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A Rogeau, R Girard, Y Abdelouadoud, Georges Kariniotakis. Retrofitting a building stock: modeling and optimization for decision aiding at territory scale. CISBAT 2019, Climate resilient cities - Energy efficiency & renewables in the digital era, Sep 2019, Lausanne, Switzerland. <10.1088/1742-6596/1343/1/012029>. <hal-02337521>

**HAL Id: hal-02337521**

**<https://hal.science/hal-02337521v1>**

Submitted on 29 May 2023

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To cite this article: A. Rogeau *et al* 2019 *J. Phys.: Conf. Ser.* **1343** 012029

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# Retrofitting a building stock: modeling and optimization for decision aiding at territory scale

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**Abstract.** Reduction of the energy consumption is a key lever to tackle climate change, but identification of the retrofit actions to undertake within a building stock remains a challenging scientific problem. This paper presents a complete methodology able to design action plans at a territory level with a building resolution. The economic and energetic modeling of the retrofit context is detailed before introducing a linear 0-1 optimization formulation which is used to arbitrate between both building envelope insulation and heating system replacement measures. A 500 buildings territory study case is then presented to illustrate the potential of the developed tool.

## 1. Introduction

In the last decades, many efforts have been put in finding new sustainable ways to generate and use energy. While global orientations are to be decided at a national or international level, the concrete measures are highly depend on the local context and local decision makers can activate various levers (renewable production, building thermal renovation, fuel substitution...). The building sector, identified as one of the principal final energy consumer, jointly with industry, and transport, accounted for nearly 40% of energy consumption in the European Union [1]. The design of retrofit measures became a major concern for local decision-makers who express a need for adequate methods and decision-support due to the complexity of this large multidisciplinary problem [2, 3]. Moreover, many sectors, e.g. housing and energy, enter a new digitization era, thus offering new tools for sustainable design.

While the problem to be dealt is complex due to the various technical solutions (for thermal renovation and heating systems) and the size of the territory to be treated, most of the proposed methods for retrofit optimization consider only envelope insulation [4, 5, 6], work with aggregated buildings resolution [7, 8] or are limited to heuristic approaches [9, 10]. Optimization are rarely lead at territory level (more than tens of buildings), with a building resolution to facilitate the implementation of actions.

Consequently, this paper presents a global methodology for optimizing the retrofit of individual buildings at a territory scale, considering both building envelope insulation (BE) and heating system replacement (HS). It is divided into three sections. A first part briefly describes the modeling of the building retrofit context and its integration into a linear 0-1 optimization. In a second part, relevant databases for describing French building stocks



are identified and integrated into a building stock modeling workflow which counts with the association of heterogeneous databases using matching and sampling methods. Finally, a third part presents case studies results, highlighting in particular the impact of some key parameters on the solution provided by the algorithm.

## 2. Modeling of the retrofit context with linear 0-1 optimization formalism

The modeling of the retrofit context is based on the approach presented by Rogeau et al. [11], which relies on three major principles:

(1) The energy needs  $Q^b$  of a building  $b$  is estimated using a simple physics based model. The final energy consumption  $E^b$  depends on the energy needs of the building  $b$  and its energy systems. Indeed, the retrofit strategy (represented by the ensemble of decision variables  $X^b$  related to building  $b$ ) modifies physical properties of buildings and systems, directly impacting the energy consumption. The participation of heating system is represented by its efficiency  $\eta^b$  while the building envelope determines the heating demand  $Q^b$  through thermal coefficients  $u_s^b$ , ventilation rate  $\tau_{vent}^b$  and solar factors  $g_s^b$ , as presented by Eq. (1). The geometry of the building is considered through the area of each surface in contact with the outside  $A_s^b$ , the volume of the building  $V^b$  and the proportion of windows oriented south  $\delta_s^b$ . Climatic condition of the area are integrated through a degree-hour and an irradiation-hour parameters  $DH$  and  $IH$ . Finally,  $c_{air}$  represents the thermal conductivity of air.

$$Q^b(X^b) = \left( DH \left( \sum_s u_s^b(X^b) A_s^b + \frac{c_{air}}{3.6} \tau_{vent}^b V^b \right) - IH \sum_s A_s^b g_s^b(X^b) \delta_s^b \right) \quad (1)$$

$$E^b(X^b) = \frac{1}{\eta^b(X^b)} Q^b(X^b) \quad (2)$$

(2) The retrofit problem is constructed using an optimization formalism where the activation of retrofit actions is modeled by binary decision variables, which represent the application of an envelope insulation solution on exterior surfaces or the replacement of the heating system in buildings. The resulting problem is formulated as the multiple-choice multidimensional variant of the knapsack problem (MMKP) [12, 13]. Investment costs are considered as objective: the investments in building envelope  $I_{BE}^b$  depend linearly of the surface to be refurbished  $A_s^b$  and are summed over all surfaces while investments in the heating system  $I_{HS}^b$  are split between a fixed cost of installation  $C^2$  and a variable cost which linearly depends on the sizing power of equipment  $Q_{peak}^b$ . This sizing power, calculated using the physics based energy model, and the costs  $C_s^1$ ,  $C^2$  and  $C^3$  depend of the technical solutions activated by the retrofit strategy  $X^b$  on building  $b$ .

$$I_{BE}^b(X^b) = \sum_s C_s^1(X^b) A_s^b \quad (3)$$

$$I_{HS}^b(X^b) = C^2(X^b) + C^3(X^b) Q_{peak}^b(X^b) \quad (4)$$

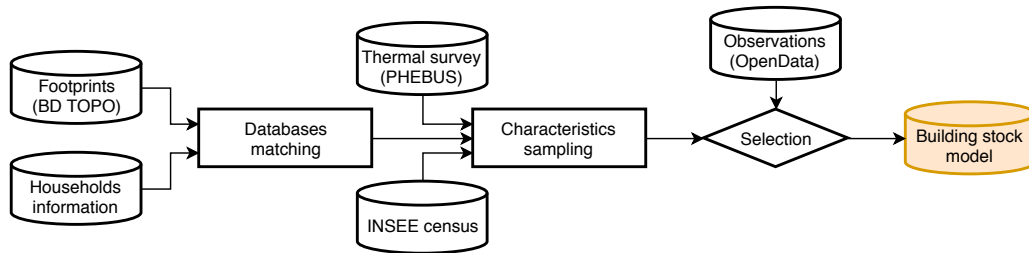
The optimization problem is defined properly and the meeting of the different strategic targets  $F_i$  of the territory is passed to constraints through the participation of each building  $f_i^b$ . They can be related to energy consumption or greenhouse gases emission reduction for instance. The second constraint line represents the activation of maximum one retrofit technology  $t$  per retrofitable element  $r$  (envelope surface or heating system).  $R^b$  is the set of retrofitable elements in building  $b$  and  $T_r^b$  the set of technical solutions available for element  $r$  of building  $b$ .

$$\begin{aligned}
& \underset{X}{\text{minimize}} && \sum_{b \in N} I_{BE}^b(X^b) + I_{HS}^b(X^b) \\
& \text{subject to} && \sum_{b \in N} f_i^b(X^b) \leq F^i, \quad i \in K, \\
& && \sum_{t \in T_r^b} x_{r,t}^b = 1, \quad b \in N, r \in R^b, \\
& && x_{r,t}^b \in \{0, 1\}, \quad b \in N, r \in R^b, t \in T_r^b
\end{aligned}$$

(3) As the consumption depends on both efficiency and thermal coefficient through a product, decision variables are coupled into new variables describing the combination of BE and HS retrofits, thus avoiding non-linearities in the problem. To integrate these coupled decision variables, a novel formulation called multidimensional multiple coupled-choice knapsack problem (MMCKP) [11] is adopted.

### 3. Construction of a local building stock model

The optimization (objective and constraints) relies heavily on the description of the initial building stock. Indeed, characteristics of buildings such as thermal coefficients of the envelope determine both the initial energy consumption and the effect of potential retrofits. In France, no global database gathers the information needed for describing physically the territory. Consequently, two processes are used to unify the information contained in heterogeneous databases: matching and sampling. The footprints and heights of buildings are first matched to households' information such as their year of construction before the thermal characteristics of envelopes and the initial heating systems are sampled from a representative survey. Confrontation with consumption observations ensures the representativeness of the final building stock model. This process is wrapped up by Fig. 1.



**Figure 1.** Representation of the building stock modeling workflow

#### 3.1. Age identification through databases matching

Two crucial databases are accessible to local decision-makers in France. The first one, a geographic information system (GIS) published by French national geographic institute IGN [14], describes footprints and heights of every building on the territory. It is used to calculate the distinct wall area in contact with the outside for each building, used for heat demand calculation in buildings. The second database is issued by French financial administration and contains, for each household paying property tax, information about the size, nature and most importantly about the age of their housing.

The GIS is enriched with the age information using a matching algorithm. These two databases come from different sources, are built at different resolution, but share two fields which can permit the unification through two different processes:

- (i) The postal address: This field can be used for matching at a building level [15]. Nonetheless, its usage highly depends of the standardization of the address field, and can be complicated when working in rural areas where several building are attached to the same address.
- (ii) The cadastral parcel: This field corresponds to the administrative division of lands, and is particularly effective for matching buildings. When more than one building is present on a parcel, households are grouped into virtual buildings exploiting fields as the year of construction or the number of floors.

### 3.2. Sampling of building characteristics

The enriched database resulting from the matching step still does not contain the thermal characteristics of building envelopes and heating systems present in buildings. The PHEBUS survey, carried out in 2012 by French statistical institute INSEE [16], describes the energy behavior and energy systems of 5,045 representative households in France. For each household, detailed information is provided as the thermal coefficients of each surface of the envelope, the types of window, the ventilation rate or the efficiency and the fuel of energy systems.

A sampling is realized within an adequate subset of the PHEBUS survey depending on the age category and the type of building, coupled with the geographic area of the territory. Thermal characteristics of a whole sampled household are attributed to a building as they can be considered homogeneous from one territory to another within a restricted area, justifying the naive sampling approach. Oppositely, heating systems are more dependent to local condition as the availability of energy networks.

The national census provides the proportions of the heating fuels used at a disaggregated level called IRIS, which corresponds to a geographical area of about 1,000 households. This information is used to shape the distribution of the heating system identified as likely to be present in the geographic area, in order to be more representative of the local energy context.

Several sampling are realized and confronted to observation of electricity and gas consumption at IRIS level, provided by DSOs on open data platforms before selecting the most accurate building stock model which will be used for the optimization.

## 4. Case studies results

### 4.1. Definition of the inputs

The modelled territory is a mixed houses-blocks suburban neighborhood located in the department of Rhone, France. It is composed of 511 buildings hosting about 2,000 inhabitants in about 800 apartments and 300 individual houses<sup>1</sup>. The initial modelled annual consumption is of 37.34 GWh.

It is considered that the four main surfaces of buildings can be retrofitted, namely walls, roof, floor and windows. Two technical solutions are implemented per surface, corresponding to a standard and a deep retrofit, and are detailed in Table 1.

For heating systems, three types of generators are considered.

- Condensing boilers can use the three main fuels are available (oil, gas and biomass) but installation of biomass and oil boilers are limited to individual houses and buildings previously using oil respectively.
- Electric air-source and geothermal heat pumps are also available, and efficiency of the system is estimated for the study case territory.
- Decentralized electric heating through the usage of radiant panels is the last available heating system.

Costs are defined for each technology but are not detailed or discussed in this paper.

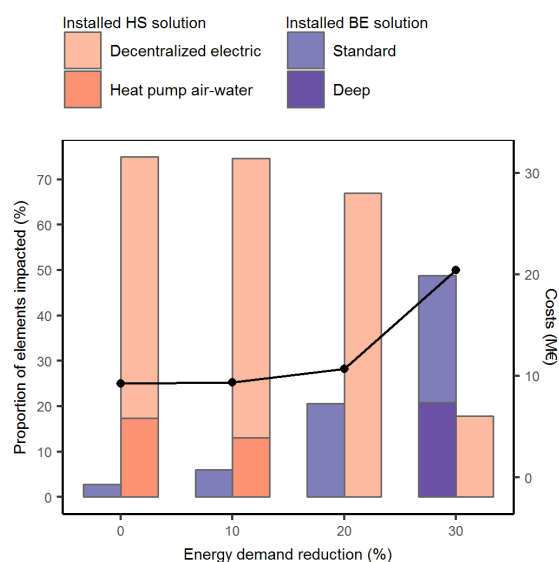
<sup>1</sup> Source: INSEE census

| Surface | Retrofit level | Technology      | U-value<br>(W.m <sup>-2</sup> .K <sup>-1</sup> ) | g-value<br>(%) | Variable cost<br>(€/m <sup>2</sup> ) |
|---------|----------------|-----------------|--|----------------|--------------------------------------|
| Wall    | Standard       | Glass wool 10cm | 0.33   | 0              | 120                                  |
|         | Deep           | Glass wool 20cm | 0.20   | 0              | 150                                  |
| Roof    | Standard       | Glass wool 15cm | 0.25   | 0              | 60                                   |
|         | Deep           | Glass wool 28cm | 0.15   | 0              | 80                                   |
| Floor   | Standard       | PSE 10cm        | 0.33   | 0              | 100                                  |
|         | Deep           | PSE 15cm        | 0.25   | 0              | 140                                  |
| Window  | Standard       | Double glazing  | 1.5  | 0.6            | 300                                  |
|         | Deep           | Triple glazing  | 0.8  | 0.5            | 500                                  |

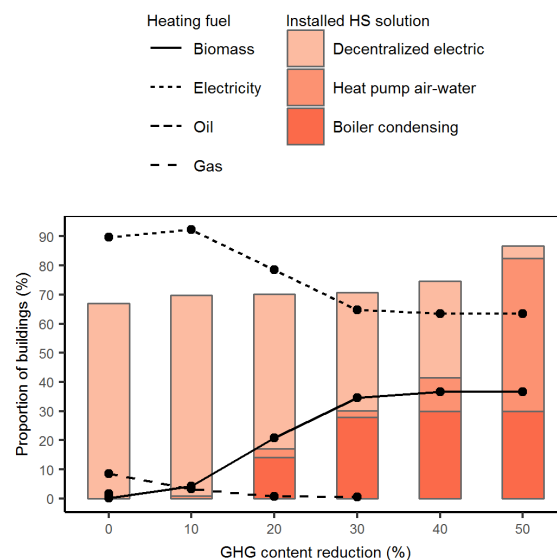
**Table 1.** Economical and technical parameters of the solutions for building envelope retrofit

#### 4.2. Results

This section presents the retrofit plans proposed by the optimization algorithm, and their evolution depending of the strategic objectives of the decision makers.



**Figure 2.** Evolution of the activated retrofit actions (bars) and investment costs (line) with energy demand reduction target.  $\Delta E$ : 40%.



**Figure 3.** Evolution of heating systems (bars) and used fuels for heating (lines) with GHG content reduction target.  $\Delta E$ : 40%.  $\Delta Q$ : 20%.

Figure 2 represents the aggregated results of the retrofit optimization when increasing the energy demand reduction target. For this study, an energy consumption reduction target is set to 40%. When considering this constraint alone (energy demand reduction set to 0%), the results indicate that 75% of the heating systems must be replaced by heat pumps and electric radiators. Moreover, very few surfaces are insulated due to their high investment costs. The total investment costs for meeting this energy consumption reduction target is of about 10M€. When increasing the ED reduction, the proportion of surfaces impacted by retrofit actions increases up to 50% when targeting a 30% reduction of the demand, part of which are deep retrofits. Oppositely, the proportion of buildings impacted by HS replacement measures decreases.

The GHG content is calculated as the ratio between the annual GHG emissions and the energy

consumption of the territory. It can be considered as a strategic objective to reduce this content and the impact of such a target on the heating systems proportions is illustrated by Figure 3. The constraints imposed to the problem on energy demand and consumption (20% and 40% respectively) barely reduce the GHG content of the heating systems without specific constraint. When increasing this objective, three phenomena can be observed. First, the proportion of heating system using gas decreases as it is the more polluting fuel available (after oil, almost nonexistent). Secondly, biomass proportion rises before reaching a threshold which is due to the limitation of biomass boilers to individual houses. The proportion of heat pumps also increases when requiring a GHG content reduction greater than 30%, as it is the only solution to impact the content through a energy better efficiency. The proportion of impacted buildings grows with the reduction target, meaning that the total investment will evolve similarly.

## 5. Conclusions and perspectives

This work presented a complete methodology, from the modeling of building stocks at a territory level to its integration into an appropriate optimization problem representing the building energy retrofit context. The utilized algorithm optimizes both building envelope insulation and heating system replacement with a building resolution to minimize the investments under aggregated territorial strategic objective constraints. Study cases present typical output which can be obtained from the optimization and represent the evolution of the activated solutions depending on the restrictiveness of the constraints. For instance, the study case highlighted that the high investment costs of building envelope retrofits implies that they will not be activated unless specific constraint is defined. This method offers great perspectives for decision makers willing to identify the buildings to target to reach their energy transition objectives. Nonetheless, the method can still be improved, as the usage of more elaborated techniques for estimating the physical characteristics of buildings such as Bayesian inference could improve the representativeness of the building stock. In relation with the optimization model, the study case highlighted the domination of decentralized electric heating due to its low investment costs. The consideration of potential network reinforcement costs in the models could balance this effect and better represent the real-life situation. Also, a penalization could be set to minimize the number of impacted buildings. Finally, integration of renewable production as one of the technical solutions to reduce the emissions is an interesting perspective to be developed.

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