A decision-making methodology of decarbonization for a dwelling stock in France

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Abstract. Decarbonization is a hot topic in the building sector. In response to the national ambition of carbon neutrality in 2050, a social housing company that manages about 100,000 housings in France, wants to know how to decarbonize its dwellings. This dwelling stock form a heterogeneous dynamic group with new constructions and demolitions every year. Carbon emission is mainly caused by fossil energy consumption in the building exploitation phase, especially in space heating and hot water. There are many instructions to reduce energy consumption in building exploitation phase, like the thermal insulation of building envelope, the update of equipment, the energy transition, and the sobriety of energy...But how to organize these methods to find out an optimum with the restrictions of resources? How to take the initiative in an ever-changing political and technical environment? Inspired by the discipline of "System Dynamics", we propose a methodology to represent and simulate the intricate system of the dwelling stock, to have a better insight into how the outside impacts, like the changes in policy and technological innovation, influence the inside system of the dwelling stock, and how the inside elements interact. This methodology is composed of two aspects: The typologies of housing type and the simulation of the dwelling stock. The 100,000 housing has been classed several times independently, which is quite distinct from the traditional classification method. The simulation part is carried out in the software "Vensim" and is based on the calculation method 3CL DPE. For each scenario of outside political-technical environment, we test several options to propose a suitable integration of concrete methods to decarbonize the whole dwelling stock.

Keywords. Decarbonization, dwelling stock, energy retrofit, system dynamics, typology
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1. Introduction

"To achieve carbon neutrality by 2050" is an objective introduced by the July 2017 France climate plan and is enshrined in French law. The National Low Carbon Strategy (SNBC for Stratégie Nationale Bas-Carbone) [1] describes a roadmap and provides guidelines for France to enable the transition to zero net emissions. It sets out objectives for reducing greenhouse gas emissions in the short and medium term in all sectors of activity in France. For the building sector, the strategy put the "Energy Efficiency" in the first place, which implies a radical thermal renovation for the existing national housing stock, from the improvement in the performance of building's envelope to that of equipment and installation. It is also important to rely on carbon-free energy sources in the building sector and have a much greater reliance on less carbonized construction materials.

This paper focuses only on the energy efficiency, the first and the most urgent aspect in the national strategy. This translates to an acceleration of renovation in the building sector to arrive at a level in line with Low Consumption Building standards (BBC in French) [2] across the whole stock by 2050. From the aspect of Life Cycle Assessment (LCA), only the exploitation phase of dwellings is researched in this study, which means not including the embodied energy and emission in building materials.

Among all types of buildings, the social dwellings are pioneers of renovation. According to the French

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climate and resilience law, it is programmed to carry out progressively the ban on the rental of high energy-consuming dwellings. In France, when selling or renting a dwelling, a Diagnostic of Energy Performance (DPE, "Diagnostic de Performance Energétique" in French) must be presented to inform the tenant of the dwelling's annual energy consumption and greenhouse gas emission. All the social dwellings are therefore classed from A to G, according to their performance grades: label A for dwellings that have the highest energy efficiency and lowest carbon emission, and label G is the worst that consumes the most energy and have the worst impacts on environment. The French climate and resilience law is translated for social housing companies to retrofit all their dwellings of label G by 2025, of label F by 2028, and of label E by 2034 [3].

A social housing company who manages about 100,000 dwellings in Paris and the parisian region, is responsive to the strategies defined in SNBC leading to carbon neutrality in 2050. The SNBC has clearly indicated the renovation objective for the whole building sector, but there is still a gap between the sectoral strategies and that for corporations. The social housing company wants to know how to do exactly to be in line with the sectoral decarbonization ambition. A decision-making tool is proposed to assist the social housing company to set guidelines to renovate their dwellings. A stock-level model is built to simulate the evolution of the dwelling stock in terms of carbon emission. It enables the policymakers to test different scenarios in terms of construction, renovation, and demolition, in order to have a better insight into the relationship between the company's strategies and that of the building sector. To subdivide and adapt the renovation strategy to different dwelling types, a dwelling-level model is proposed to complete the stock-level model. This dwelling-level sub model can calculate the carbon emission of each dwelling type defined in this study and is able to simulate different concrete retrofit scenarios, which provide, in the end, retrofit suggestions for the dwelling type given.

This study references the work of the European project TABULA EPISCOPE. The first part of this European project is to establish the TABULA concept for developing national building typologies representing the residential building stock of each country partner [4]. A calculation method focusing only on the energy use for space heating and domestic hot water is developed during the TABULA project. The follow-up EPISCOPE project aims to make energy-saving processes in the European housing sector more transparent and effective by developing targeted monitoring approaches, combined with scenario analyses and building typologies. As part of the EPISCOPE project, 40 types of buildings are proposed in France [5], each represented by an example building. For each example building, the energy performance is calculated, and two energy efficiency improvement plans of different grades are proposed. The social dwelling stock of OPHM (Office Public de l'Habitat Montreuillois) is selected to set up a pilot process in France to apply the EPISCOPE methodology [6]. The typology has been adapted to fit in the specifies of the OPHM social dwelling stock. Assumptions have been made on the rate of demolition and construction, and on the evolution of the carbon content per kWh of energy consumed. Three refurbishment scenarios have been proposed with different renovation rates to compare with the national objectives. The refurbishment scenarios proposed in OPHM study are established only from a view of the whole dwelling stock. The fact that the dwellings of different types have not been distinguished stops this study from going further to have a more detailed strategies for each dwelling type.

In response to this argument, the authors come up with this two-level model to combine the strategies for the whole stock and that for each dwelling type.

The remaining part of the paper is structured as follows. Section 2 presents the two principal aspects of the research method. Section 3 and 4 then describe in detail the two-level model, while Section 5 summarises and concludes the paper.

2. Research Methods

2.1 System Dynamics approach

System Dynamics (SD) is a computer-aided approach for strategy design, it helps people to make better decisions when confronted with complex, dynamic systems. System Dynamics aims to gain a better understanding of the structural causes of a system's behaviour, which implies an increased knowledge of the role of each element by assessing how different actions on different parts of the system influence its behavioural tendencies [7].

To model the complexity involved in housing energy and carbon emissions, the SD is an appropriate approach [8] [9]. SD approach is capable of managing processes by involving changes over time and allowing the transmission of information to build feedbacks. SD models are able to capture multiple interdependencies.

The two-level model is carried out by the system dynamics software Vensim, which provides an effective platform for implementing SD simulations. Vensim offers 4 types of variable expressions for SD models: 1) Level variables, representing the accumulation over time of a given quantity; 2) Rate variables, the flow of quantity, representing the amount of the variation of level variables each time step; 3) Auxiliary variables, assisting the transformation of the system which can also be an indicator variable for later analyses; 4) Constant variables, which remain the same value over time.

Vensim proposes a subscription language to represent arrayed variables, it is a way to simplify the repeated parts of a model and can also make the model structure more comprehensible. Two types of simulation are used to analyse the model: "SyntheSim", running simulations on each movement of sliders, and "Sensitivity Simulations" simulating by varying parameters. The details of the simulations part will be discussed in section 3.

The construction of a SD model starts from a causal diagram which helps to represent the key elements of the system and the relationships between them [10]. For the stock-level model, the causal diagram is inspired by the real evolutional pattern of the social dwelling stock given, and for the dwelling-level model, the causal diagram is based on the French calculation method 3CL DPE [11].

2.2 Typologies

Building stock modelling usually deploys representative archetypes from building typology to obtain reliable results of energy consumption. It is found that in the French residential sector, different levels of energy consumption are related to socio-economic, dwelling, and regional characteristics [12]. The dwellings of this social dwelling stock have the same regional characteristics and the households of these stock have almost the same socio-economic characteristics. Therefore, only the characteristics related to dwelling, combined with the energy carriers type in considering the liaison between the energy consumption and the GES emission, will be considered in this paper to define the building archetypes. Previous TABULA studies define archetypes by the physical characteristics of buildings. These archetypes, however, have not been integrated into the building stock modelling and have no direct relationship with the stock's energy and GES emission result. The new classing method is proposed here to help in connecting the GES emission of the entire dwelling stock and that of a dwelling type under different retrofit scenarios.

Tab. 1 – Four categories defined in stock-level sub model

Categories name for short	Corresponding DPE labels	Carbon emission range (Kg CO2eq/m2.an)	Current company policies
AB	A and B	x <=11	Not to have efficiency retrofit for the dwellings of label A and B before 2050
CD	C and D	11< x <=50	-
E	E	50< x <=70	Refurbish all the dwellings of label E by 2030
FG	F and G	x > 70	Refurbish all the dwellings of label F and G by 2025

In the stock-level sub model, the dwelling stock has been classed into four categories (shown in **Tab.1**), according to their energy-environment label (DPE), to integrate the current national energy-environmental policies. The latest version of DPE, which has been implemented since the 1st July 2021, is applied in this research. The potential rescaling of DPE labels due to the future legislation is not considered in this study.

And in the dwelling-level sub model, all the dwellings have been firstly classed by their envelope performance and then classed by their type of system and equipment. With the basic information of a building's envelope, the heat loss can be measured by applying a simplified 3CL method. A threshold is set to identify the high-performance envelope and that which need to be retrofitted. The two categories defined according to the performance of building's envelope in the dwelling-level sub model is showed in **Tab.2**.

Tab. 2 – Two categories defined by the performance of envelope in the dwelling-level sub model

Nb. of category	Explication of categories
1	The envelopes of dwellings are not suggested to be retrofitted by 2050.
2	The envelopes of dwellings are suggested to be retrofitted.

Meanwhile, the dwellings are classed by their types of energy carrier and that of system and equipment for space heating and domestic hot water. According to the database of this social housing company,13 categories have been found in this stock. They are listed in the **Tab. 3**.

Tab. 3 -Thirteen categories of the system aspect in the dwelling-level sub model.

Nb. of category	Space heating	Domestic hot water
1	Urban heat, collective	Urban heat, collective
2	Urban heat, collective	Electricity, individual
3	Urban heat, collective	Natural gas, individual
4	Natural gas, collective	Natural gas, collective
5	Natural gas, collective	Natural gas, individual
6	Natural gas, individual	Natural gas, individual
7	Natural gas, collective	Electricity, individual
8	Natural gas, individual	Electricity, individual
9	Electricity, collective	Electricity, collective
10	Electricity, collective	Electricity, individual
11	Electricity, individual	Electricity, collective
12	Electricity, individual	Electricity, individual
13	Electricity, individual	Natural gas, individual

3. Stock-level sub model

The stock-level model gives a general orientation and the overall goal for the dwelling stock renovation. The objective of this sub-model is to find out how to manage and renovate the different type of dwellings, from A to G, to be in line with the BBC standards, which is indicated in SNBC. The model calculates the total emission of all types of dwellings under different scenarios, and to come up with renovation suggestions for each type.

3.1 from the causal diagram to model

The model construction starts from the causal diagram. **Fig. 1** shows the causal diagram of the stock-level sub model. The social dwelling stock is divided into two parts: the existing dwellings built before 2020 and the new dwellings built after 2020. The existing dwellings which have been refurbished are distinguished from those to be refurbished on account of the dwellings' performance improvement. In addition to the process of refurbishment, the dynamic of the existing dwelling stock is influenced by the acquisition, the demolition, and the selling. The total carbon emission of this stock depends both on existing dwellings and new dwellings.

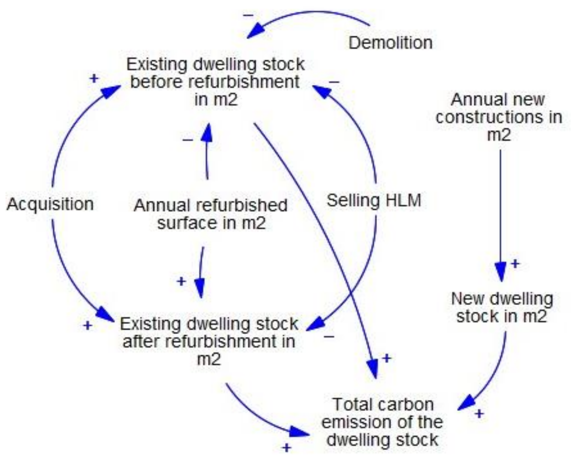

Fig. 1 – causal diagram of stock-level sub model

3.2 The stock-level model and variables

The diagram is then enriched by integrating the typology of dwellings to build a stock-flow model. The time of the model is set from the year 2020 to

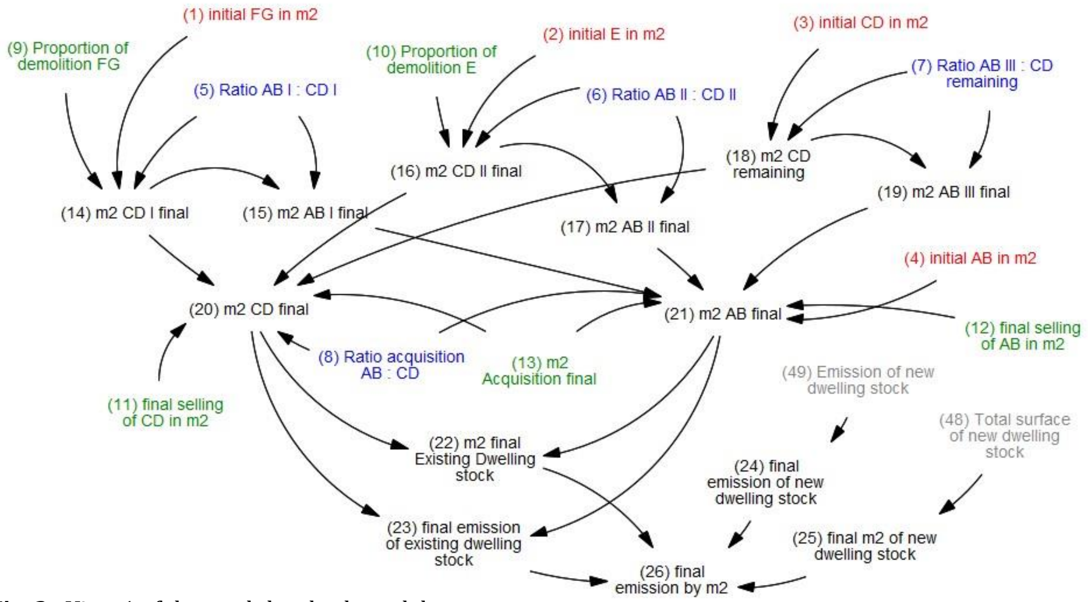

Fig. 2 –View 1 of the stock-level sub model.

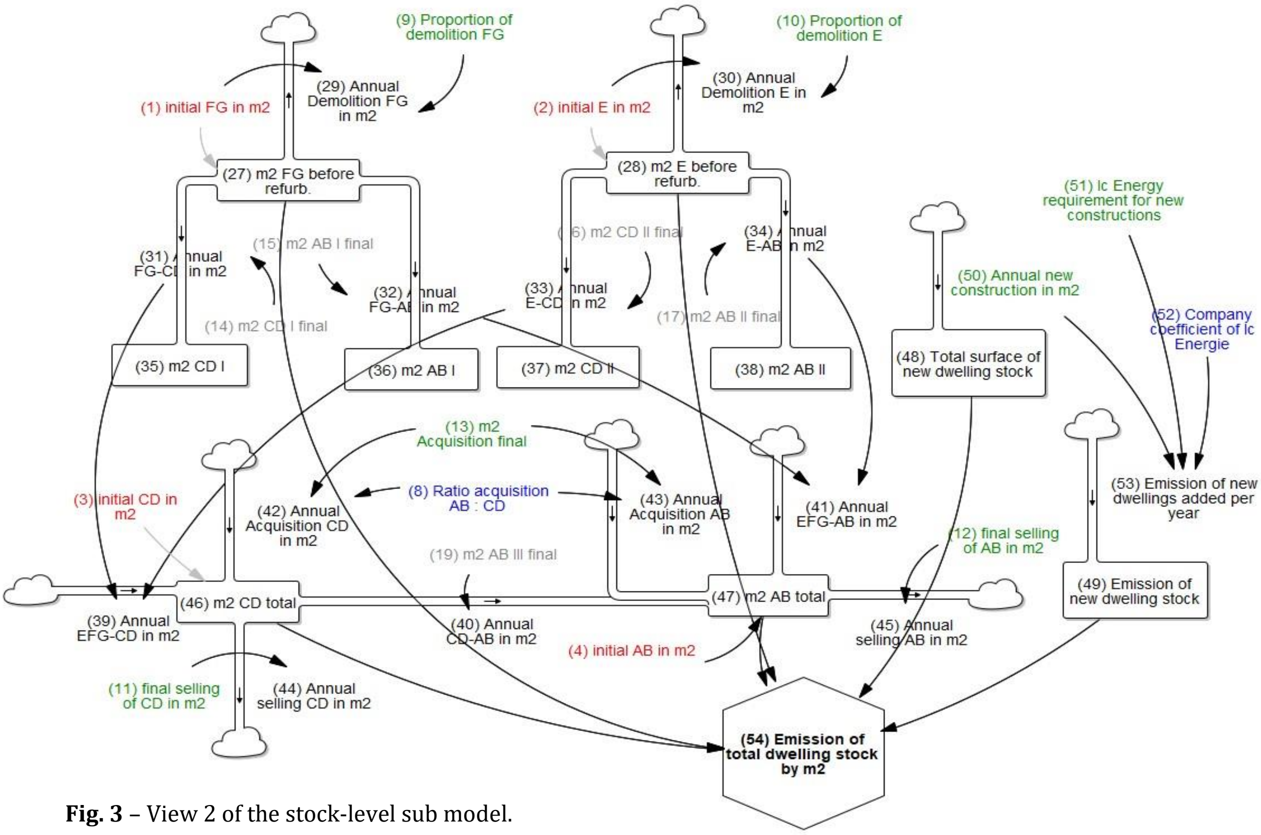

Fig. 3 – View 2 of the stock-level sub model.

2050. This model is made up of two views: The view 1(shown in the **Fig. 2**) describes the final projected state of the dynamic dwelling system in 2050, while the view 2 (shown in the **Fig. 3**) displays a constantly changing system from the year 2020 to 2050. These two views are connected by the duplicate variables, which are black in one view and turn to grey in the other view. The variables in red are input data, they are unchangeable constants whose values do not change over time. The variables in green and blue are also constant variables, but their values can be modulated according to different political scenarios. The blue variables depend only on the company's internal decisions, while the green variables can be influenced by external policies as well.

The variables (1)(2)(3)(4) represent respectively the initial dwelling surface of category FG, E, CD and AB. The data is available in the company's database.

The variables (9) and (10) are in the form of percentage, they represent the proportions of demolition in the categories FG and E.

The variables (14)-(19) are the final dwelling surface of each type refurbished by 2050. They are distinguished by their initial performance category and also by their final category after refurbishment.

The variable (20) represents the final dwelling surface that enters in CD category after retrofit by 2050, and (21) is the final dwelling surface that enters in AB category after retrofit by 2050.

The variables (11)(12)(13) represent the final acquisition and selling surface of the stock by 2050.

The variables (5)(6)(7)(8) represent the ratio of AB dwellings' surface to that of CD dwellings. The sliders are created for these variables to generate different internal political scenarios. For example, the increase of (5) can reflect the increase of FG dwellings entered in AB category after retrofit, which means the company has a greater ambition in the FG dwellings' performance improvement. And for the variable (8), its increase results in the increase of the AB acquisitions, which means the company tries to get more AB dwellings from outside.

The variable (50) is the annual new construction surface from 2020 to 2050, which can be influenced by external sectorial politics and companys' internal decisions. The variable (48) is the integral of (50), it represents the total surface of all the new dwellings built after 2020.

The variable (51) is the environmental requirement settled for new constructions by the national legislations. Scenarios can be generated to test the varies tendencies of future requirements. The variable (52) is an internal coefficient depending on the company's decision. It is the ratio between the company's internal carbon requirement for new buildings and that of the national requirement. The added carbon emission to the new dwelling stock per year (53) is then calculated by (53) = (50)x(51)x(52).

3.3 Scenario analysis and simulations

The variable (52) is chosen to demonstrate the first step of the model analysis. The value range of this variable is set from 0.1 to 1. When the value is equal to 1, the company's internal carbon requirement has the same maximum threshold as the national requirement. And when the coefficient (52) is set to 0.1, the threshold defined by the company is one-tenth of that defined in national strategies. Three different values (0,3 0,5 and 0,7) have been tested for the coefficient (52) in the displayed simulations. Three different curves are then generated to show the variation of the variable (54) due to the three values of (52). The variable (54) is an observation object in this model.

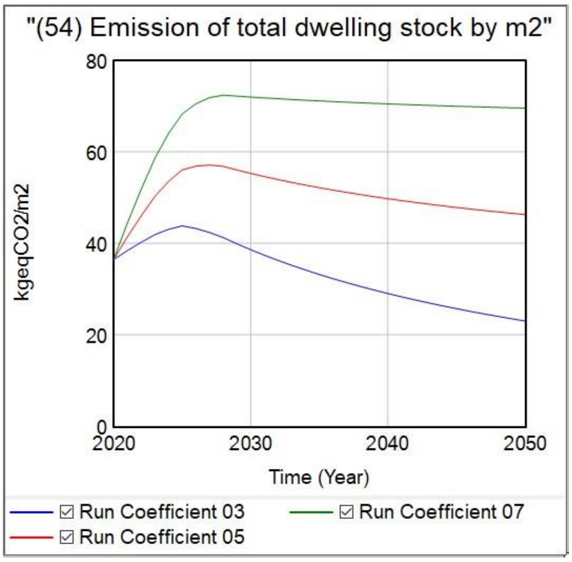

Fig. 4 – Three simulations of different coefficient values

Fig. 4 shows the three simulations**.** It is observed that the coefficient (52) is influential to the target variable (54), and a great difference of the stock emission in 2050 can be observed when the coefficient changes from 0.3 to 0.7.

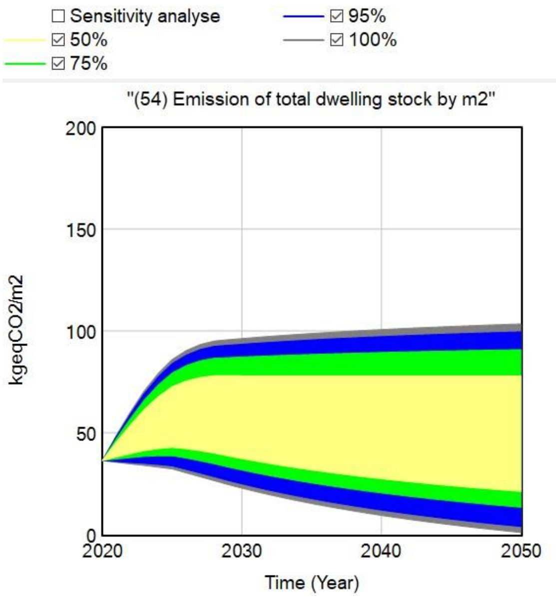

Fig. 5 - Sensitivity analysis.

A sensitivity analysis was then lanced to find out the value range of the target emission (54) when the coefficient (52) varies between 0.1 and 1. The value range of (54) from the year 2020 to 2050 is shown in the **Fig.5**.

It is found that the emission of dwelling stock is sensitive to the coefficient (52). For the further research, it is suggested to reduce the interval of scenarios to test more values between 0.1 and 1.

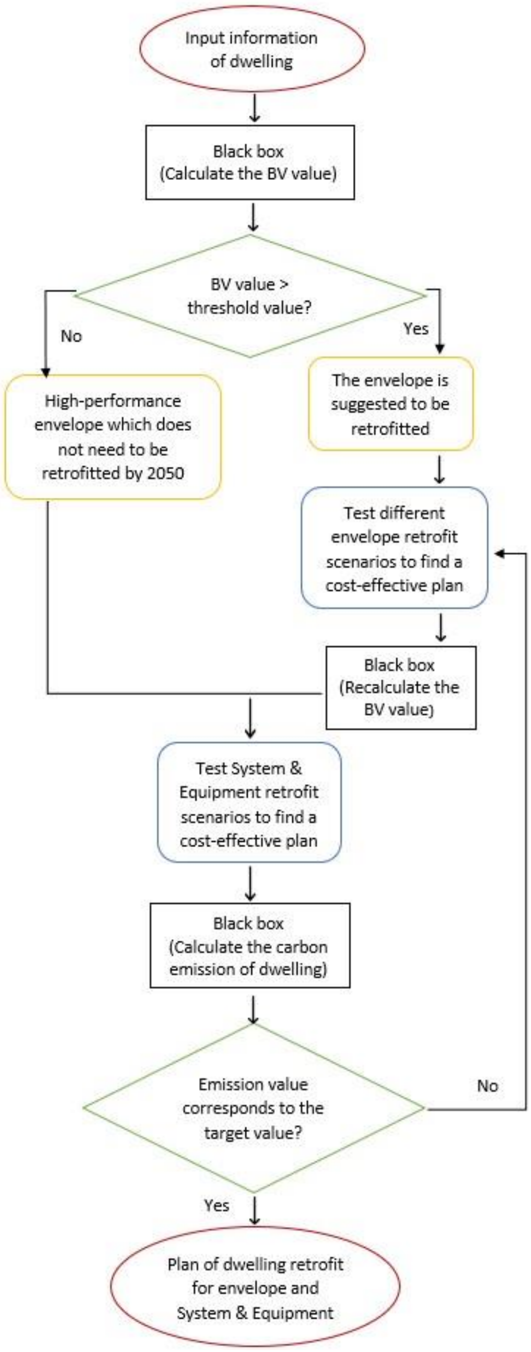

Fig. 6 – Using steps of the dwelling level decision-making tool

4. Dwelling-level sub model

The dwelling-level sub-model gives retrofit suggestions for a dwelling. For example, if the stock-level sub-model suggested refurbishing all the E dwellings into AB dwellings, the dwelling-level sub-model will indicate how to retrofit from E to AB for each dwelling type (in terms of envelope and equipment).

This sub model, which is based on the 3CL method, can be seen as a calculation engine, but more than a calculation engine. It also provides a functioning to test the options of retrofit methods to find the best solution.

Many hypotheses have been made to simplify and adapt the 3CL method to different type of dwellings. To justify theses hypotheses and to calibrate this model, the calculation results of the model is compared to the carbon emission value indicated in the DPE label.

The flow chart **Fig.6** demonstrates the steps of using this decision-making tool. The first step is to collect the dwelling data from the aspect of envelope and that of system and equipment. These data are then input into the model to calculate the BV value. BV is an intermediate variable defined by the 3CL method. It represents the monthly home heating requirement of a dwelling and can reflect the performance of building's envelope. The obtained BV value is then compared with a predefined threshold value to see if the envelope needs to be retrofitted or not. If yes, different envelope retrofit scenarios can be tested to find out an appropriate envelope retrofit plan. And meanwhile, the BV values of different scenarios have been recalculated. The same process is for the system and equipment aspect. The two scenario tests can be repeated to find out an appropriate retrofit plan, for a given dwelling type, to meet the target emission value.

5. Conclusions

This paper presents a new decision-making tool to help a social housing company make strategies in response to the national emission ambition. The model tool is built by using the system dynamic approach, which helps to represent, simulate, and analyse the carbon emission of the social dwelling stock in France. A new class method is proposed not only to distinguish different types of dwellings by their characteristics but also to match with the current sectoral politics. The model tool is composed of two parts: the stock-level sub-model for a big scale and the dwelling-level sub-model for a dwelling-scope simulation. The two sub-models cooperate to offer a more comprehensive analysis of the dwelling stock. The next stage of the research is to generate appropriates scenarios of renovation for the scale of the stock and for each concrete dwelling type. After the identification of theses scenarios, the process of analysis can be conducted by comparing the simulation results of each scenario, to propose suggestions for the renovation strategies.

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Data Statement

The datasets analysed during the current study are not available because of the confidentiality agreement with the social housing company, but the authors will make reasonable effort to publish part of them in near future.