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Dynamic building energy demand modelling at urban scale for the case of Switzerland

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Abstract

This paper presents an approach to simulate buildings energy demand for districts at large scale for the case of Switzerland. The method is based on bottom-up dynamic modelling techniques taking the time varying behaviour of the system into account. As input information, Swiss 3D building geo-data and available housing stock data have been used. The modelling approach is structured the following: i) Accessible building geographical information from Swiss building geo-data are pre-processed. Based on actual building floorplans, 3D thermal zones including external shading by neighbouring buildings are created. ii) According to Swiss building statistics and Swiss standard SIA 2024, other non-geometry related building characteristics are identified, such as user behaviour, building type and usage, etc. iii) For each building, a complete Energy Plus file is automatically generated, using geometry and building characteristics. Subsequently, a dynamic hourly based load profile is simulated automatically for each building in the district. The methodology provides a flexible approach that can be easily applied to simulate the energy demand for any district in multiple scales with adequate building information inputs. To validate the approach a case study, comprising of 112 residential buildings, in a small village in Switzerland has been modelled. A statistical analysis between simulated and measured data was conducted, in order to validate the methodology. While results show for some cases relatively high discrepancies at individual building level, overall a relatively good match (below 10%) between simulated and measured could be achieved.

Keywords - dynamic building simulation;urban scale;automation process;geographical information

1. Introduction

It is well known that the energy consumption of buildings for heating, cooling and electricity varies significantly over time, building type, usage and user behaviour. For the integration and balancing of production and consumption of intermittent energy from decentralized sources, detailed knowledge on energy demand profiles of buildings in a district or at the urban scale is highly required. Often standardized values are taken into consideration to represent energy demand of buildings. This is a relatively accurate solution to represent the overall energy consumption of a neighbourhood, but not necessarily for individual buildings and their related demand peaks and variations due to occupancy behaviour.

Modelling each building individually by using bottom up methods, with certain level of building details is time consuming, computational expensive and case specific, especially not flexible with building level modification when dealing with thousands of buildings at large scale. Most recent studies of bottom up modelling methods rely on modelling of typical buildings to represent the entire building stocks at urban scale. However detailed geometric differences, building orientation and shading by neighbor buildings are in this case neglected [1,2].

Within this paper, an automated building energy modeling and simulation approach is presented, which generates a set of realistic load profiles for heating and cooling demand of the Swiss building stock at large scale. This housing stock model is built upon Swiss 3D building geo-data [3] to represent the geometry and layout of buildings and GWR data (Gebäude- und Wohnungsregister) [4,5]to take building characteristics and usage of the buildings into account. The goal is to develop a method, which is so flexible that any kind of neighbourhood or city within Switzerland can be modelled and subsequently retrofitting improvement options developed. To test the methodology, a case study comprising of 112 residential building in a village in Switzerland is selected and modeled. A statistical analysis between simulated and measured data is conducted in order to validate the methodology.

2. Methodology

For the simulation approach, a bottom up modelling method is developed to compute hourly energy demand profiles for a set of buildings within a neighbourhood. The method is based on an automated process which can compute out of building 3D data and a set of available building characteristics dynamic load profiles of the buildings. Figure 1 displays the workflow of the methodology, starting from input database, with the help of modeling and simulation tools (ArcGIS, Matlab, Energy plus), and then generating the final output. Three major input categories are highlighted in Figure 1, whereby the process is structured into the following categories namely the representation of:

- building geometry with relevant parameters such as thermal zones, glazing ratio, building orientation and shading by neighbouring buildings,
- building characteristics with relevant parameters such as building construction, occupancy, thermal settings such as cooling and heating temperature, infiltration, user behaviour, etc.
- building location with information on local weather conditions such as hourly temperatures, solar radiation, etc.

Collected information on geometry and building characteristics is further processed to define input information (idf-files) for the building simulation tool EnergyPlus for each building separately considering shading of neighbouring buildings. The following sections describe the different steps to retrieve building information within the simulation environment.

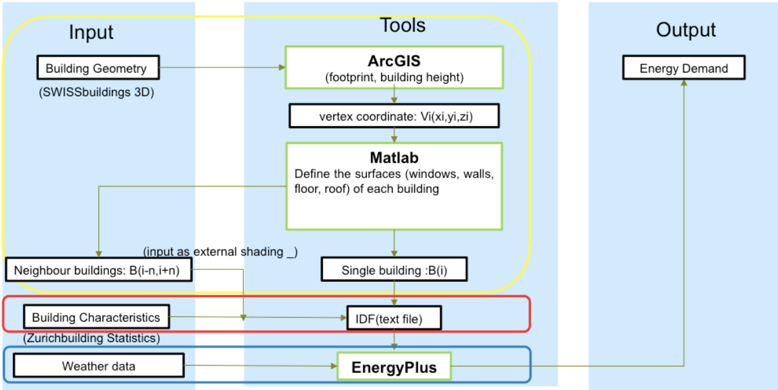

Figure 1. Workflow of the modelling and simulation process

2.1. Building geometry

Accessible building geographical information from Swiss building geodata (Swisstopo) are pre-processed through ArcGIS, defining the geographical coordinates for the floorplan vertices. Based on actual building floorplan and building height, 3D thermal zones for each building are created taking floors, walls and roof constructions into account. Based on available information on glazing ratios of the different façade directions, windows are represented within the model. Geodata of Swiss 3D buildings define not only the building envelop itself, but also the absolute geographical location and orientation of each building. This gives us abundant geometrical information for any specific building in a neighbourhood. Moreover, it allows to study the interaction among the buildings in a certain distance in terms of external shading behaviour. According to global geographical coordinates, buildings within a neighbourhood Ni are clustered within an area of R=50m from the central building Bi as the origin (see Figure 2). Within each simulation run the central building is modelled in detail taking the different thermal zones of the building into account, and the neighbouring buildings are modelled as shading components in order to account for local shading through the buildings but also beam and sky solar radiation that is reflected from exterior surfaces and then strikes the central building. The radius of the area can be modified within the model, depending on the building density within the district. Figure 2(b) shows an example idf file displayed by Sketchup Openstudio representing the final 3D geometry of the buildings created, starting from Swisstopo data.

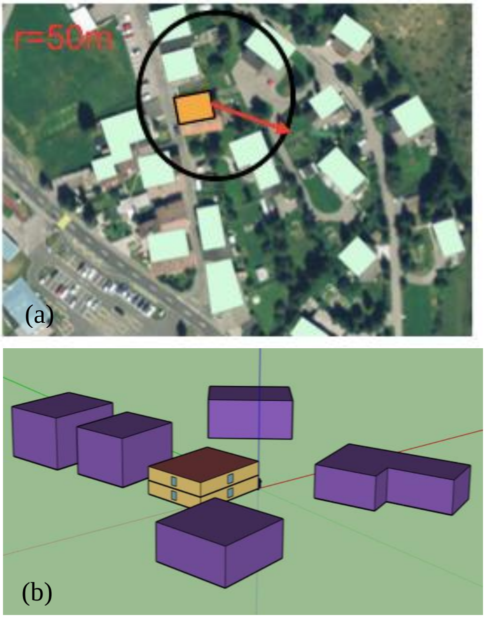

Figure 2. 2D Footprint of center Building B_i and neighbouring buildings B_{i+n} (a) and Resulting idf input file showing 3D thermal zones defined for center Building B_i and neighbouring buildings B_{i+n} in the neighbourhood N_i in an example district (b).

2.2. Building characteristics

Other non-geometry related building characteristics are additionally identified. Relevant input information pertains to building construction, type and usage, user behaviour, etc. However, reliable input information, which is consistently available throughout Switzerland is difficult to retrieve. The suggested modelling approach builds on GWR data of Swiss building statistics where for every building in Switzerland information on building construction time and building usage are available. In order to use this information for building energy simulation, information has to be further processed. An archetypical approach is taken into consideration, which defines material properties and schedules of a group of buildings with similar building types, usage and year of construction. To represent internal conditions within the buildings the Swiss energy standard SIA 2024 is taken into account [6], which distinguishes different schedule types according to building usage, specifying representative user behaviour and control systems.

As a starting point only residential buildings are taken into account. Construction methods changed considerably over time and thus also resulting heat transfer coefficients (U-Values). A categorization which clusters construction types into intervals depending on the year of construction was adopted. U-values for constructions were taken from regional literature (e.g. [7, 8]) and matched with typical constructions layouts. Since construction types vary considerably depending on the location, data gathering at regional level is crucial. As an initial starting point constructions for the canton of Zurich and for the mountain region in Engadin were defined. Available construction types were structured into a database format and connected to the simulation engine.

Building simulation tools require a range of input data to represent the building's internal conditions pertaining to the presence of building occupants, their activities and their indoor environment requirements and preferences. These inputs are a combination of scalar values, like the floor area per person (m^2/P), the installed lighting and equipment power density (W/m^2), and of information about the temporal variation of the occupants' presence and the utilisation of lighting and equipment, usually referred to as schedules. Additional information includes heating and cooling setpoints, their temporal variation (if any), and the ventilation and infiltration rates. Such information is very well standardized at building level in Switzerland, according to the norm SIA 2024 , which is incorporated in the modelling environment. Building on the information available, a database was developed for the different room types, and further aggregated to building level, which can then be used for simulations.

2.3. Location of the neighbourhood

For the representation of the outer conditions local weather data with hourly resolution are required. Switzerland disposes of a number of weather stations, which monitor information on temperatures, relative humidity, solar radiation, wind direction and wind speed. This information is available through Meteoswiss and already processed by the weather file software Meteonorm [9]. Based on these data a database of EnergyPlus (epw) weather files is generated and connected to the housing stock model in order to represent external weather conditions of relevant locations.

2.4. Building simulations

With all the relevant information summarized in the input file a complete Energy Plus file is automatically generated for each building including the neighbouring buildings. By calling the operation system to run EnergyPlus files, dynamic hourly based load profiles are calculated automatically for each building. The process is repeated until loads for all buildings within the neighbourhood are calculated. Output information is collected in a database at building level in hourly resolution for a whole year and is further processed to weekly, monthly and yearly data. Relevant output information pertains to:

- energy demand for heating, cooling, electricity, and domestic hot water
- indoor temperature profiles

3. Swiss case study

To validate the developed methodology, a case study comprising 112 residential buildings in a small village in Switzerland is selected and modelled with the automated process. Information pertaining to energy usage was retrieved by energy bills, and information provided by the inhabitants. The majority of the buildings are equipped with electrical heating systems; additional energy sources are oil, wood chips for a small district heating biomass boiler, wood for wood stoves, and some renewables such as photovoltaic, solar thermal collectors, and ground source heat pumps. The village is connected to the national electricity network. Additionally it is equipped with a small district heating network, which is connected to a wood-fired power-station. To identify the energy consumption of the buildings information pertaining to annual electricity, oil, and wood consumption and delivered energy from the district heating network have been analysed. Installed heating systems differ from building to building in terms of age, size, and parameter settings, which makes it difficult to identify the exact efficiency value of each system. To get a rough estimate of the net energy demand required for space heating, standard efficiency values depending on energy carriers have been assumed. More information on processing the data can be found in Orehounig et al [10].

To generate the simulation model, required input data, as discussed above in the methodology section, are collected and pre-processed, including geometry, other building characteristics and local weather conditions. 112 residential buildings are clustered into 5 categories depending on building construction time. Assumed U-values for building constructions are correspondent to each construction time period, as shown in Table 1.

Table 1. Assumed U-values according to building construction time

U-value [W/m2K]				
Construction time	Walls	Roof	Ground floor	Windows
Before 1900	1.54	0.79	1.42	2.5
1900-1959	2.04	1.29	1.18	2.5
1960-1979	1.78	1.38	1.95	2.5
1980-1999	0.53	0.33	0.56	2.5
After 2000	0.2	0.2	0.2	1.3

For most of the buildings, the deviation resides within a certain range. While comparing measured and simulated energy consumption for single buildings showed in some cases high discrepancies, the comparison of the yearly energy consumption of multiple buildings at a large scale showed a relatively good match, resulting in 9.79% overestimation for the 112 residential buildings. Table 2 shows the resulting total yearly heating demand for measured and simulation results.

Table 2. Total annual space heating demand for simulated results and measurements

	measurements	simulations
∑ heating demand[MWh/a]	4772.14	5239.47
Deviation		+9.79%

To further analyze sources of error, figure 3 shows simulated versus measured heating demand, clustered by different building characteristics such as time of construction, heated area and type of heating system. In addition, figure 4 displays the difference of simulated yearly heating demand to measured values of individual buildings sorted by the above mentioned categories. Results structured into time of construction show a much better correlation between measured and simulated heating demand for relatively new buildings, which are constructed between 1960 and 1999 but also buildings, which are constructed or renovated after the year 2000. Discrepancies are especially high for buildings erected before 1900, and the only two unrenovated buildings built between 1900-1959. Results structured into heated area show no clear characteristics. It suggests some huge overestimation of simulated versus measured data for bigger floor areas (>800m^2). For small heated areas (<400m^2), it indicates a much better match, and also the total deviation is relative low in each range below 400m^2. Results structured into different heating system indicate a high discrepancy between measured and simulated values for buildings heated by electricity. A possible source of error might be due to overestimating the heated floor area for those buildings, since electrical heating systems are generally decentralised systems, often only individual rooms are heated to desired temperatures compared to centralised systems. For oil heated buildings simulated results show a tendency of underpredicting the actual consumption. Surprisingly, oil and solar with additional heating sources are located quite close to the liner approximation line. This may also correlate with other factors influencing the results. For example, solar heated buildings are usually recently built, which is in consistency with the close approximation by the building construction time category.

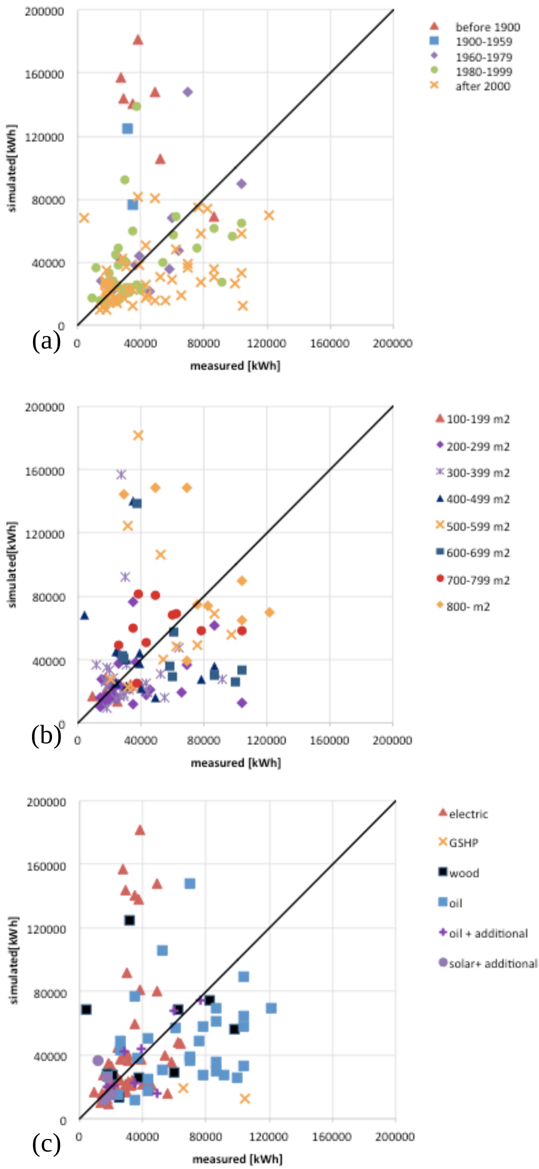

Figure 3. Simulated results vs measured yearly demand by time of building construction time (a) ,building heated area (b) and by heating system (c).

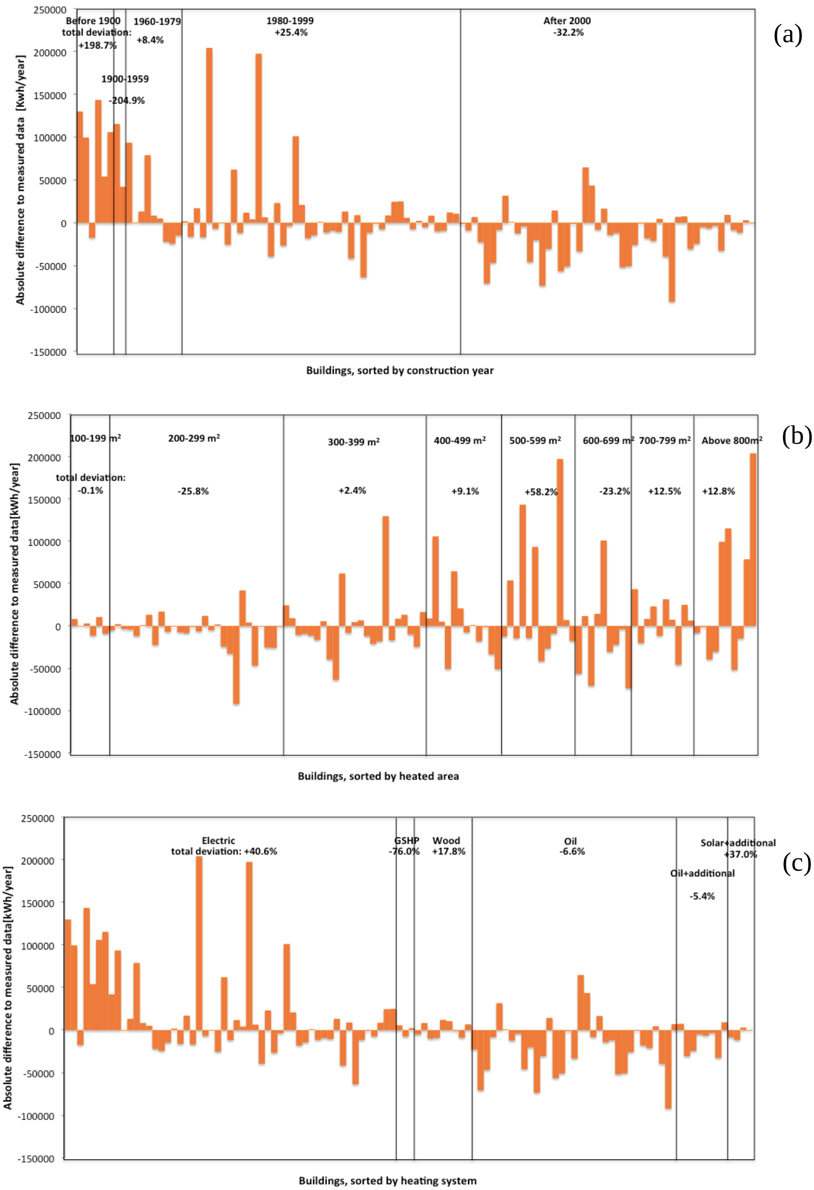

Figure 4. Absolute diffrence of simulated results to measured data for each building sorted by year of construction (a), heated area (b) and heating system(c).

4. Conclusion

The methodology provides a flexible approach that can be easily applied to simulate the energy demand for any district in multiple scales with adequate building information inputs. The method deploys dynamic modelling techniques taking time varying behaviour of the system into account, however in a simplified way in order to reduce computational costs while simulating a large set of buildings within a neighbourhood. The advantage of using a bottom up modelling method at the urban scale, lies in the possibility to run simplified simulation runs for buildings where not a lot of information is available, but also to further incorporate more modelling details (such as detailed system representations, thermal zones, user behaviour) for those buildings where more accurate information is available and desired.

With this tool not only the present condition of building stocks in a specific neighbourhood can be depicted but also for future scenarios evaluation. For predicting energy demand of buildings in the future, transformation strategies pertaining to retrofitting of the building envelopes could be executed by using the automated approach, together with weather prediction data taking effects of climate change into account. Furthermore, sensitivity studies could be carried out in order to study influences of certain important building characteristics on energy performance, such as U-values, building orientation, shading effects, user behaviour, etc.

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