Methods for determining occupant behavioural models for energy-efficient retrofitting of 20th-century buildings

Antonella Mastrorilli1, Roberta Zarcone2, Sabrina Chenafi1, Téva Colonneau1,
1 Laboratoire LACTH, Ecole Nationale Supérieure d’Architecture et de Paysage de Lille, 2 Rue Verte, 59650 Villeneuve-d'Ascq, France
2 Laboratoire GSA, Ecole Nationale Supérieure d’Architecture Paris-Malaquais, 14 rue Bonaparte, 75006 Paris

Abstract
The aim of this research is to facilitate the decision-making process for a range of scenarios when undertaking energy renovation projects on 20th century social housing. Achieving this objective requires immediately setting complex processes in motion, while taking into consideration not only the historical, aesthetic and technical attributes of buildings and materials, but also the interactions of the residents and the site itself. Through an in-depth analysis of energy usage in social housing estate, we shall demonstrate that, in the context of 20th-century architecture, including behavioural models in BPS tools constitutes a fundamental preliminary stage in determining efficient energy solutions adapted on a case by case basis, rather than systematically undertaking full-scale renovation.

Key Innovations
- Identifying variable occupancy scenarios
- SED&BIM processes for energy-efficient retrofitting of 20th-century buildings

Practical Implications
This paper is aimed principally at architects and construction industry professionals who seek to undertake renovation in a non-standardised way. Interacting with residents and modelling their way of life offers an interesting approach to renovation, particularly in terms of energy-efficient renovation of 20th-century buildings.

Introduction
Recent studies have shown the impact of occupants’ behaviour and energy use over time in residential buildings (Ademe, 2017; Sovacool et al., 2015; Janda 2011; Andersen, 2009; Calli et al., 2016). Simulation programmes (BPES programmes) provide an opportunity to undertake detailed analyses of energy performance, taking account of the dynamic nature of different parameters from the outset, including occupants’ behaviour (Andersen et al. 2016; O’Neill & Eisenhower, 2013; Lam, 2014). However, simulated energy use identifies a ‘performance gap’ in relation to actual consumption (Majcen et al., 2013). This gap is due, inter alia, to uncertainty over the initial objective and subjective data linked to the occupants as well as to the simulated behavioural model.

The inclusion of behavioural models in BPS tools represents a crucial stage in reducing the difference between simulated and real energy performance. Three approaches are currently used to model occupants’ behaviour: the deterministic approach according to which the scenario is defined by deterministic responses to physical stimuli (Vorger et al., 2014); the agent-based modelling approach which takes occupants’ behavioural patterns and interactions into account (Lee et al., 2014); and the stochastic approach, based on the laws of probability emerging from data identified in several cases and multiple, random variables (Hong et al., 2017).

Other studies have also highlighted the importance of social and psychological factors, (like faith, values, social status and habits, culture and awareness of environmental issues) which can influence occupants’ behaviour and are often overlooked (Sovacool, 2013).

In France, current regulations for improving buildings’ energy performance are based mainly on deterministic approaches due to their simpler implementation and interpretation. Many of these norms meet the energy standards for existing buildings and new builds: norm RT2012 (Ministere de la transition ecologique, 2012), the current RT (Ministere du logement et de l’habitat durable, 2016) and the Décret n° 2017 919 du 9 mai 2017 « travaux embarqués » [law on construction work in progress] (Ministere du logement et de l’habitat durable, 2017). Conventional scenarios are modelled on ‘standard’ behaviour, differentiated in terms of different types of building and total useful floor area. These norms are calculated according to method Th-B-C-E 2012 (Vorger, 2014) in order to describe the regulatory calculation. Nonetheless, the main drawback of this deterministic approach is the generalisation of behaviour models and their repetition over time.

To address the limitations of conventional calculation methods and the influence of their results on the quality of energy-efficient renovation projects, our study aims to integrate data on consumption, variations based on residency and actual human activity in order to undertake detailed analysis of energy use on a case by case basis.

In this paper we shall present the research undertaken on a case study, financed by the French Minister of Culture in the context of their initiative: « Architecture du XXe
The objective of this study is to create a methodology for defining the most effective intervention strategies best adapted to the wide variety and quality of 20th-century buildings. One of the most significant examples this research aims to call into question is Décret n° 2017 919 du 9 mai 2017 [Order no. 2017 of May 9, 2017] governing “ongoing construction work”. It sparked the thinking behind our research because it advocates the practice of isolating the exterior when renovating the façades of all buildings constructed after 1945.

We compared the impact of internal contributing factors on energy performance in a social housing project, with results obtained from applying conventional usage scenarios based on the French norm RT2012. Another major objective of the research was to include input in the decision-making process from the residents, which allowed for more precise models and energy scenarios to be constructed by taking the specific characteristics of each housing unit into account. The study thus links the range of different occupant behavioural models based on actual data to technical and constructional information.

In the following section, we shall present the roll out of this methodology, based on the characterisation of occupant behavioural models, coupled with the use of BIM software for modelling and dynamic energy simulation (DES) in the framework of the study.

Methodology of ‘in-depth’ occupant behaviour study

In order to take the occupancy variables into account and assess how that impacts on energy needs and usage within the home, we established a methodology using 5 successive phases.

Phase 1 – Knowledge
Starting out from archive documents found on site and historical research, we collected data on materials and building types essential to understanding the context of the existing building and developing an up-to-date digital model.

Phase 2 – Modelling
During this phase, we included several levels of information (structures, spaces, envelopes, ambiances and parameters of the site and systems performance) in a digital model (Autodesk Revit® 2018) necessary for defining the energy simulations. Modelling using BIM software allowed us simultaneously to grasp the cause and effect of the variation in factors relating to transition, transformation and change selected with regard to observed intervention strategies for renovating the energy usage of the housing units.

Phase 3 – Survey
In order to prepare for the energy analyses of different types of modelled housing units, we compiled a questionnaire for the residents, so as to collect as much data as possible on energy consumption and behaviours within their homes. It identified two levels of information (Table 1).

<table>
<thead>
<tr>
<th>Constant Data</th>
<th>Variable Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of household</td>
<td>Occupation of each room</td>
</tr>
<tr>
<td>Heating System</td>
<td>Activity &amp; habits</td>
</tr>
<tr>
<td>Nominal heating temperatures</td>
<td>Usual clothing</td>
</tr>
<tr>
<td>Ventilation System</td>
<td>Pump system for domestic hot water</td>
</tr>
<tr>
<td>Type of lighting</td>
<td>Type of joinery</td>
</tr>
</tbody>
</table>

This phase of the survey allowed us to make contact with the residents and include them as active participants in the creation of typical occupancy profiles.

Phase 4 – Characterisation of detailed occupant profiles
With the aid of digital interpretation and representation tools, identifying occupant profiles allowed us to undertake “in-depth analysis” of every situation described and experienced by the residents. This phase required particular attention to data entry, as it relies essentially on calculation methods and tools selected to create the DES. We then incorporated and supplemented this information with data generated by BIM software during the modelling phase.

In the calculation method relating to residents’ behaviour, 5 variables were taken into consideration in order to identify a detailed scenario of their energy needs: heating, indoor gains due to occupancy and device usage, hot sanitary water consumption, ventilation and lighting.

Heating
We combined information regarding the time the heating was on, nominal and reduced temperature controls and with hourly rate of occupancy $O_t$ [0,1] defined as follows (Eq.1):

$$O_t = \frac{\sum_{i} N_{t,i}}{N_{max}}$$

Where $N_{t,i}$ is the number of occupants present at each point in time, $N_{max}$ is the number of occupants per

---

**Table 1: Constant and Variable Data Identified**
housing unit. Three types of heating were considered in order to define the parameters of the heating temperature \(T_H\): heating at a nominal temperature \(T_n\); heating at a low, or reduced temperature, \(T_r\) and no heating. The hourly scenario was determined as follows:

\[ 0 < O_t \leq 1 \Rightarrow T_H = T_n; \]
\[ O_t = 0 \Rightarrow \text{Two outcomes can occur depending on how long occupants are absent from a housing unit:} \]
\[ \Rightarrow T_H = T_r \text{ for } h_{O_t=0} \leq 48h \]
\[ \Rightarrow \text{No Heating for } h_{O_t=0} > 48h \]

Indoor gains due to occupancy and the use of household appliances

Then we considered two indoor gains scenarios based on household appliances and occupants’ activities.

In order to define the first scenario, we calculated the hourly rate, \(Q_{e,t}\) as follows (Eq.2):

\[ Q_{e,t} = Q_{base} + \sum_{i=1}^{na} p_i \cdot D_{t,i} \quad (2) \]

With \(Q_{base}\) the energy required for household appliances connected constantly on standby, \(p_i\) the rated power of the appliances, \(D_{t}\) the time-factor per hour of usage \([0,1]\) and \(na\) the number of appliances in each housing unit.

To define the second scenario we calculated the hourly rate, \(Q_{o,t}\) as follows (Eq.3):

\[ Q_{o,t} = \sum_{i=1}^{no} \sum_{j=1}^{na} q_j \cdot D_{t,i} \quad (3) \]

With \(q_j\) the heat generated for each activity undertaken by each occupant, \(D_{t}\) the time-factor per hour of each activity \([0,1]\), \(no\) the number of occupants present in each housing unit, and \(na\) the activity undertaken.

Ventilation

We modelled this variable taking the opening and closing of windows into consideration based on answers given in the questionnaire. This allowed us to define a scenario with parameters for both time and activities undertaken in different rooms, without including thermal comfort temperatures. Two types of ventilation were considered: peak ventilation \(vent_{peak}\) (Eq.4) and basic ventilation \(vent_{base}\) (Eq.6), calculated in line with the number of rooms influencing the flow of the ventilation (main rooms, kitchens, bathrooms with and without toilets, separate toilets).

\[ vent_{peak} = Db_{peak} + Db_{unforced} \quad (4) \]

\(vent_{peak}\) relates to a window being opened. \(Db_{peak}\) denotes the maximal ventilation \((\text{m}^3/\text{h})\) in relation to \(m^2\) (Eq.5), \(Db_{unforced}\) is the ventilation rate due to uncontrolled draughts in the housing unit (value corresponding to 0.6 m3/h.m² according to the norm RT2012).

\[ Db_{peak} = \sum_{i=1}^{nk} Db_{pi(a)} + \sum_{i=1}^{nb} Db_{pi(b)} + \sum_{i=1}^{nr} Db_{pi(c)} \quad (5) \]

With \(nk\) number of kitchen(s), \(nb\) number of bathrooms (BA), toilets (WC) or BA+WC, \(nr\) number of main rooms \((\geq 1)\).

The values \(Db_{peak}\) included in the method Th-B-C-E 2012 en vol/h then variations depending on total useful floor area.

\[ Vent_{base} = Db_{base} + Db_{unforced} \quad (6) \]

\(Vent_{base}\) corresponds to a window being closed. \(Db_{base}\) is the minimal ventilation rate \((\text{m}^3/\text{h})\) relative to the \(m^2\) (Eq.7). \(Db_{unforced}\) (seen in equation (4))

\[ Db_{base} = \sum_{i=1}^{nk} Db_{bi(a)} + \sum_{i=1}^{nb} Db_{bi(b)} + \sum_{i=1}^{nr} Db_{bi(c)} \quad (7) \]

With \(nk\) number of kitchen(s), \(nb\) number of BA, WC or BA+WC, \(nr\) number of main rooms \((\geq 1)\).

The values \(Db_{base}\) included in the method “Th BCE” en vol/h then variations depending on total useful floor area.

Domestic hot water consumption (DHW)

This variable was calculated in relation to activities which involve the use of water and the presence of the occupants (Eq.8):

\[ L_T = \sum_{i=1}^{no} \sum_{j=1}^{na} l_j \cdot D_{t,i} \quad (8) \]

\(l_j\) represents the number of litres of domestic hot water used for each activity by each occupant. \(D_{t}\) the the time-factor per hour for each usage \([0,1]\), \(no\) the number of occupants present in each housing unit, and \(na\) the activity undertaken.

Lighting

This variable was calculated by combining usage data with desired luminosity levels. At each time period of the scenario, the lighting levels were measured as follows (Eq.9):

\[ E_L = E_n \cdot T_u \quad (9) \]

With \(E_L\), luminosity levels, \(E_n\) nominal lighting and \(T_u\) usage rates, three cases of \(T_u\), relative to occupancy were considered:

\[ T_u = 100\%, T_u = 50\% \text{ and } T_u = 0\%. \]

Taking data relative to different types of lamps (for example lumens) into consideration and the power of light fittings, the luminosity levels may not have been attained.

Phase 5 – Dynamic energy simulation

After having selected DES (dynamic energy simulation) tools, in the framework of our research study, we proceeded to a simulation of the case study using the calculation engine EnergyPlus v8® (available on
Archiwizard® v2018 & DesignBuilder v6®), followed by the definition of data entry methods appropriate to the functionality of each software programme, in order to translate quantitative data on the occupants which had actually been observed (Figure 1). In addition to the functionalities permitting the construction of a detailed timetable of the occupants’ profiles including time and seasonal variations, the range of activities in every room of each housing unit, a correlation between the usage patterns and daily energy needs and rates relative to occupancy, the DES software (in GBXML format) also utilised all the information collected using BIM software.

The case study on a social housing project in the Haut-de-France region

Through this method, we have been able to check our initial research hypothesis there as well as carry out proposed minimal interventions.

The social housing complex « La Salamandre », designed by the architect André Wogensky and Sud Atelier Architecture and unveiled in 1979 is part of the Modèles Innovation [Innovation Models] put forward in France over the course of three competition campaigns (in 1973, 1974 & 1975) and intended to be ‘mass-produced’ throughout the country. The project is made up of 422 housing units (comprising 105 for home ownership and 317 rental properties managed by a social landlord). In 1994, fifteen years after it was unveiled, all the rental section underwent renovation. The renovation aimed to address the ageing facade and damp-proofing problems on several joints, however it considerably altered the architecture of the original project. Installing cladding on the whole of the exterior facade, (ETI), replacing the old wood joinery with PVC as well as adding a terracotta finish, marked a brutal departure from all the architectural and landscaped qualities of the original ‘innovation model’ (Figure 2).

Systematically choosing technical solutions with far-reaching implications for such a housing project raised numerous questions for us in relation to the validity of conventional, standardised renovation methods (Geslin, 2017), like those advocated in the aforementioned (Décret n° 2017 919 du 9 mai 2017[Order no. 2017 of May 9, 2017]). In that sense, “La Salamandre” represented an opportunity to test our initial research hypothesis and explore an alternative to heavy renovation work.

Using digital modelling as an operational tool.
On the basis of the subject of our study we constructed a digital model using BIM methods (Figure 2). At the end of this phase, we identified six typical housing units and their residents, including a 3-room flat measuring 78m² on the 6th floor of the rental housing section, occupied by a family comprising two adults and one child who were interested in saving energy. We selected their flat as a case study for DES (Figure 3).
The interoperable approach allowed us to share and implement physical and thermal data relating to precise analyses of the building envelopes in both the rented and owner-occupied parts of the building project. Then, on the basis of investigations carried out on site and the analysis of archival data on “La Salamandre”, our chosen approach allowed us to take the environmental context of the project into consideration as well as its overall performance, without overlooking the housing project’s specific characteristics (Figure 4).

Inclusion of the occupancy variable in our analysis of “La Salamandre”
The ongoing survey phase enabled us to construct detailed profiles of all those residents who participated in our study. We launched a major campaign gathering data on residents’ behaviour which allowed us to collect an overview of the energy consumption history. Through the questionnaire, the households could inform us of their occupancy habits, energy use and consumption. We were also interested in any changes the residents had made to their homes which impacted, in the main, on their energy efficiency and comfort. With a view to implementing these behavioural models in the DES, a rigorous schedule of energy sources (be it heating, hot water, appliances or human presence) enabled us to synthesise factors affecting use and behaviour of the residents in their homes.

The influence of the occupancy variable on the DES of the case study flat
In order to justify the relevance of applying this methodology, we shall present below results of energy use obtained in the case study of a three roomed flat and the occupancy model based on information gathered in the questionnaire, as opposed to a fictitious occupancy model in accordance with conditions imposed by building regulations.

Actual energy consumption of the case study flat
The presence of underfloor heating in the Salamandre housing project, makes it impossible to calculate the actual heating consumption in each flat (as heating is included in the shared service charges of the estate). This is the reason why the analysis of energy needs of the case study flat does not include heating.

Electricity bills collected during the survey phase of our research takes electricity used by household appliances, lighting and appliances related to the production and distribution of domestic hot water (DHW) into account. In relation to residents’ actual energy use and habits, we
considered these values by comparing detailed energy profile scenarios with the norm RT 2012. With regard to the case study flat, the individual electricity consumption was 3295 kWh per year on average. In comparison to the data issued on energy consumption in line with the norm (2798 KWh/ per year) and a detailed profile scenario (3473 KWh/per year), we were able to observe a performance gap between the value simulated in a detailed profile and the amount shown on bills which was less than the standard simulation (RT2012) (Figure 5).

Figure 5: Variation of electrical energy consumption per month (KWh)

A comparison of a standard RT 2012 occupancy profile and an actual occupancy profile
The internal consumption of the unit, determined by occupancy, use of appliances and DHW consumption were approximately 3400 kWh a year. Occupancy alone represented only 17 kWh/m²/a year and the use of appliances 26.4 kWh/m²/a year. The cost of these internal gains combined cover 30% of heating needs. These initial results obtained by applying scenarios that comply with RT2012, were then compared to those obtained by constructing actual occupants’ profiles (Figure 6). In this instance, electric heating needs (under floor heating system) were in the order of 73 kWh/m²/a year (or 5694 kWh a year), representing a gain of 5 kWh/m²/a year of consumption in comparison with the thermal analysis of the case study flat, according to RT2012. The internal gains of the unit, due to occupancy, use of appliances and DHW consumption, were around 3611 kWh a year. The occupancy alone represented 20.3 kWh/m²/a year, and use of appliances 26 kWh/m²/a year. The internal gains covered the actual occupancy profile, a total of 40% of the heating needs of the housing unit, i.e. 10% more than results obtained in the RT2012 profile.

From heavy renovation work to strategic minimal intervention on 20th-century buildings
The approach identified by the analysis methodology on a ‘case by case’ basis demonstrates the influence of energy behaviours recorded in the housing unit. It justifies the inclusion of occupancy variables in identifying intervention strategies better adapted to energy renovation.

A comparison of the original and current states
For this application, we compared the DES of the case study flat by distinguishing between the original state (using the actual occupancy profile) and the current state (using the RT2102 occupancy profile). We noticed that just modifying the factors impacting the internal gains - energy consumption, thermal comfort and the presence of occupants – can sometimes be equal to the gain and projected performance levels of major renovation of the housing units. In fact, the heating needs expressed in the flat in its original state, that is without installing cladding (ETI) or replacing the joinery, went up to 76.2 kWh.m²/a year (or 5943.6 kWh a year), rather than 78kWh.m²/a year (or 6084 kWh a year) as opposed to the needs analysed for the units’ current state, according to the RT2102 standard occupancy profile.

The replacement of exterior joinery as an efficient alternative to ETI
By way of an alternative to ETI, the hypothesis of a projected intervention prior to the energy renovation, aimed solely at replacing the joinery from the Salamandre housing project becomes plausible.

The scenario chosen subsequently reflects the results of the simulation obtained on the existing state of the privately owned part of the building, where only the original wooden windows were changed to PVC double glazing and paid for by the residents.
As we have seen, the inclusion of variation factors in actual occupancy profiles, combined with the intervention of simply replacing joinery would boost energy savings by 21 kWh/m²/a year in terms of the heating needs in the building (Figure 7). These observations demonstrate similar results for both of simulated energy renovation approaches – heavy large-scale renovation and occasional renovation.

In the light of these findings, the strategic approach, characterised by analytical methodology on a case by case basis, favours replacing the exterior joinery rather than over insulating the exterior of the Résidence Salamandre, as it appears to have a greater impact on energy saving. Therefore, overhauling the buildings with large-scale energy renovation following conventional housing project methodologies seems to have been unnecessary. Relying instead on detailed analysis on a case by case basis (using the actual measurements of occupancy variables in each housing unit) would have been more advisable, so as to preserve the original material and architectural qualities.

Whether it is a result of variations in gains due to occupancy and metabolic activity or even gains due to various appliances, the scenarios presented here have allowed us to identify ‘typical usage patterns’ of residents’ behaviour. These usage patterns themselves now demonstrate just how crucial they are in developing tailor-made, innovative, action plans for energy-efficient retrofitting of 20th-century buildings. Thanks to these results we have extended our reach, investigating other types of social housing in order to demonstrate that the approach outlined in this study can be adapted and applied to other building contexts.

Acknowledgement
We should like to thank the residents of the Résidence la Salamandre for their time and patience while completing the questionnaires. We should also like to thank the Masters students at ENSAPL who helped compile the questionnaires.

References

Figure 7: Results of comparative energy analysis of external joinery replacement in the privately-owned section (actual profile in blue line) and rented section (RT2012 profile in green line).

Conclusion
Improving the energy efficiency of 20th-century buildings calls for interventions which can meet the demands of energy efficiency, internal comfort and the conservation of the original architectural vocabulary. The variety of models and construction techniques of these projects requires the implementation of an alternative, non-standard approach for energy-efficient retrofitting. The development of digital tools in architecture and construction now enables us to rise to this challenge, by incorporating the information throughout the process of the project. Consequently, it is now possible to:

- optimise complex systems despite varying restrictions while controlling the parameters at play
- produce and test interventions using shared models
- introduce collaborative exchanges between the different actors.


MINISTERE DU LOGEMENT ET DE L'HABITAT DURABLE, Décret n° 2016-711 du 30 mai 2016 relatif aux travaux d'isolation en cas de travaux de ravalement de façade, de réfection de toiture ou d'aménagement de locaux en vue de les rendre habitables, JORF n°0125 du 31 mai 2016.(https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000032611310&categorieLie n=id, 30/01/2019)


