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A GIS based methodology to support multi-criteria decision making for the retrofitting process of residential buildings

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ABSTRACT
This paper presents a workflow to support the decision making for building retrofit and building systems update at urban scale. The workflow includes *i)* a method to extract information from a geographical information system including information on building characteristics, building systems and building typology, *ii)* a method to evaluate the current and future energy demand of buildings using a dynamic building simulation tool, and *iii)* an updated version of the energy hub approach to evaluate best performing options in terms of energy systems update. The developed method is applied to the city of Zurich to evaluate the optimal energy system update for all existing buildings within the city. Modelling results include best performing options in terms of CO_2 emissions, renewable energy share, or energy efficiency while minimizing resulting costs for possible system and retrofitting solutions.

KEYWORDS
Urban energy, energy system optimization, retrofitting of buildings, energy hub.

INTRODUCTION

Buildings and urban energy systems have an important potential to reduce energy consumption and greenhouse gas emissions to meet future energy strategy targets. A combination of measures are usually required to achieve the envisaged targets, which include replacing current fossil fuel based heating systems with more sustainable solutions, to integrate decentralized energy systems, and retrofitting the existing building envelopes. To support the decision making process, optimization tools are required, which allow for a multi-criteria assessment of an optimal combination of measures within urban energy systems. Finding suitable solutions for already existing neighbourhoods depends thereby strongly on the buildings and their installed systems. Questions such as which buildings need to be updated first in order to meet the targets as soon as possible, or which measures are more important compared to others play thereby a critical role.

This paper presents a workflow which builds on simulation and optimization techniques to support the decision making for building retrofit and building systems update at urban scale. Thereby information which is retrieved from Geographic Information Systems (GIS) about the current situation of the buildings (such as layout, U-values, occupancy, etc.) and their systems is integrated in the model. The method can be used to evaluate best performing options in terms of CO_2 emissions, renewable energy share, or energy efficiency while minimizing resulting costs for possible system and retrofitting solutions. In this paper the developed method is applied to 12802 residential buildings of the city of Zurich.

METHODS

The workflow which was developed, shall support the decision making for identifying optimal building retrofitting measures at urban scale. It includes: *i)* A method to extract geo-spatial information, including information on building characteristics and building energy systems, based on building and census data, *ii)* A method to evaluate current and future energy demands of buildings using an automated process developed in Matlab to deploy EnergyPlus at urban scale, that includes a connection to geo-spatial information and facilitates the computation of energy demand profiles for different scenarios at individual building level, and *iii)* an optimization model to evaluate best performing options in terms of retrofitting and energy system updates, based on multi-criteria decision making. As a result, input information on existing buildings, including their system state, is integrated into the modelling methodology. The tool allows for the evaluation of individual building level solutions, and is additionally able to take renewable energy potentials and boundary conditions of the neighborhood into account.

Geo-spatial information

To describe the current situation of buildings within a neighbourhood GIS based building information is required such as building layout, building characteristics and environmental information. Relevant input information is collected from different sources, such as census data from Switzerland (BFS, 2013), 3D building information (Swisstopo, 2016), weather information (Meteotest, 2016), etc. This information is further processed in a database structure and connected to the different models presented below.

Buildings energy demand modelling

Modelling of current energy demand of buildings

To represent the current situation in terms of energy demand pertaining to heating, cooling, electricity and domestic hot water the bottom up modelling tool CESAR is deployed (Wang et al., 2018). The tool allows for calculation of hourly energy demand profiles for multiple buildings within a neighbourhood. Thereby geo-spatial information pertaining to building floorplans, their height (2.5D shape) and a set of additional input information to derive relevant building characteristics are used as model input. The CESAR tool utilizes the building simulation engine EnergyPlus (U.S. Department of Energy, 2015) to compute for each building heating, cooling and electricity loads separately. Neighbouring buildings are considered as shading objects.

Modelling of building envelope retrofitting potential

The model can be used to evaluate different envelope retrofitting options. In case of a retrofit of the building envelope, additional insulation is added to the original constructions until required U-Values for retrofitted constructions according to SIA 380/1 are met (SIA, 2009). Additional envelope retrofitting options include replacement of windows, partial retrofitting of individual constructions, such as roofs or facades, and whole building retrofitting solutions which combines all the different measures. The resulting retrofit constructions are structured in a database similar to the non-retrofitted constructions and linked with the model.

Modelling of solar potential

For calculating the building integrated renewable potential pertaining to the utilization of the solar resource also the tool EnergyPlus is used. The variation of different roof inclinations, and orientations was evaluated. Thereby values between 0 and 60 degrees, with 5 degrees step for roof inclinations, while the roof orientation could take discrete values from East (90 degrees) to South (270 degrees) with a step of 45 degrees. In total 65 solar simulations were performed to calculate the annual solar profiles for the selected combinations of roof slopes and orientations stored in a solar database. For each building the total roof area was calculated and based on the building orientation and slope of the roof a respective solar profile was assigned to the building.

Simulation results

Results are computed for individual buildings at an hourly resolution, including actual and future demand for heating, domestic hot water, cooling and electricity, as well as solar potential on roof surfaces. Additionally, annual primary energy consumption and GHG emissions for operation of the buildings, as well as operational energy, embodied energy and economical aspects of retrofit measures are analyzed in detail.

Optimization model for optimal retrofitting option

For selecting the optimal retrofitting strategy for each building an optimization tool based on the energy hub approach is utilized. The model takes a combination of both building envelope retrofitting options and energy supply systems to provide electricity, space heating and DHW into account. The approach is based on a Mixed Integer Linear Programming (MILP) optimization framework (Wu et al., 2017, Mavromatidis et al., 2014). To evaluate multiple objectives the epsilon constraint method is deployed. In this study, the two objective functions for annualized costs and life cycle environmental impacts are considered. The generated energy demand profiles together with the solar potential profiles of individual buildings are taken as input to the model. The demand profiles are further processed to extract typical days, which are then used for the optimizations. A representation of the current system based on the above mentioned database (BFS, 2013) is included in the model. Additionally the following system options are implemented into the optimization framework which pertain to: air source heat-pumps (ASHP), ground source heat-pumps (GSHP), biomass boilers, photovoltaic panels (PV), solar thermal collectors (ST), oil boilers and gas boilers as conversion technologies and hot water thermal storage tanks and batteries as storage technologies. The building envelope retrofitting scenario is implemented as an additional decision variable within the optimization framework.

CASE STUDY

The city of Zurich in Switzerland is taken as a case study. The city has about 400 000 inhabitants, who live in around 35000 residential buildings. Zürich has a heating dominated climate, with an average outside temperature of 9.5°C. From about 20 800 buildings were input information was available, about 12800 buildings were selected for the analysis. Characteristics such as building type, existing building energy carrier, age of building, size of ground floor and building height of the sample set is summarized in Figure 1. As can be seen from this figure, the majority of the buildings are multi-family houses, equipped with a gas or oil heating system and built before 1960.

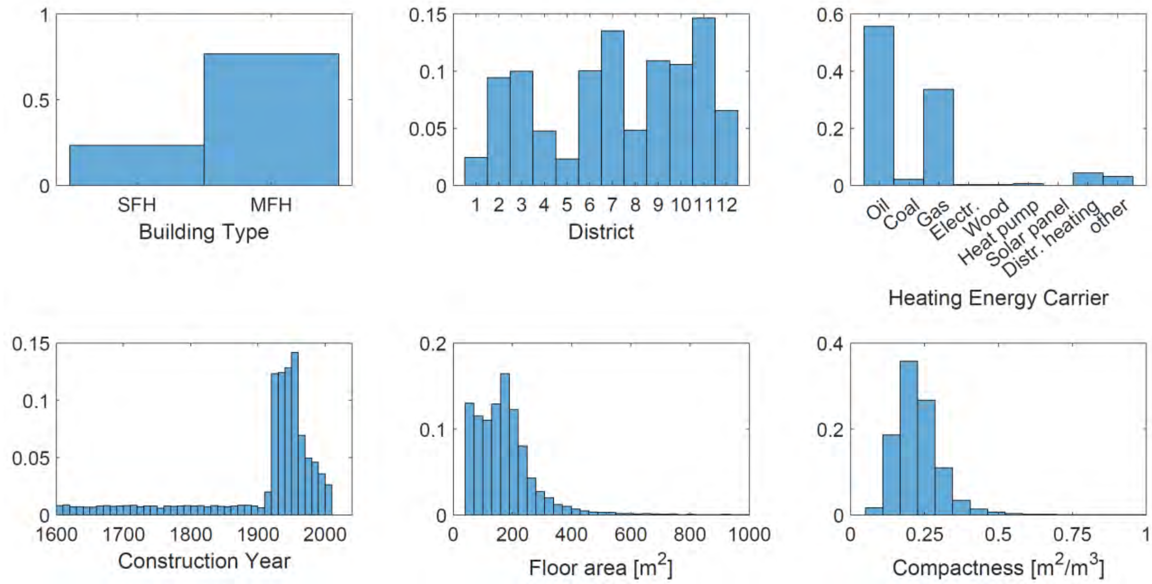

Figure 1. Distribution of building characteristics of all 20863 residential buildings.

RESULTS AND DISCUSSION

Results were retrieved for the 12802 selected buildings. In a first step the current energy demand of the sample set was calculated with the CESAR tool, as described above. Energy demand of buildings pertain to space heating, domestic hot water and electricity demand. Results are computed for each individual building, Figure 2 shows a histogram of mean annual space heating demand distribution of all buildings. The space heating demand varies between 30 to 280 kWh.m^{-2}a^{-1}. In a next step, different envelope retrofitting strategies are calculated. Retrofit options considered vary between no retrofit, roof, wall, window retrofit and combinations between them. Additionally, the building integrated maximum solar potential is calculated. Results of the current building characteristics, current energy demand, and potential options for retrofitting as well as the solar potential act as input information for the optimization framework. In a final step, the optimization tool is deployed to evaluate the most cost and CO2 friendly retrofitting solution. Thereby building envelope retrofitting options together with building system solutions are taken into account. Results are given as pareto optimal solutions for each individual building. Pareto optimal solutions are the set of solutions for which no criterion can be improved without making another criterion worse off. Figure 3 shows Pareto fronts of 3 different buildings in Zurich.

Results of the 3 different buildings show that the shape of the Pareto curve and the selection of retrofitting interventions can vary considerable between buildings. However, results also show that the best performing option in terms of CO_2 is usually a biomass based heating system, which is due to very low CO_2 emissions of biomass. Results also show that the set of Pareto-optimal transformation strategies are depend on the original heating system, while age and size of the building influence the achievable GHG emissions and related costs. The retrofitting of the building envelope option varies considerable between the different buildings. While for some buildings no retrofitting of the envelope was selected, buildings like the one shown in Figure 3a have a wall and window retrofit, and only a few a full retrofitting of the envelope. Figure 4 shows the distribution of optimal solutions for system selection (a) and retrofitting (b) for all Pareto points. As can be seen from these figures the majority of optimal solutions are distributed between no retrofitting, which are clearly the cost optimal solutions and partly retrofitting of single elements such as roof or wall insulation. A full retrofit of windows, walls roofs and floor construction is only selected for a minority of buildings. This is mainly due to very high costs for retrofitting in Switzerland. At the system side, it can be seen that for the majority of solutions an ASHP is selected, followed by biomass boilers and GSHP.

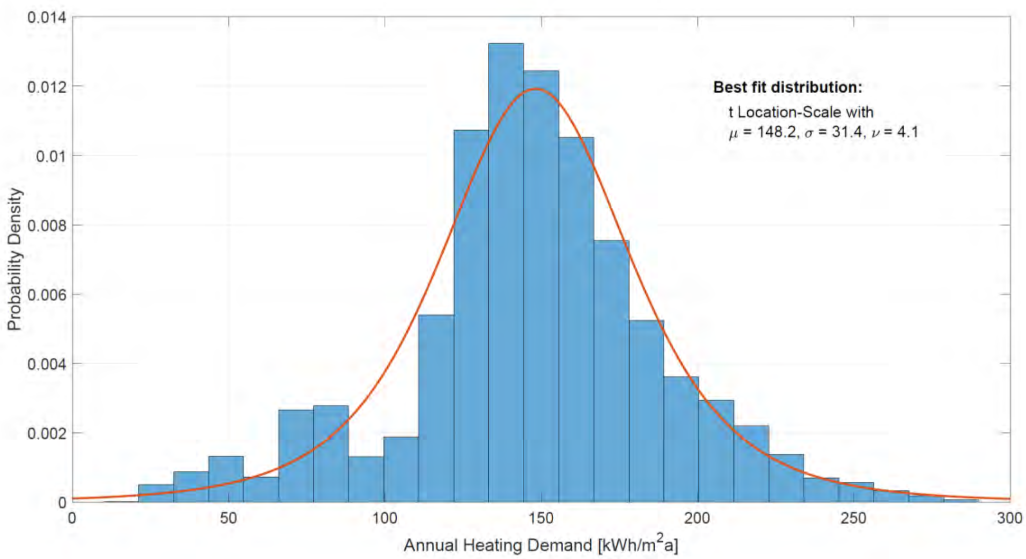

Figure 2. Histogram of current heating demand of the sample set of buildings.

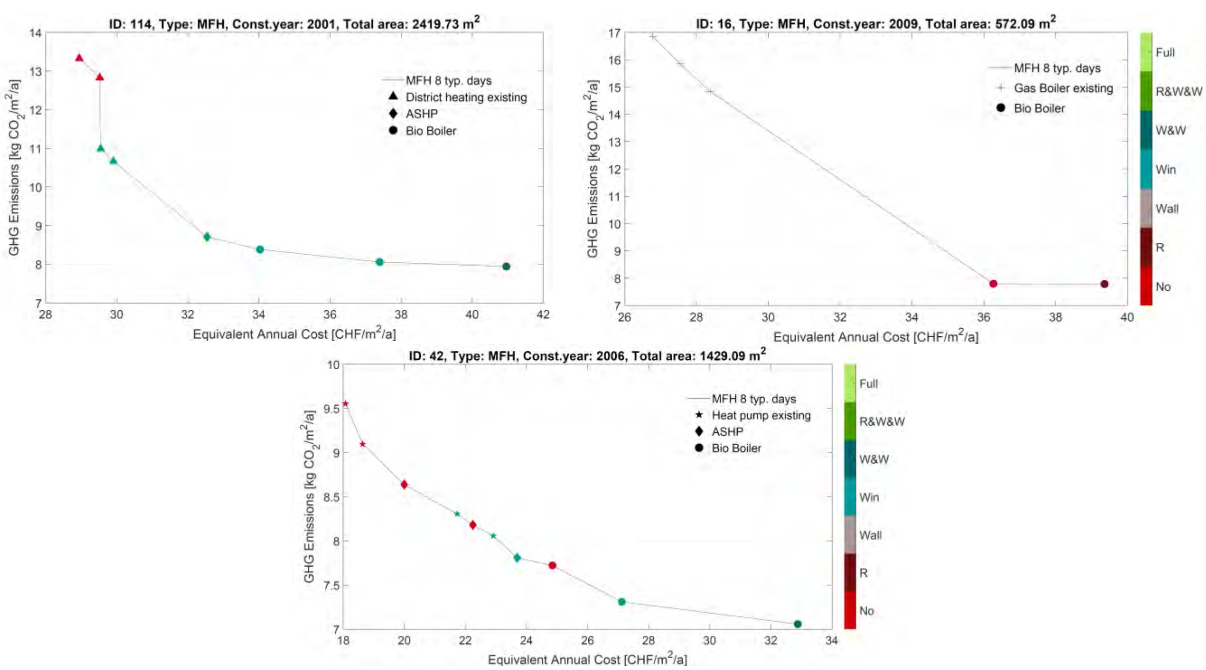

Figure 3. Example of Pareto fronts

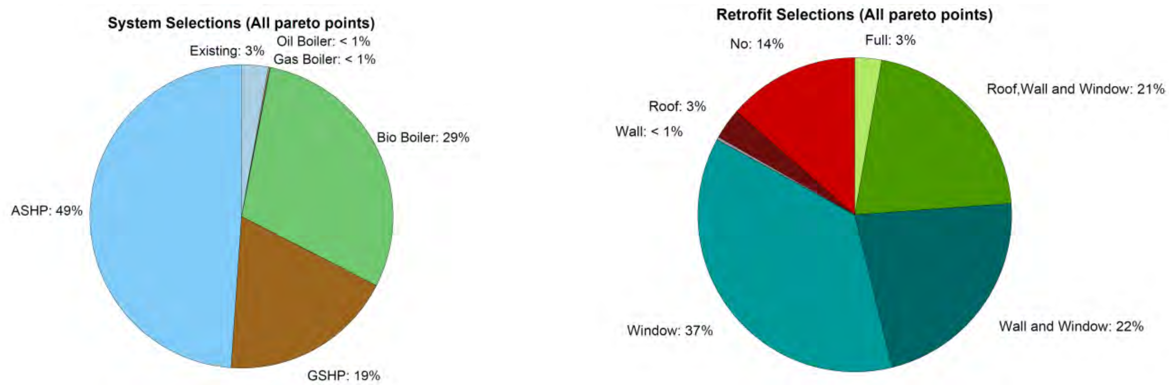

Figure 4. Retrofit and system selection shares of the sample set of buildings

CONCLUSIONS

This paper presents a workflow for evaluating sustainable retrofitting options for buildings at an urban scale. The workflow consists of a combination of a GIS based data collection which is connected to different tools to identify building energy consumption, retrofitting options and finally to evaluate the CO2 and cost optimal solutions for buildings within a city. The approach can be easily applied to residential buildings in Switzerland. As a case study, 12802 buildings of the city of Zurich are selected. Results of the case study show that solutions vary considerable between the buildings. As a conclusion, it can be summarized that the optimal transformation strategies depend on the original heating system, while age and size of the building influence the achievable GHG emissions and related costs.

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