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Optimization module for filtering and ranking alternative energy replacement systems, in an online ICT design tool for building retrofits

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Abstract. This paper describes the development of an innovative optimizer component as part of a calculation tool for evaluating and comparing a set of retrofitting options for domestic heating and cooling systems. At the initial stage of the process, a filtering sub-module has been developed to pre-process the information introduced by the user and generate a limited set of simulations, thus speeding up the calculation process. At a later stage, the optimizer collects and post-processes outputs from the simulation core before displaying them as a result. In this later stage, a series of performance indicators are calculated and an analytical hierarchical process (AHP) is performed to rank the results based on the user's prioritization weighting for each key performance indicator. As the main outcome of this contribution, the benefits of implementing this optimizer are evaluated in increasing the efficiency of the rest of the components of the tool and, consequently, of the overall calculation process.

1. Introduction

Many efforts are ongoing to develop and provide innovative solutions to improve the energy performance of the building stock. In Europe, where buildings account for approximately 40% of total energy consumption and 30% of the total greenhouse gas emissions, the EU has adopted Nearly Zero Energy Building (NZEB) as a target concept towards more sustainable and energy-efficient buildings. The definition of a global reference pattern facilitates direct comparison as well as an overview of current and future scenarios at continental level, for considering and evaluating specific strategies and initiatives to overcome the current situation [1].

Besides the requirement of modern and highly efficient new buildings, the existing ones urgently need to be renovated and updated as well. Indeed, even if highly energy efficient buildings are built in the next years, the replacement rate would not be sufficient to turn the situation around until some decades in the future [2]. Making energy-efficient technologies more accessible and cost-efficient are key steps for moving forward towards a more sustainable built environment. However, the return of investment and the potential benefits of each retrofit approach depend strongly on the specific use case considered, and so any set of renovation alternatives needs to be analyzed in the context of the target building. Energy improvement of buildings can be achieved in different ways by combining numerous technologies. However, when approaching the renovation of a building, the identification and selection of feasible alternative solutions is not an easy task for owners, designers and building managers. The experience required in different fields and the interpretation of available information on the overwhelming number of available technologies add to the complexity of the decision-making process. The selection of the better-fitting solution is usually far from straightforward and requires orientation with specific consideration to the use case.

This paper describes the development of an optimizer, as a key component of a web tool for orienting the early decision-making process of an energy-focused building retrofits. The tool is aimed at evaluating the potential energy improvement resulting from such retrofits, and the optimizer is designed to enhance the data processing capabilities. The benefits of incorporating this component are described under a double approach for optimizing the numerical calculation and orienting the user decisions.

2. Description of the H4C Retrosim Tool

Heat4Cool, an EU-funded project [3], is currently developing, integrating and demonstrating easy-to-install and energy efficient solution systems for building retrofitting, primarily based on the combination of heat pumps and renewable energy systems. Looking to orient relevant stakeholders involved in the renovation sector, an online ICT tool has been developed: the H4C Retrosim Tool. The main functionality of this tool is to suggest and simulate alternatives for the renovation of domestic heating and/or cooling systems. Considering the main characteristics of the building to be renovated, retrofit alternatives are suggested by the tool and a series of key performance indicators (KPIs) are calculated.

A relevant characteristic of the H4C Retrosim Tool is that it is oriented both to expert and inexperienced users. While advanced users can edit most of the input parameters used for the calculation, non-expert users are aided by recommendations and default values. Minimal data entries are required from the user, namely the location, age of the building and current main technologies used for heating and cooling. The tool can estimate the remaining inputs based on the basic information introduced. The post-processing of outputs into four simplified KPIs (related to energy consumption, greenhouse gas emissions, payback calculation and user comfort) represents another relevant feature to orient inexperienced users, while experts can consult and evaluate the complete set of output parameters.

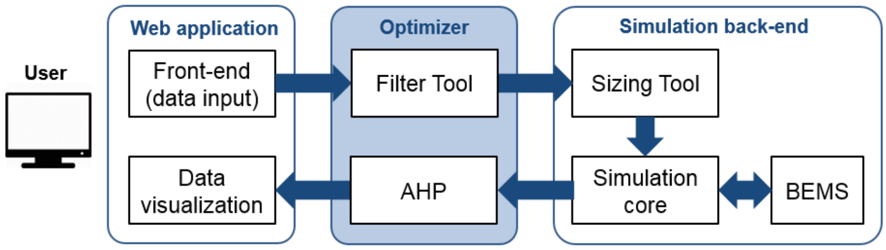


Figure 1. Simplified description of the H4C Retrosim Tool's architecture

An initial working version of the tool has been developed and will shortly be benchmarked with pilot demonstration buildings to be implemented within the project. Three main modules cover each step defined for the assessment process (figure 1): the web application, the optimizer and the simulation back-end [4]. Each module comprises also submodules for specific tasks. The web application front-end is where the user describes the existing building and its systems. These inputs are then forwarded to the optimizer, a component where the information is treated both before and after the calculation to filter and interpret the data. The numerical calculation is carried out at the simulation back-end, where an initial sizing process is carried out based on the alternatives provided by the Filter Tool of the optimizer. The energy consumption is then calculated in the simulation core for each of the considered layouts, while a coupled BEMS submodule models the control strategy and estimates the deviation from comfort conditions. All results are forwarded to the optimizer and post-processed to obtain KPIs. Finally, all the combined information is displayed at the data visualization section of the website. In the following sections, the two submodules of the optimizer are described, namely the Filter Tool and the AHP.

3. Development of the Filter Tool

The aim of the Filter Tool is to generate suitable retrofit alternatives to be forwarded to the simulation back-end for their evaluation. This set of alternatives is tailored to the existing layout of the building, learned through user inputs. For facilitating such inputs, the user is aided by suggestions for default values based on the most common layouts and systems for each European country [5].

The architecture of the Filter Tool is based on a set of constraint-based rules. Such rules are predefined based on prior knowledge, aimed at selecting the alternatives that are most compatible with the existing condition. The existing and proposed heating and cooling systems of the building are characterized as a layout configuration comprising a number of devices or elements. These devices are classified as energy supply systems (e.g. boilers, heaters or heat pumps), energy storage systems (e.g. water or PCM-based tanks) or control systems (thermostat-based or building energy management systems). A sequential layout has been developed to set a framework for the allowed combination of elements, such as concurrent energy supply systems (e.g. boiler, heat pump and solar collector) or the position of the elements within the layout (e.g. storage systems before or after the heat pump). A set of parameters has been defined, each with a limited set of possible options. These parameters are ordered in a linear sequence, linking the fundamental steps from energy consumption (fuel) to the fulfilment of the energy demand of the building (heating and/or cooling loads). The control system is included as an additional parameter governing the system. The full list of elements is graphically depicted in figure 2.

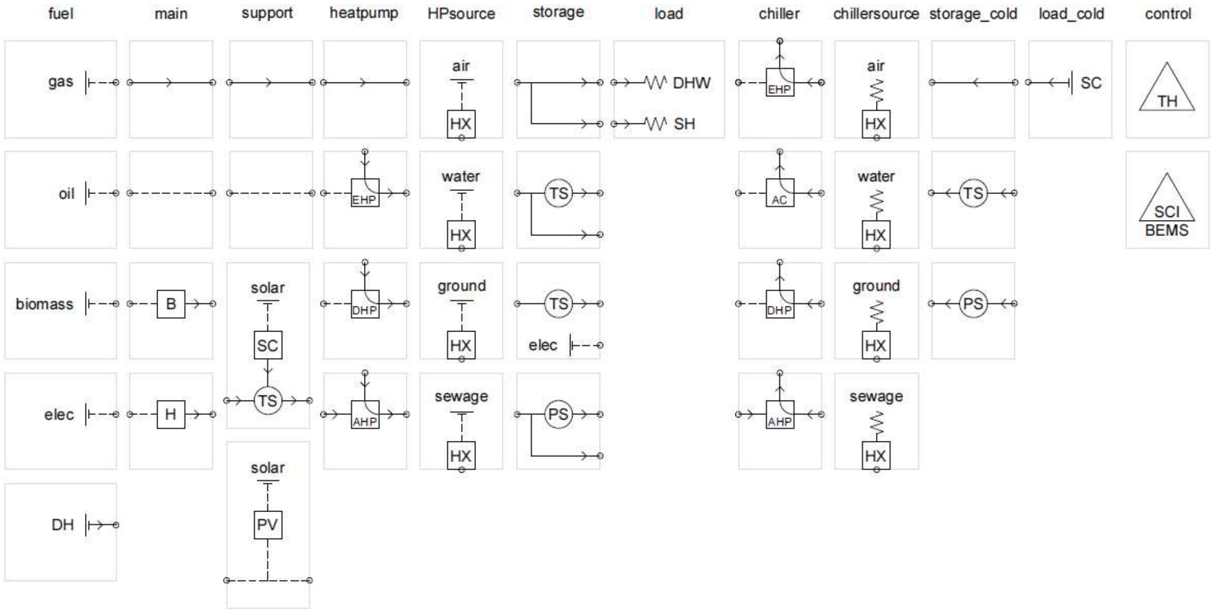


Figure 2. Parameters and element choices for heating, cooling and control systems

Information on the existing systems of the building is collected from the user inputs at the front-end and characterized as a layout configuration through a combination of the elements described in figure 2. The options that can be selected from the user are constrained by a series of rules provided by the Filter Tool, to ensure that the devices are compatible with each other and that their combination is both technically feasible and likely to be found in an existing building. For instance, it is assumed that if the main fuel used for heating is gas, oil or coal, a boiler will provide both space heating and domestic hot water. On the other hand, if a heat pump is installed, the presence of a storage tank for domestic hot water is assumed. The implementation of the complete set of constraints results in 23 possible combinations, covering the majority of existing domestic heating and cooling system configurations in Europe.

Each layout can be graphically represented through schematic diagrams as a combination of elements (figure 3). Flows are represented from source (left) to load (right). Fuels considered as main energy sources are placed at the very left, while renewable energy sources are represented at the top of the flow line (as their energy provision has no associated emissions or fuel costs). Heating and cooling cycles are indicated as separate lines in the diagram of figure 3: heat pumps and chillers are depicted twice as they might be used in different modes for heating and cooling.

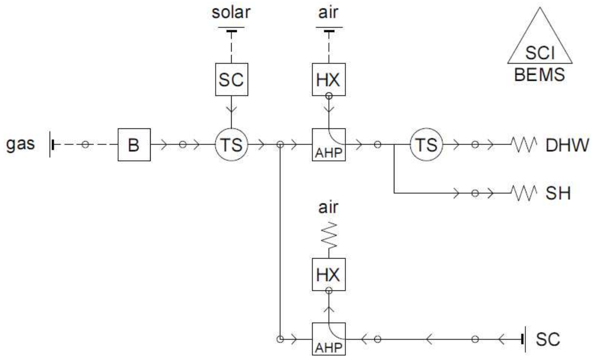


Figure 3. Example diagram for a heating and cooling system incorporating a thermally driven air-sourced heat pump (AHP) combined with a solar collector (SC) and back-up gas boiler (B), delivering space heating (SH) and space cooling (SC), as well as feeding a thermal storage (TS) for domestic hot water (DHW). The system is controlled by a self-controlling intelligent building energy management system (SCI-BEMS).

Starting from the existing layout, the Filter Tool generates a list of proposed retrofit options for the heating and cooling systems of the building. As each proposed layout needs to be simulated by the back-end, it is critical to set a limit on the total number of alternatives. A further set of constraint rules is implemented in the Filter Tool for this purpose. In contrast to the existing layout, which is selected by the user through the front-end, the possible retrofit alternatives are automatically generated by the Filter Tool based on 34 predefined rules. A selection of these rules is provided for illustrative purposes:

- If an electric heater is used to heat domestic hot water, it is substituted by an electric-driven heat pump and thus electricity remains the main energy source.
- If the existing heating system is based on hot water either from a boiler or district heating, a further alternative is considered where the existing hot water source (boiler/district heating) is kept as a backup to a thermally driven heat pump.
- If an existing heat pump is maintained, two alternatives are considered: feeding it directly from the electrical grid, or both by the electrical grid and a solar PV array.

The retrofit layout alternatives suggested by the Filter Tool depend on the initial existing layout selected by the user, as per the constraints described above. As a result, the number of alternatives for any given existing scenario is kept between 4 and 10, out of a total of 175 possible combinations.

4. Development of the AHP

The main aim of this subcomponent of the optimizer is to manage the results outcoming from the simulation engine, by arranging and ranking them so that they can be forwarded to the data visualization section of the tool. However, the management of the information needs to be fully adapted to the type and structure of information that users are expecting depending on their level of expertise. Those results can be displayed in a summarized way by just representing the most relevant KPIs, or else more detailed information for the complete set of calculated results can be consulted.

Thus, the main functions of the AHP module are to firstly calculate the set of complete indicators combining the information provided by the simulator with additional design parameters and, secondly, to organize the alternatives simulated and to display them ranked weighting the KPIs in accordance with different user profile prioritizations. For this purpose, eleven AHP pairwise comparison weighting profiles have been predefined. These profiles are displayed as choices that can be selected by the user from a combo box to define the criteria for ranking the feasible solutions.

Although all indicators to be displayed depend on results of the simulation process, not all of them are directly calculated by the simulation back-end. The AHP receives a series of parameters that can be clustered into four main groups: energetic (reduction in energy consumption), environmental (reduction in greenhouse gas emissions), financial (cost-effectiveness and return of investment) and comfort (occupant perception based on achieved internal room temperatures). A total of 16 KPIs are calculated, and 4 of them are selected for representing the overall performance in each field of interest: energy, cost, sustainability and comfort. The main energy KPI is the non-renewable primary energy consumption (kWh/m²a). Additional energy-related indicators include the renewable energy consumption (kWh/m²a), the renewable energy share from the total (%) and the peak hourly electricity consumption (kW). Environmental sustainability is measured by the greenhouse gas emissions (kgCO2eq/m²a), which are considered a KPI. The economic KPI is the payback period (a), obtained by processing a series of additional indicators which can also be consulted: investment cost (€), operation and maintenance cost (€/a), energy cost (€/a) and return of investment at service life (%). The comfort KPI is the mean deviation from comfort range (°C), which is obtained as the sum of subheating (°C) and overheating (°C) conditions averaged over one year.

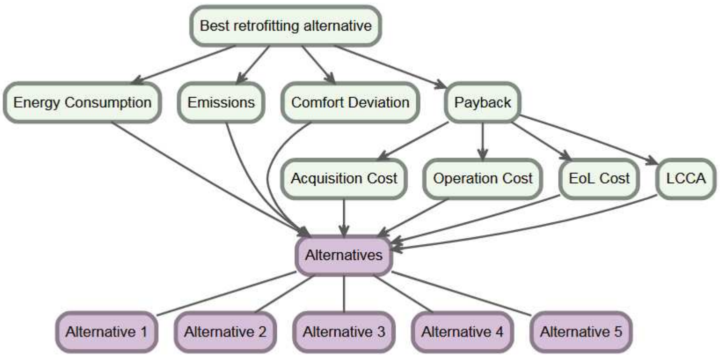
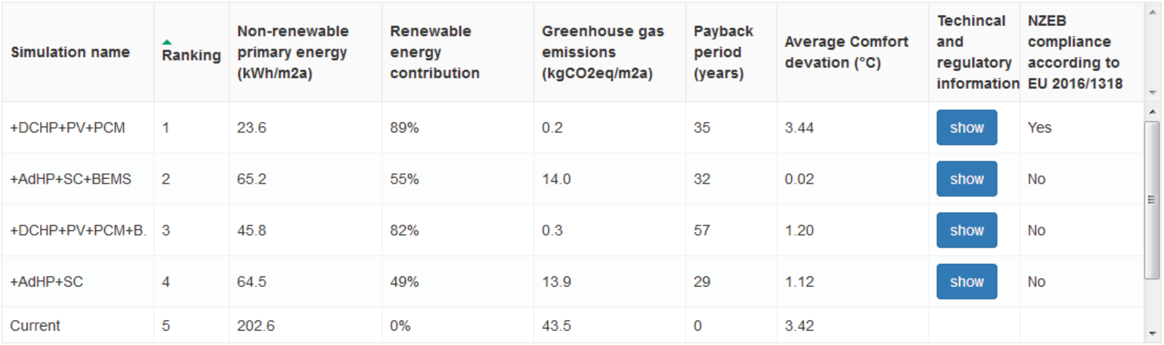


Figure 4. Graphical description of the retrofitting alternative problem

Comfort-based metrics outcoming from the simulator are directly forwarded as results, while many others require to be post-processed to get the final KPIs. Likewise, some of the energy indicators are provided by the simulator (like renewable energy contribution), but for some others additional calculations are required to transform simulation outputs into final KPIs (like non-renewable primary energy or greenhouse gas emissions).



Simulation name	Ranking	Non-renewable primary energy (kWh/m2a)	Renewable energy contribution	Greenhouse gas emissions (kgCO2eq/m2a)	Payback period (years)	Average Comfort devation (°C)	Techincal and regulatory information	NZEB compliance according to EU 2016/1318
+DCHP+PV+PCM	1	23.6	89%	0.2	35	3.44	show	Yes
+AdHP+SC+BEMS	2	65.2	55%	14.0	32	0.02	show	No
+DCHP+PV+PCM+B.	3	45.8	82%	0.3	57	1.20	show	No
+AdHP+SC	4	64.5	49%	13.9	29	1.12	show	No
Current	5	202.6	0%	43.5	0	3.42		

Figure 5. Display of results for the evaluated alternatives

To rank the feasible alternatives, an Analytical Hierarchy Process (AHP) algorithm performs a classification of the list of alternatives according to the main four KPIs considering the selected weighting profiles, developing a user driven optimization for the result categorization. Figure 4 shows the description of the problem at hand, where the goal is described as identifying the best retrofitting alternative and the ranking of alternatives is modulated by the criteria specified by the user in terms of energy, emissions, payback period and comfort deviation. The prioritization among the different KPIs is selected by the user from a set of eleven predefined possibilities as described above.

The display of results is presented in figure 5, where the four main KPIs are represented beside an additional energetic indicator (renewable energy contribution), as well as technical and regulatory information (containing a description of the technology stack proposed for the retrofitting) and whether this solution might comply with the NZEB EU 2016/1318 Commission Recommendation. Each solution is positioned according to the ranking resulting from the AHP calculation.

5. Conclusions

A web tool has been developed, aimed at stakeholders involved in the energy-efficient renovation of buildings. This tool provides a set of alternative retrofit strategies for domestic heating and cooling systems and ranks their expected performance in terms of energy performance, environmental impact, cost efficiency and user comfort. This paper has focused on the optimizer module of the tool, conceived as a key innovative component to orient the decision-making, improving the time and the efficiency of the process. A key requirement has been facilitating use for both expert and non-expert users, and hence a strategy has been developed for layering the complexity of input and output data. The tool allows the simulation of a building largely based on default values compiled from typical characteristics of the European building stock, yet most of these default parameters can be edited by more advanced users in order to improve accuracy.

The optimizer is composed by the two submodules described: Filter Tool and analytical hierarchical process (AHP). The Filter Tool generates a set of retrofit alternatives suited to the configuration of existing heating and/or cooling systems. This has been achieved by a constraint-based rule system described in the article, based on prior knowledge about the potentialities and limits of each component and the possibility for combinations. Additionally, a sequential method has been developed to classify and link all the different components of a system, covering the whole process from load demand to fuel consumption. The AHP is designed as a post-processing submodule that ranks the outputs for each simulation according to key performance indicators. A specific AHP process has been generated as described in the article, which is based on predefined weighting values suited to each user profile.

The result of the above process is a web tool that can generate, simulate and present a ranked set of alternative interventions for the retrofit of domestic heating and/or cooling systems, even with a minimal set of inputs. Its main contribution is the empowerment of non-expert users, who can obtain tailored information on established and novel technologies that might suit their building. In addition, advanced users can fine-tune parameters and analyse a more comprehensive set of output indicators. A fully functional initial version of the tool has been completed and will be validated with different use cases and monitoring data from pilot buildings.

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