building.

Following conclusions were drawn from each of the three mono-disciplinary studies. First, the immersive and co-reflexive sociological study showed through discussions between inhabitants and a sociologist, that inhabitants adapted their use and habits to the building design and that their relations with energy systems is quite complex. Second, the building monitoring highlighted disparities in the consumptions and comfort conditions of similar flats. Third, the LCA shows that the use phase, mainly driven by heating impacts, leads to the highest impacts for most of the environmental indicators, when considering a 50-years building lifetime. These disciplinary results provide interesting insight into the building performance but most of them are poorly generalizable to other buildings.

Disciplinary approaches and results were then jointly analysed. A two-step method was developed for the cross-disciplinary assessment. In a first step, key concepts, that are of importance for several disciplines, were found. They are related to people in the building, interior atmosphere, outdoor

conditions, man-machine interface and standards. Identified points of convergence and discipline specific terminologies will help in a better understanding between disciplinary fields. In a second step, results were cross-analysed and lessons were learned from the three analyses. Among them, all actors, including future inhabitants, should be involved from the design stage of the building in order to take into account situations of use and to share useful information. Furthermore, inhabitants should be accompanied on the way to operate energy systems. Highlighted points of improvement will allow to perform more integrated multidisciplinary analyses in both design and post-occupancy phases.

These are the findings and contributions that can be released from a research protocol and reflections nourished by a perspective of echoing different approaches and disciplinary knowledge. An extended understanding of the building thus reveals its heuristic potential, whose scope could be further increased, depending on the quantity of disciplinary points of view considered, as well as on the quality of the cross-analysis that can be developed.

# 7 Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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# 9 Bibliography


[1] K.B. Janda, Buildings don't use energy: people do, Archit. Sci. Rev. 54 (2011) 15–22. https://doi.org/10.3763/asre.2009.0050.

[2] Y. Zhang, X. Bai, F.P. Mills, J.C.V. Pezzey, Rethinking the role of occupant behavior in building energy performance: A review, Energy Build. 172 (2018) 279–294. https://doi.org/10.1016/j.enbuild.2018.05.017.

[3] S. Carlucci, M. De Simone, S.K. Firth, M.B. Kjærgaard, R. Markovic, M.S. Rahaman, M.K. Annaqeeb, S. Biandrate, A. Das, J.W. Dziedzic, G. Fajilla, M. Favero, M. Ferrando, J. Hahn, M. Han, Y. Peng, F. Salim, A. Schlüter, C. van Treeck, Modeling occupant behavior in buildings, Build. Environ. 174 (2020) 106768. https://doi.org/10.1016/j.buildenv.2020.106768.

[4] T. Ingold, Making: Anthropology, Archaeology, Art and Architecture, Routledge, London ; New York, 2013.

[5] A.C.G. Cooper, Building physics into the social: Enhancing the policy impact of energy studies and energy social science research, Energy Res. Soc. Sci. 26 (2017) 80–86. https://doi.org/10.1016/j.erss.2017.01.013.

[6] A. Wolff, I. Weber, B. Gill, J. Schubert, M. Schneider, Tackling the interplay of occupants' heating practices and building physics: Insights from a German mixed methods study, Energy Res. Soc. Sci. 32 (2017) 65–75. https://doi.org/10.1016/j.erss.2017.07.003.

[7] C. Tweed, G. Zapata-Lancaster, Interdisciplinary perspectives on building thermal performance, Build. Res. Inf. 46 (2018) 552–565. https://doi.org/10.1080/09613218.2018.1379815.

[8] S. Kalantari, M. Shepley, Psychological and social impacts of high-rise buildings: a review of the post-occupancy evaluation literature, Hous. Stud. 0 (2020) 1–30. https://doi.org/10.1080/02673037.2020.1752630.

[9] S. D'Oca, C.-F. Chen, T. Hong, Z. Belafi, Synthesizing building physics with social psychology: An interdisciplinary framework for context and occupant behavior in office buildings, Energy Res. Soc. Sci. 34 (2017) 240–251. https://doi.org/10.1016/j.erss.2017.08.002.

[10] M. Pellegrino, M. Musy, Seven questions around interdisciplinarity in energy research, Energy Res. Soc. Sci. 32 (2017) 1–12. https://doi.org/10.1016/j.erss.2017.07.007.

[11] W. Tian, A review of sensitivity analysis methods in buildings energy analysis, Renew. Sustain. Energy Rev. 20 (2013) 411–419. https://doi.org/10.1016/j.rser.2012.12.014.

[12] A. Ioannou, L.C.M. Itard, Energy performance and comfort in residential buildings: Sensitivity for building parameters and occupancy, Energy Build. 92 (2015) 216–233. https://doi.org/10.1016/j.enbuild.2015.01.055.

[13] W. Belazi, S.-E. Ouldboukhitine, A. Chateauneuf, A. Bouchair, Uncertainty analysis of occupant behavior and building envelope materials in office building performance simulation, J. Build. Eng. 19 (2018) 434–448. https://doi.org/10.1016/j.jobe.2018.06.005.

[14] W. Tian, Y. Heo, P. de Wilde, Z. Li, D. Yan, C.S. Park, X. Feng, G. Augenbroe, A review of uncertainty analysis in building energy assessment, Renew. Sustain. Energy Rev. 93 (2018) 285–301. https://doi.org/10.1016/j.rser.2018.05.029.

[15] J. Rouleau, L. Gosselin, P. Blanchet, Robustness of energy consumption and comfort in high-performance residential building with respect to occupant behavior, Energy. 188 (2019) 115978. https://doi.org/10.1016/j.energy.2019.115978.

[16] T. de Meester, A.-F. Marique, A. De Herde, S. Reiter, Impacts of occupant behaviours on residential heating consumption for detached houses in a temperate climate in the northern part of Europe, Energy Build. 57 (2013) 313–323. https://doi.org/10.1016/j.enbuild.2012.11.005.

[17] M.M. Salehi, B. Terim Cavka, A. Frisque, D. Whitehead, W.K. Bushe, A case study: The energy performance gap of the Center for Interactive Research on Sustainability at the University of British Columbia, J. Build. Eng. 4 (2015) 127–139. https://doi.org/10.1016/j.jobe.2015.09.002.

[18] C. Carpino, E. Loukou, P. Heiselberg, N. Arcuri, Energy performance gap of a nearly Zero Energy Building (nZEB) in Denmark: the influence of occupancy modelling, Build. Res. Inf. 0 (2020) 1–23. https://doi.org/10.1080/09613218.2019.1707639.

[19] B. Simanic, B. Nordquist, H. Bagge, D. Johansson, Predicted and measured user-related energy usage in newly built low-energy schools in Sweden, J. Build. Eng. 29 (2020) 101142. https://doi.org/10.1016/j.jobe.2019.101142.

[20] T. Hong, S.C. Taylor-Lange, S. D'Oca, D. Yan, S.P. Corgnati, Advances in research and applications of energy-related occupant behavior in buildings, Energy Build. 116 (2016) 694–702. https://doi.org/10.1016/j.enbuild.2015.11.052.

[21] L. Cabeza, L. Rincon, V. Vilarino, G. Perez, A. Castell, Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the buildings sector : A review, Renew. Sustain. Energy Rev. 29 (2014) 394–416. https://doi.org/10.1016/j.rser.2013.08.037.

[22] C.K. Anand, B. Amor, Recent developments, future challenges and new research directions in LCA of buildings: A critical review, Renew. Sustain. Energy Rev. 67 (2017) 408–416. https://doi.org/10.1016/j.rser.2016.09.058.

[23] S. Su, X. Li, Y. Zhu, B. Lin, Dynamic LCA framework for environmental impact assessment of buildings, Energy Build. 149 (2017) 310–320. https://doi.org/10.1016/j.enbuild.2017.05.042.

[24] K. Negishi, L. Tiruta-Barna, N. Schiopu, A. Lebert, J. Chevalier, An operational methodology for applying dynamic Life Cycle Assessment to buildings, Build. Environ. 144 (2018) 611–621. https://doi.org/10.1016/j.buildenv.2018.09.005.

[25] D. Vuarnoz, E. Hoxha, J. Nembrini, T. Jusselme, S. Cozza, Assessing the gap between a normative and a reality-based model of building LCA, J. Build. Eng. 31 (2020) 101454. https://doi.org/10.1016/j.jobe.2020.101454.

[26] M.V. Bavaresco, E. Ghisi, A low-cost framework to establish internal blind control patterns and enable simulation-based user-centric design, J. Build. Eng. 28 (2020) 101077. https://doi.org/10.1016/j.jobe.2019.101077.

[27] L. Yan, M. Liu, K. Xue, Z. Zhang, A study on temperature-setting behavior for room air conditioners based on big data, J. Build. Eng. 30 (2020) 101197. https://doi.org/10.1016/j.jobe.2020.101197.

[28] H.N. Rafsanjani, A. Ghahramani, Towards utilizing internet of things (IoT) devices for understanding individual occupants' energy usage of personal and shared appliances in office buildings, J. Build. Eng. 27 (2020) 100948. https://doi.org/10.1016/j.jobe.2019.100948.

[29] M.S. Andargie, M. Touchie, W. O'Brien, A review of factors affecting occupant comfort in multi-unit residential buildings, Build. Environ. 160 (2019) 106182. https://doi.org/10.1016/j.buildenv.2019.106182.

[30] F. Fantozzi, M. Rocca, An Extensive Collection of Evaluation Indicators to Assess Occupants' Health and Comfort in Indoor Environment, Atmosphere. 11 (2020) 90. https://doi.org/10.3390/atmos11010090.

[31] S.K. Sansaniwal, J. Mathur, S. Mathur, Review of practices for human thermal comfort in buildings: present and future perspectives, Int. J. Ambient Energy. 0 (2020) 1–27. https://doi.org/10.1080/01430750.2020.1725629.

[32] M.V. Bavaresco, S. D'Oca, E. Ghisi, R. Lamberts, Methods used in social sciences that suit energy research: A literature review on qualitative methods to assess the human dimension of energy use in buildings, Energy Build. 209 (2020) 109702. https://doi.org/10.1016/j.enbuild.2019.109702.

[33] J. Du, W. Pan, C. Yu, In-situ monitoring of occupant behavior in residential buildings – a timely review, Energy Build. 212 (2020) 109811. https://doi.org/10.1016/j.enbuild.2020.109811.

[34] Y. Zhu, S. Saeidi, T. Rizzuto, A. Roetzel, R. Kooima, Potential and challenges of immersive virtual environments for occupant energy behavior modeling and validation: A literature review, J. Build. Eng. 19 (2018) 302–319. https://doi.org/10.1016/j.jobe.2018.05.017.

[35] V. Fabi, M.V. Di Nicoli, G. Spigliantini, S.P. Corgnati, Insights on pro-environmental behavior towards post-carbon society, Energy Procedia. 134 (2017) 462–469. https://doi.org/10.1016/j.egypro.2017.09.604.

[36] C. Zeng, S. Liu, A. Shukla, B. Yang, Identifying the occupant's satisfaction and awareness for the performance of Eco houses in the United Kingdom, J. Build. Eng. 18 (2018) 281–291. https://doi.org/10.1016/j.jobe.2018.03.023.

[37] M.C. Celuppi, C.R.M. Meirelles, R. Cymrot, B. De Alencar Borst, J.P.A. Gobo, Preliminary approach to the analysis of climate perception and human thermal comfort for riverside dwellings the Brazilian Amazon, J. Build. Eng. 23 (2019) 77–89. https://doi.org/10.1016/j.jobe.2019.01.019.

[38] J.A. Diaz-Acevedo, L.F. Grisales-Noreña, A. Escobar, A method for estimating electricity consumption patterns of buildings to implement Energy Management Systems, J. Build. Eng. 25 (2019) 100774. https://doi.org/10.1016/j.jobe.2019.100774.

[39] V. Moghimi, M.B.M. Jusan, P. Izadpanahi, J. Mahdinejad, Incorporating user values into housing design through indirect user participation using MEC-QFD model, J. Build. Eng. 9 (2017) 76–83. https://doi.org/10.1016/j.jobe.2016.11.012.

[40] U. Wilke, F. Haldi, J.-L. Scartezzini, D. Robinson, A bottom-up stochastic model to predict building occupants' time-dependent activities, Build. Environ. 60 (2013) 254–264. https://doi.org/10.1016/j.buildenv.2012.10.021.

[41] E. Vorger, P. Schalbart, B. Peuportier, Integration of a comprehensive stochastic model of occupancy in building simulation to study how inhabitants influence energy performance, in: Proc. PLEA 2014, Ahmedabad (India), 2014: p. 8.

[42] V. Aragon, S. Gauthier, P. Warren, P.A.B. James, B. Anderson, Developing English domestic occupancy profiles, Build. Res. Inf. 47 (2019) 375–393. https://doi.org/10.1080/09613218.2017.1399719.

[43] A. Heydarian, C. McIlvennie, L. Arpan, S. Yousefi, M. Syndicus, M. Schweiker, F. Jazizadeh, R. Rissetto, A.L. Pisello, C. Piselli, C. Berger, Z. Yan, A. Mahdavi, What drives our behaviors in buildings? A review on occupant interactions with building systems from the lens of behavioral theories, Build. Environ. 179 (2020) 106928. https://doi.org/10.1016/j.buildenv.2020.106928.

[44] G. Cerinsek, D. Bancic, D. Podjed, S. D'Oca, J. Vetrsek, S. Dolinsek, P. op't Veld, Boosting affordability, acceptability and attractiveness of deep energy renovations of residential buildings – a people-centred ethnographic approach, E3S Web Conf. 111 (2019) 03026. https://doi.org/10.1051/e3sconf/201911103026.

[45] S. Hampton, An ethnography of energy demand and working from home: Exploring the affective dimensions of social practice in the United Kingdom, Energy Res. Soc. Sci. 28 (2017) 1–10. https://doi.org/10.1016/j.erss.2017.03.012.

[46] I. Cieraad, At Home: An Anthropology of Domestic Space, Syracuse University Press, 2006.

[47] M. Ségaud, Anthropologie de l'espace, Armand Colin, 2010. https://doi.org/10.3917/arco.segau.2010.01.

[48] L. Grésillon, Sentir son lieu (ou ne pas le sentir). De l'importance de la sensorialité, in: Fabr. Modes Habiter Homme Lieux Milieux Vie Morel-Brochet Annabelle Ortar Nathalie, Editions L'Harmattan (Paris), Collection Habitat et Sociétés, 2012.

[49] J.-F. Augoyard, Pas à pas. Essai sur le cheminement quotidien en milieu urbain, Editions du Seuil, 1979.

[50] M. De Certeau, L'invention du quotidien, I : Arts de faire, Gallimard, 1990. http://www.gallimard.fr/Catalogue/GALLIMARD/Folio/Folio-essais/L-invention-du-quotidien-I (accessed November 27, 2018).

[51] M. Augé, Non Lieux. Introduction à une anthropologie de la surmodernité, Editions du Seuil, 1992. http://www.seuil.com/ouvrage/non-lieux-marc-auge/9782020125260 (accessed November 27, 2018).

[52] M. De Certeau, L'invention du quotidien, II : Habiter, cuisiner, Gallimard, 1994. http://www.gallimard.fr/Catalogue/GALLIMARD/Folio/Folio-essais/L-invention-du-quotidien-I (accessed November 27, 2018).

[53] F. Chateauraynaud, Argumenter dans un champ de forces. Essai de balistique sociologique, Edtions Petra. (2011) 477.

[54] H. Lefebvre, La production de l'espace, 4e édition, Economica, Paris, 2000.

[55] A. Gras, Le choix du feu: Aux origines de la crise climatique, Fayard, Paris, 2007.

[56] R.K. Wright, Mass Observation and the Emotional Energy Consumer, Can. J. Hist. (2018). https://doi.org/10.3138/cjh.ach.53.3.04.

[57] W. Abrahamse, L. Steg, C. Vlek, T. Rothengatter, A review of intervention studies aimed at household energy conservation, J. Environ. Psychol. 25 (2005) 273–291. https://doi.org/10.1016/j.jenvp.2005.08.002.

[58] W. Abrahamse, R. Shwom, Domestic energy consumption and climate change mitigation, WIREs Clim. Change. 9 (2018) e525. https://doi.org/10.1002/wcc.525.

[59] B. Mallaband, G. Wood, K. Buchanan, S. Staddon, N.M. Mogles, E. Gabe-Thomas, The reality of cross-disciplinary energy research in the United Kingdom: A social science perspective, Energy Res. Soc. Sci. 25 (2017) 9–18. https://doi.org/10.1016/j.erss.2016.11.001.

[60] A.R. Hansen, The social structure of heat consumption in Denmark: New interpretations from quantitative analysis, Energy Res. Soc. Sci. 11 (2016) 109–118. https://doi.org/10.1016/j.erss.2015.09.002.

[61] K.J. Lomas, Carbon reduction in existing buildings: a transdisciplinary approach, Build. Res. Inf. 38 (2010) 1–11. https://doi.org/10.1080/09613210903350937.

[62] M. Sibilla, E. Kurul, Transdisciplinarity in energy retrofit. A Conceptual Framework, J. Clean. Prod. 250 (2020) 119461. https://doi.org/10.1016/j.jclepro.2019.119461.

[63] P. Femenías, L. Thuvander, Transdisciplinary Research in the Built Environment: A Question of Time, Technol. Innov. Manag. Rev. 8 (2018) 27–40. https://doi.org/10.22215/timreview/1176.

[64] K. Mjörnell, The Role of Trans-Disciplinary Research in Sustainable Renovation, J. Manag. Sustain. 10 (2019) p1. https://doi.org/10.5539/jms.v10n1p1.

[65] A. Wierzbicka, E. Pedersen, R. Persson, B. Nordquist, K. Stålne, C. Gao, L.-E. Harderup, J. Borell, H. Caltenco, B. Ness, E. Stroh, Y. Li, M. Dahlblom, K. Lundgren-Kownacki, C. Isaxon, A. Gudmundsson, P. Wargocki, Healthy Indoor Environments: The Need for a Holistic Approach, Int. J. Environ. Res. Public. Health. 15 (2018) 1874. https://doi.org/10.3390/ijerph15091874.

[66] République française, Arrêté du 26 octobre 2010 relatif aux caractéristiques thermiques et aux exigences de performance énergétique des bâtiments nouveaux et des parties nouvelles de bâtiments, n.d. https://www.legifrance.gouv.fr/eli/arrete/2010/10/26/DEVU1026270A/jo/texte.

[67] République française, Arrêté du 28 décembre 2012 relatif aux caractéristiques thermiques et aux exigences de performance énergétique des bâtiments nouveaux et des parties nouvelles de bâtiments autres que ceux concernés par l'article 2 du décret du 26 octobre 2010 relatif aux caractéristiques thermiques et à la performance énergétique des constructions, n.d. https://www.legifrance.gouv.fr/eli/arrete/2012/12/28/ETLL1233337A/jo/texte.

[68] R. Raymond, Système social énergétique et mouvement créatif ordinaire, Ann. Hist. L'électricité. N° 11 (2013) 73–86.

[69] CETE Lyon, Cahier des charges de métrologie pour un suivi énergétique, 2010. http://docplayer.fr/63269795-Cahier-des-charges-de-metrologie.html.

[70] COSTIC, ADEME Rhône-Alpes, INSTRUMENT, Instrumentation des bâtiments pour un suivi des consommations énergétiques, 2015. https://www.ademe.fr/sites/default/files/assets/documents/guide-instrumentation-des-batiments-pour-suivi-consommations-energetiques-8287-201505.pdf.

[71] RAGE, Compteurs et capteurs – Bonnes pratiques pour choisir et installer les points de mesure, 2015. https://www.programmepacte.fr/sites/default/files/pdf/guide-rage-compteurs-capteurs-points-de-mesure-2015-07.pdf.

[72] ISO 14040, Environmental management - Life cycle assessment - Principles and framework, n.d.

[73] ISO 14044, Environmental management - Life cycle assessment - Requirements and guidelines, 2006.

[74] B. Polster, B. Peuportier, I. Blanc Sommereux, P. Diaz Pedregal, C. Gobin, E. Durand, Evaluation of the environmental quality of buildings towards a more environmentally conscious design, Sol. Energy. 57 (1996) 219–230. https://doi.org/10.1016/S0038-092X(96)00071-0.

[75] E. Popovici, Contribution to the life cycle assessment of settlements, Thèse de doctorat, École Nationale Supérieure des Mines de Paris, 2005.

[76] B. Peuportier, I. Blanc-Sommereux, Simulation tool with its expert interface for the thermal design of multizone buildings, Int. J. Sol. Energy. 8 (1990) 109--120. https://doi.org/10.1080/01425919008909714.

[77] R. Frischknecht, N. Jungbluth, H.-J. Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, M. Spielmann, The ecoinvent Database: Overview and Methodological Framework, Int. J. Life Cycle Assess. 10 (2007) 7. https://doi.org/10.1065.

[78] S. Solomon, D. Qin, M. Manning, M. Marquis, K. Averyt, M.M.B. Tignor, H.J. LeRoy Miller, Z. Chen, Climate Change 2007 : The physical science basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2007.

https://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm.

[79] J.B. Guinée, Handbook on life cycle assessment operational guide to the ISO standards, Int. J. Life Cycle Assess. 7 (2002) 311–313. https://doi.org/10.1007/BF02978897.

[80] M. Goedkoop, R. Spriensma, The Eco-indicator 99: A damage oriented method for life cycle impact assessment, PRé Consultants, Amersfoort, The Netherlands, 2000.

[81] European Standards, EN 15978. Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, 2011. https://viewer.afnor.org/Pdf/Viewer/?token=LdcAcCLhGfY1 (accessed June 14, 2020).

[82] European Standards, EN 15804. Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction, 2016. https://viewer.afnor.org/Pdf/Viewer/?token=LdcAcCLhGfY1 (accessed June 14, 2020).

[83] R.J. Cole, Z. Brown, S. McKay, Building human agency: a timely manifesto, Build. Res. Inf. 38 (2010) 339–350. https://doi.org/10.1080/09613211003747071.

[84] T. Peffer, M. Pritoni, A. Meier, C. Aragon, D. Perry, How people use thermostats in homes: A review, Build. Environ. 46 (2011) 2529–2541. https://doi.org/10.1016/j.buildenv.2011.06.002.

[85] J.K. Day, D.E. Gunderson, Understanding high performance buildings: The link between occupant knowledge of passive design systems, corresponding behaviors, occupant comfort and environmental satisfaction, Build. Environ. 84 (2015) 114–124. https://doi.org/10.1016/j.buildenv.2014.11.003.

[86] S. D'Oca, T. Hong, J. Langevin, The human dimensions of energy use in buildings: A review, Renew. Sustain. Energy Rev. 81 (2018) 731–742. https://doi.org/10.1016/j.rser.2017.08.019.

[87] T. Hong, D. Yan, S. D'Oca, C. Chen, Ten questions concerning occupant behavior in buildings: The big picture, Build. Environ. 114 (2017) 518–530. https://doi.org/10.1016/j.buildenv.2016.12.006.

[88] ADEME Rhône-Alpes, Performances réelles des bâtiments - retours d'expériences. Enseignements des campagnes de suivi et d'évaluation de 14 opérations instrumentées par l'ADEME en Rhône-Alpes, ADEME, 2016. http://www.ville-amenagement-durable.org/IMG/pdf/1601_sommaire_enseignements_campagnes_suivi_evaluation_vad.pdf.

[89] C. Fan, F. Xiao, Y. Zhao, A short-term building cooling load prediction method using deep learning algorithms, Appl. Energy. 195 (2017) 222–233. https://doi.org/10.1016/j.apenergy.2017.03.064.

[90] J. Reynolds, Y. Rezgui, A. Kwan, S. Piriou, A zone-level, building energy optimisation combining an artificial neural network, a genetic algorithm, and model predictive control, Energy. 151 (2018) 729–739. https://doi.org/10.1016/j.energy.2018.03.113.

[91] M. Lavagna, C. Baldassarri, A. Campioli, S. Giorgi, A.D. Valle, V. Castellani, S. Sala, Benchmarks for environmental impact of housing in Europe: Definition of archetypes and LCA of the residential building stock, Build. Environ. (2018). https://doi.org/10.1016/j.buildenv.2018.09.008.

[92] A. Sharma, A. Saxena, M. Sethi, V. Shree, Varun, Life cycle assessment of buildings: A review, Renew. Sustain. Energy Rev. 15 (2011) 871–875. https://doi.org/10.1016/j.rser.2010.09.008.

[93] E. Hoxha, G. Habert, J. Chevalier, M. Bazzana, R. Le Roy, Method to analyse the contribution of material's sensitivity in buildings' environmental impact, J. Clean. Prod. 66 (2014) 54–64. https://doi.org/10.1016/j.jclepro.2013.10.056.

[94] N. Heeren, C.L. Mutel, B. Steubing, Y. Ostermeyer, H. Wallbaum, S. Hellweg, Environmental Impact of Buildings—What Matters?, Environ. Sci. Technol. 49 (2015) 9832–9841. https://doi.org/10.1021/acs.est.5b01735.

[95] M.-L. Pannier, P. Schalbart, B. Peuportier, Comprehensive assessment of sensitivity analysis methods for the identification of influential factors in building life cycle assessment, J. Clean. Prod. 199 (2018) 466–480. https://doi.org/10.1016/j.jclepro.2018.07.070.

[96] K. Goulouti, P. Padey, A. Galimshina, G. Habert, S. Lasvaux, Uncertainty of building elements' service lives in building LCA & LCC: What matters?, Build. Environ. (2020) 106904. https://doi.org/10.1016/j.buildenv.2020.106904.

[97] M. Fouquet, A. Levasseur, M. Margni, A. Lebert, S. Lasvaux, B. Souyri, C. Buhé, M. Woloszyn, Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment, Build. Environ. 90 (2015) 51–59. https://doi.org/10.1016/j.buildenv.2015.03.022.

[98] C. Roux, P. Schalbart, E. Assoumou, B. Peuportier, Integrating climate change and energy mix scenarios in LCA of buildings and districts, Appl. Energy. 184 (2016) 619–629. https://doi.org/10.1016/j.apenergy.2016.10.043.

[99] D.A. Waddicor, E. Fuentes, L. Sisó, J. Salom, B. Favre, C. Jiménez, M. Azar, Climate change and building ageing impact on building energy performance and mitigation measures application: A case study in Turin, northern Italy, Build. Environ. 102 (2016) 13–25. https://doi.org/10.1016/j.buildenv.2016.03.003.