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Genetic Algorithm for a Combinatorial Optimization for Energy Retrofit of Buildings

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Abstract

The building sector must reduce its energy consumption and integrate more renewable energy sources in its supply systems if countries are to achieve energy security and manage climate change. Several technological and constructive options are available to improve building's energy efficiency. However, building owners do often remain unmotivated, are overwhelmed by different technologies and do not know the best investment strategy for a limited budget. To identify the most appropriate retrofit options for single and two family house owners we propose a Pareto optimisation using genetic algorithm. We use a dynamic calculation of the thermal building and system engineering behaviour programmed in Python. The building is modelled with a low-order model. For the system engineering we use a new approach based on dynamic plant expenditure figures.

Keywords – building retrofit, combinatorial optimization, genetic algorithm

1. Introduction

Energy efficiency measures in the building sector provide an enormous potential to energy saving and reduction of CO2 emissions. However, the refurbishment rate in whole Europe is very low. Across different countries, the rate is approximately between 0.4 % of up to 2.4 %. [1] Different constraints are in conflict with an expansion of the refurbishment rate. In many cases, the investment costs are too high [2] and the building owner sets the refurbishment aside or only selective measures are undertaken which might be suboptimal from an energetic point of view. Furthermore, there exist prejudices against refurbishment measures and a lack of information but also an overload of information may stop decisions for an energetic refurbishment. [3] Different studies and concepts try to counteract the constraints with an optimization-based decision in building design and retrofit. Since the year 2000 a noticeable rise in publications about the optimization of building energy systems can be found. Evins [4] summarizes all relevant publications between 1990 and 2012. Almost 40 % of the considered papers focus on optimal solutions for the building envelops. The geometric building shape, the system engineering and the usage of renewable energy is considered in about 20 % of the papers.

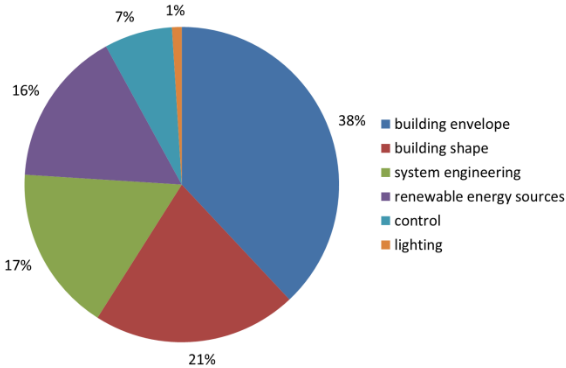

Fig. 1 Considered areas for optimization of building energy systems according Evins [4]

Only few papers (e.g. [5], [6]) consider a combinatorial optimization of retrofit measures for the building's envelope and its system engineering. However, for an efficient system operation the coordinated implementation is of major relevance.

Additionally, the refurbishment of existing buildings is always a compromise between different aspects like capital expenditure, primary energy or CO2 savings. This leads to the need to identify a combination of measures. Within the papers taken into account by Evins about 50 % optimize the systems with regard to one target. Nevertheless, an increasing number use a multi-criteria optimization according to the Pareto-principle. In the simulation-based multi-objective optimization schemes, a coupling between different tools can be found. Especially for a better resolution of the thermal building behaviour a coupling with different energy simulation packages can be found (e.g. [5]) which also extend the calculations from static to dynamic considerations.

From the work done so far, we identified a lack of a dynamic system evaluation with simplified models as a reasonable compromise between system resolution and computational effort. The approach presented in this paper aims at a combinatorial optimization approach for retrofit measures concerning the building envelope and the heating system under consideration of dynamic effects and different target figures. As a decision support tool the model approach only needs easy accessible system data from the user. The results are assigned to different personal needs but also to appropriate collateral requirements relative to regional or national goals in energy savings.

2. Methodology and Methods
Optimization Approach

Most of the optimization approaches for energetic retrofit present one optimal solution. But the optimum is often a very flat optimum and different combinations of measures deliver comparable solutions. Taking into account the uncertainties and the required simplifications for the model development a single optimal solution cannot be clearly stated. In point to fact a classification of appropriate and non-appropriate solutions can be given. Building energy retrofit solutions involve a number of choices between building physics and system engineering to satisfy many criteria. For an efficient exploration of the search space we choose a genetic algorithm. Genetic algorithms are an optimization method that has been applied to many types of optimization problems associated with buildings and its application is proved. ([7], [8]) The genetic algorithms belong to the group of evolutionary algorithms as a stochastic search method that mimics the principle of natural biological evolution. [9] They can efficiently handle non-linear problems with discontinuities and many local minima. [8]

The basis for the genetic algorithm is a population of individuals. The individuals produce by selection and mutation descendants. The selection forces the search direction for results regarding the optimization goal. Good individuals are preferred and bad individuals are avoided. To avoid a loss of diversity the mechanism of recombination and mutation cause new individuals.

Each individual consists of a set of parameters to be optimized and encoded in a binary string known as a chromosome. We consider the following retrofit measures as variables:

- Outer wall insulation
- Roof insulation/ top ceiling insulation
- Cellar ceiling insulation
- Window replacement
- Buffer storage size
- Heating system
- Solar system (PV and/or solar thermal)

A discrete list of variables was drawn up for each parameter.

If there is only one objective function, the results of the genetic algorithm give directly the solution. However, in most cases the solution has to compensate environmental, energy, financial and social factors which are mainly conflicting objectives. [10] In a weighted-sum approach, the various objectives are combined to form a single objective, which is then optimised in the normal way. [4] As an a priori approach the user must fix precise evaluation criteria beforehand together with a clear formal consideration. With a wide variety in user/occupant or owner needs this is in practice rarely possible.

With a view to the individual decision process and the idea to show always a portfolio of solutions, we implemented a Pareto optimisation as an a posteriori approach. The user can choose from a set of solutions after the optimisation. In the Pareto optimisation a set of solutions with regard to the different objectives is characterized by the fact that their cost cannot be improved for one objective without worsened in another. The set of all Pareto solutions forms the Pareto front.

The whole algorithm is programmed in Python.

House Model

To account for the dynamic interactions among all thermal-based elements associated with energy consumption, including the building envelope and heating, ventilating and air-conditioning (HVAC) systems, the building's heat demand is calculated on an hourly basis with a low-order building model. This model is based on the ISO 13790 standard [11] and consists of thermal resistances and capacities (R-C) for a single thermal zone. Lauster et al. have shown that these models are suitable as a well-balanced approach with sufficient resolution and low simulation effort. [12]

The low-order model gives us the possibility to do a model parametrization with a simple data set easy available for the user. The basic parameters are:

- Location of the building
- Building type
- Year of construction
- Roof construction
- Cellar available
- Net floor area
- Number of floors
- Floor height
- Number of persons

With the input data the building element sizes can be estimated based on correlation functions. Based on the year of construction and the type of construction the heat transfer coefficients can be estimated.

For the building occupancy, we use occupancy profiles according standard SIA 2024. [13] Each person has a heat production of 120 W with a share of 80 % radiative and 20 % convective heat distribution. For hot water consumption and the electrical load profiles for internal heat gains we use the European load profiles from Annex 42. We make the assumption that the electrical power is completely converted into heat with a heat distribution of 50 % radiative and 50 % convective.

System Engineering

Actual research work examines rarely the combined optimization of building's envelope and system engineering. The limited work available describes the system engineering mainly by overall system efficiency (e.g. [14]), average competence efficiency data from the manufacturer (e.g. [5]) or steady state component models. (e.g. [15]) Those concepts neglect the overall system interaction and its dynamic behaviour with an efficiency reduction under part load. This can lead to a wrong system design and especially wrong assumptions in the possibilities to integrate renewable energies with a strong volatile behaviour. To overcome those limitations we propose a new concept of a dynamic plant expenditure figure.

Plant expenditures figures are typically used for the energetic evaluation of HVAC systems [16] and are widely used, e.g. in the German Energy Saving Ordinance (EnEV).

In real HVAC systems occurs an energy expenditure, which is higher than the poor energy demand due to energy losses and a non-ideal control strategy. The relation between the energy expenditure to the ideal heat demand as reference heat demand gives the plant expenditure figure. The classical plant expenditure figure is based on various simulations with a time integral over one year. We now extend this approach from the consideration of the yearly average load state to the current load state. For this purpose we consider a reference building with a detailed building model together with the energy conversion unit, the hydraulics and the heat transfer in the room in Modelica. For the reference energy demand an ideal heater is implemented. The plant expenditure figure is calculated from the hourly averaged energy demand:

$$e_{\mathrm{dyn}}\,(\mathrm{t}) = Q(t)/Q_{ideal}(t) \qquad (1)$$

The plant expenditure figure is then given as a functional correlation with the relative heat demand, the ratio of the reference energy demand to the design heat load. Figure 2 shows as an example the curve progression for a gas condensing boiler with radiators as heat transferral system.

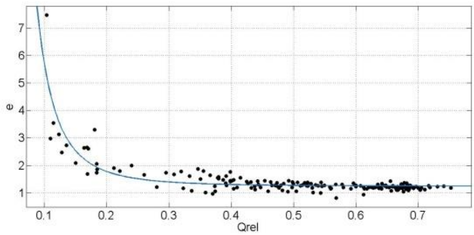

Fig. 2 Plant expenditure figure e depending on the relative heat load Qrel

The electrical output power from photovoltaics is dependent on the solar irradiance and ambient temperature as well as the characteristics of the module itself. The calculation is done according to Masters. [17] For the thermal output of the solar collector the steady-state collector model as in DIN EN 12975 [18] standard is used. All effects of the thermal capacitance of the collector are neglected within this formulation. For both systems, the performance parameters are taken from manufacturer data.

3. Results

In the following exemplary results are given for a single family house with 150 m² heated floor area which was constructed before 1948. The cellar and top floor are not heated. The end energy demand without any refurbishments is 329 kWh/(m²a). Figure 3 shows the Pareto front for an optimization calculation on primary energy demand and euro per saved kWh heat energy.

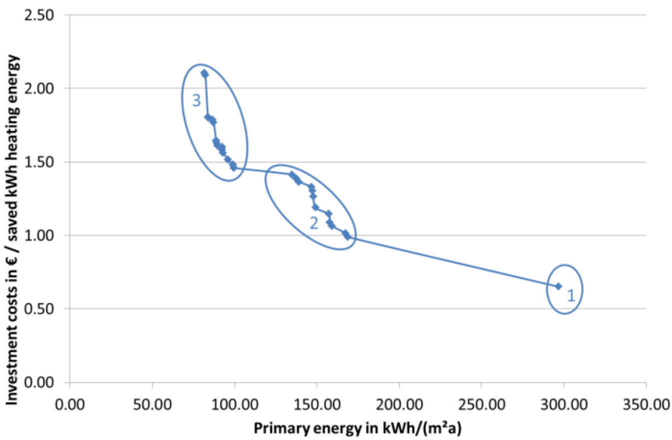

Fig. 3 Pareto front of retrofit options for the exemplary single family house

Three possible refurbishment categories can be separated. In a first step the cellar ceiling and the top storey ceiling are insulated. In the second category an insulation of the outer walls with a moderate insulation thickness is added. The existing heating system, which is assumed to be an oil boiler, is replaced by a gas condensing boiler. To further reduce the primary energy demand solar thermal collectors are installed for a domestic hot water support. In the third category the heating system is replaced by a heat pump system. In a first step it is an air-water system (A/W HP) and for further primary energy savings a brine water heat pump is chosen.

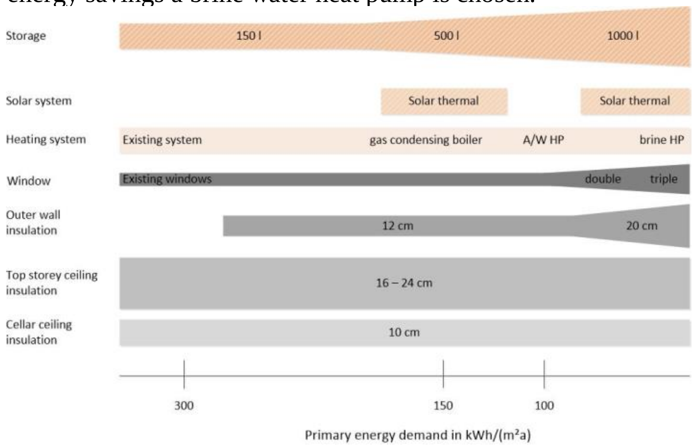

Fig. 4 Retrofit measures for the building envelope and system engineering according the optimization

In figure 3 each point represents a retrofit package. Figure 4 illustrates the chosen system solutions and the thickness of insulation for the different building elements in dependence of the primary energy demand. From the left to the right the energetic building standard increases with a decreasing primary energy demand.

4. Conclusions ans Outlook

Buildings today account for 40 % of the world's energy use. The change to a sustainable energy supply depends on a high degree on the development in the building sector.

For home owners it is often difficult to find their own individual pathway for building energy retrofit and to understand the relation between different energy efficiency measures. Without this knowledge a stepwise building refurbishment where single steps do not avoid future measures is very difficult and a limited budget cannot be used efficiently.

The chosen combinatorial optimization with an evaluation of different combinations of retrofit measures on a Pareto front enables the house owner to decide on his own which objective between environmental, energetic and financial aspects is the most important for him and gives a coordination of a stepwise refurbishment.

This paper proposes a Pareto optimisation using genetic algorithm to identify the most appropriate retrofitting options for single and two family house owners. We consider the possibilities for the building's envelope together with options for the system engineering. With the use of reference buildings, we can reduce the necessary input to an easy available data set.

To allow a detailed modelling of the whole thermo-hydraulic system the heat sources, the energy conversion units, the heat distribution, transfer system and the building as heat sink, we do dynamic calculations on an hourly basis. This enables a detailed resolution of storage effects and efficiency changes of energy conversion units under part load. For the description of the building we use a low-order building model. For the system engineering, we propose a new approach using dynamic plant expenditure figures. This seems to be a promising compromise between sufficient resolution and low simulation effort.

In a next step, it is planned to integrate the approach together with project partners in a free accessible online advising tool. Furthermore with an extrapolation of the user's decision to all buildings in the considered building class we hope to help to sensitize house owners to the needed joint efforts for a change of energy supply of buildings.

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