International Journal on Advances in Systems and Measurements, vol 6 no 3 & 4, year 2013, http://www.iariajournals.org/systems_and_measurements/

Urban Area Energy Flow Microsimulation for Planning Support: a Calibration and Verification Study

Diane Perez, Jérôme Henri Kämpf, and Jean-Louis Scartezzini
Solar Energy and Building Physics Laboratory (LESO-PB)
École Polytechnique Fédérale de Lausanne (EPFL)
1015 Lausanne, Switzerland
{diane.perez; jerome.kaempf; jean-louis.scartezzini}@epfl.ch

***Abstract*—A recently developed energy management platform named MEU (an acronym for Management of Energy in Urban areas) has been tested on three case study urban areas of a few hundred buildings in the Swiss cities of la Chaux-de-Fonds, Neuchâtel and Martigny. The MEU simulation framework for energy-efficient systems simulates the buildings' energy demand, infers the production of the connected energy conversion systems, and simulates the complete demand and supply energy flow picture. The platform is designed to use monitored consumption data if available, and, where it is not, intends to produce correct estimates of the average energy demands of housing and administrative buildings. This article explores in detail the capacity of the platform to correctly represent existing urban areas' energy flow based on the limited data available by comparing the simulated values with monitored data. Default values are carefully chosen to obtain a statistically adequate match, thus strengthening the confidence in simulation results when no monitored data is available. The study also leads to interesting observations and hypotheses regarding the energy efficiency of existing buildings, and provides useful conclusions about the possibilities and limitations of the simulation of disaggregated urban energy flow.**

Keywords*—*urban energy flow simulation, heating demand simulation, calibration, verification, monitored energy consumption, energy demand and supply.

I. INTRODUCTION

DESPITE raising awareness of the problems associated with the widely unsustainable modern energy use, much improvement is still needed to reduce resource consumption. A large part of energy use can be attributed to buildings in urban zones, and urban populations are increasing. It is thus of interest for research to propose innovative energy efficiency measures and energy management tools for the urban context. Such a tool, the MEU platform, is described and tested in detail in this paper, after the first results were presented in [1].

The MEU platform was developed through a collaboration between several Swiss research labs (CREM in Martigny, Hes-so Valais, CEN, LENI and LESO-PB at EPFL), cities (Lausanne, La Chaux-de-Fonds, Martigny and Neuchâtel) and energy utilities (Synergy, Viteos, SSIGE). Its objective is to offer a platform for the management of energy in urban areas, considering neighbourhoods of a few hundred buildings and based on the limited available data. Among the functionalities required, specific features of this platform include:

- consideration of individual buildings,
- modelling of supply as well as demand,
- combined use of available monitored data and specialised simulation tools to produce a coherent picture of the urban energy flow,
- parallel modelling of the existing situation and of energy efficiency scenarios.

The third point in particular is, to our knowledge, an uncommon feature. A specific approach is required to deal with conflicting simulation results and monitored values. On the other hand, the procedure offers a valuable opportunity to study how micro-simulation tools for energy demand and supply can be used to estimate real urban energy consumptions. The study presented here exploits this opportunity as part of the verification and calibration process of the MEU platform.

The next section of this article reviews related research in the domain of urban energy modelling. Section III gives an overview of the methodology of the MEU platform, covering its modelling approach, simulation method and implementation structure. Section IV describes the models of the case study neighbourhoods, the data sources used to create the models and the choice of default values. Section V presents the results of the calibration and comparisons between simulated and monitored values. The results obtained through simulations are discussed in Section VI, and Section VII provides a concise conclusion of this paper.

II. STATE OF THE ART

Among the large number of research domains concerned by urban energy simulation [2] [3], there is now a growing interest in the evaluation of the energy need of larger and/or pre-existing urban areas [4], to evaluate the energy performance associated with alternative development or improvement scenarios. However, it remains a challenge today to simulate the detailed energy flow at the scale of a few hundred buildings, including the demand and the supply sides [5]. The advantage of this simulation approach is that it allows for the test of scenarios of various levels of detail, covering in a large part the options available to local politicians and energy departments. The simulation of existing buildings' disaggregated energy flow at a large scale is however complicated by a lack of information regarding the buildings' characteristics and energy supply situation, and a limited number of verification studies comparing simulation tools' results and monitored data.

Even when simulating individual new buildings, where construction characteristics are well known, the simulated energy demands and real consumption can differ significantly [6]. Regarding existing buildings, a successful method is to use well-calibrated statistical models, for which aggregated results match monitored data quite well [7]. Nevertheless, more detailed data sources exist: cadaster and building geometry data, building registers, monitored consumption data, other geographical information system (GIS) data, etc. Together with the development of decentralised energy production systems and the need for more localised information, this supports the development of disaggregated urban energy simulation models [8]. An interesting verification study at this level was performed on a 700-building area in Germany [9], evidencing an average dispersion between simulated and monitored consumption of individual buildings above 30%, while the overall annual consumption was reasonably well estimated.

Two factors explain the difficulty to simulate individual buildings at a large scale: the limited level of detail of data available for such simulation, and the stochastic behaviour of occupants. Nevertheless, acknowledging our inability to model all parameters does not decrease the benefits of using all available data: a disaggregated model making an intelligent use of default or standard data to mitigate unavailable data has the potential to provide better results than statistical models, without limiting possible improvements of the model. The calibration of the model and verification of default values, which is the primary focus of this article, is however of uttermost importance.

As discussed in [10], the amount of data (whether real or default) involved in this kind of study, as well as its quality and longevity are important concerns. However, few publications in the domain tackle this problem. The MEU platform presented in this study was developed with this concern in mind. It was designed to provide the simulation functionalities necessary for the energy management of urban zones, accounting for both demand and supply sides, whilst addressing some of the data concerns related to this domain.

III. METHODOLOGY

The simulations presented here were performed with the MEU platform, an urban energy management tool developed these last four years through a collaboration between research units, energy utilities and municipalities. Not just an energy demand simulation tool, the MEU platform intends to manage energy-related data in an adapted data model, represent the demand and supply energy picture, offer a structure for a combined use of monitored data and simulation tools, and integrate standard analysis functionalities.

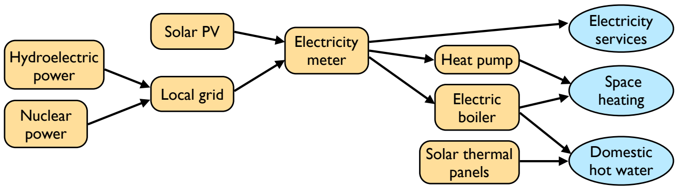


Figure 1. Example graph representation of the energy flow providing a building's energy services.

A. Energy system model

The MEU platform models the urban energy flow as an oriented graph, with the following rules: *source* nodes (in a broad sense) are linked to (i.e., provide energy to) *energy conversion system (ECS)* nodes or *network* nodes. The network nodes themselves are linked to other network or ECS nodes, and the ECS nodes in turn are linked to other ECS nodes or *building* nodes, seen as energy sink nodes (Figure 1).

This graph approach was chosen for two main reasons: without it, even simple situations where a building's domestic hot water (DHW) is provided by solar thermal panels completed with an electrical boiler while space heating is supplied by an oil boiler soon become very complicated to model. Furthermore, the intent to consider monitored data highlights its natural attribution to ECS instead of buildings: a gas consumption usually corresponds to a gas boiler, whether this boiler provides only one energy service in one building or several services in a group of buildings. In the MEU graph model, monitored energy consumptions can be attributed to any ECS node as its input flow.

Energy demands for space heating, DHW, electricity and cooling services are associated to each building node. An arbitrary number of connections link each of these demands with the ECS nodes supplying them. Each connection records information about which fraction of the demand is supplied through this connection.

The source nodes actually represent energy in any form that does not need to be investigated further: it can be natural gas as delivered in the country, or a pre-defined standard electricity mix. These nodes are defined along with their name by environmental factors, such as a *kWh primary energy per kWh* coefficient and a $kg\ CO_{2,eq}$ *per kWh* coefficient, based on the EcoInvent database [11], which intend to unite such sustainability data in one coherent data bank.

Network nodes are mainly characterised by a loss factor, whereas ECS nodes refer to a dedicated black-box simulation model including any number of modifiable parameters. Building nodes include data about address, location (footprint), allocation and a physical model used for the estimation of heating and cooling demand with the simulation program CitySim presented below. Electricity and DHW needs are estimated using Swiss norms [12], based on main allocation and treated floor area.

B. Energy flow simulation

The simulation process consists of three main steps:

- The whole annual energy flows are first estimated, creating a complete but fully-simulated energy flow picture. The energy service demands of each building are simulated by a dedicated module: the CitySim web service. The graph model structure then ensures sufficient information is available to resolve the energy flow providing those demands. The ECS nodes losses are simulated using the corresponding black-box models, offering flexibility regarding the available ECS models.
- The simulated energy flow picture is then adapted (scaled) to match the monitored consumption values available. The intent is to create an energy flow picture as close to reality as possible, by combining the incomplete information of monitored data with the structuring simulation results. Both original *simulated values* and subsequently *adapted values* are saved for later analyses.
- The last step consists in retrieving usually required results from the fully-informed energy flow picture, including building-based values of primary, final (delivered) and useful energy use per service (as defined in [13]). The results produced also include map representations of the relative energy efficiency of buildings, as well as overall results, such as the relative shares of energy carrier used or the renewable fraction of the primary energy consumed.

The first results presented in [1] confirmed that the approach described above could correctly represent urban energy flow. The test scene included several cases of centralised ECS providing space heating and / or DHW in different buildings, buildings where space heating is produced by both the district heating network and a gas boiler (in order to free power on the district heating network during heavy load periods), and electricity meters providing both the electricity demand and an electrical boiler, which were correctly simulated by the MEU platform.

On top of the pre-computed results, the energy flow picture obtained contains a large amount of information that can be accessed to perform more detailed analyses. In particular, the co-existence of the simulated and adapted values provides a valuable tool for the analysis of the validity of the model. We will consider the discrepancy of those two values at the level of the buildings' energy demands, using a discrepancy factor f_2 defined as the logarithm in base 2 of their ratio:

$$f_2 = \log_2 \left(\frac{\text{simulated value}}{\text{adapted value}} \right) \quad (1)$$

The choice of this indicator comes from two observations: firstly, when dealing with a large number of buildings, the meaning of a particular monitored consumption value is often uncertain, i.e., it is not always well defined which services and buildings are concerned. As such, using the monitored values as reference was not deemed a reliable method, no more than using the simulated values as reference. Secondly, using the percentage of deviation from a reference value has the drawback of not being a symmetrical indicator: a 50% result can be considered as an equivalent error to a 200% result. The use of the f_2 factor avoids such problems with symmetric values around zero (which corresponds to a perfect match). An f_2 value of -1 corresponds to a simulated value twice smaller than the adapted value, and an f_2 value of 1 corresponds to a simulated value two times higher than the adapted value, without any hypothesis regarding which is more reliable. A map representation of this indicator is also very useful to quickly spot locations where simulated values and monitored data do not match, in order to verify and correct the underlying model.

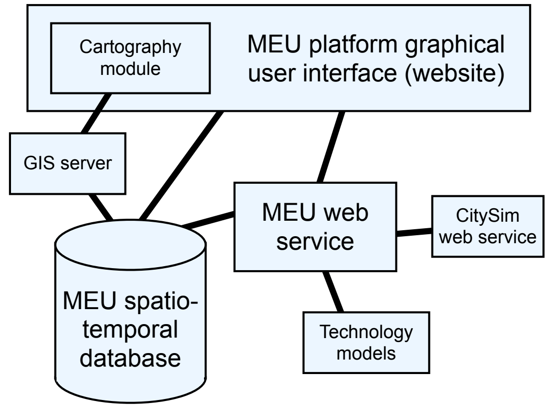


Figure 2. Web-based structure of the MEU platform.

C. The MEU platform

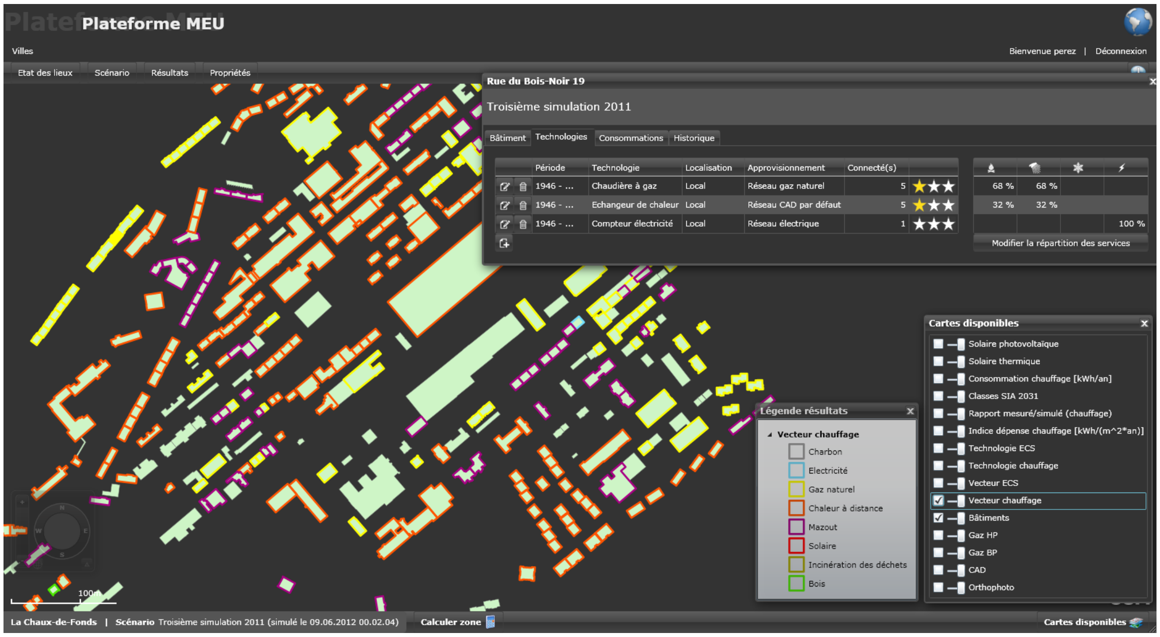
The MEU simulation framework was implemented as a web-based platform with decentralised web services (Figure 2). A GIS-based web interface provides access and editing functionalities to the model through a map representation (Figure 3). It also grants access to the simulation results, in the form of map representations as well as numerical results, for individual buildings or aggregated for the whole scene.

The data is stored in a spatio-temporal PostgreSQL (open-source) database and can also be accessed directly. The simulation of the energy flow is implemented in the dedicated MEU web service. During the simulation process the MEU web service connects to the database to retrieve the necessary input data and later to save results, calls the CitySim web service for the estimation of energy demands, and uses the "technology models" module to simulates the production of an ECS based on its consumption or vice-versa.

D. CitySim

The urban energy use simulator CitySim [14] was developed at EPFL based on multiple physical models coupled together. Its simulation results have been compared against ESP-r, EnergyPlus and the European norm CEN 13790, demonstrating similar results [14]–[16]. The verification study presented here concerns to a large extent the simulation of heating needs by the CitySim web service, which is described in some detail.

CitySim can compute an estimation of the on-site energy use for heating, cooling and lighting with an hourly time step. A radiation model first computes the irradiation incident on



Période	Technologie	Localisation	Approvisionnement	Connecté(s)		🔥	🚿	❄	⚡
1946 - ...	Chaudière à gaz	Local	Réseau gaz naturel	5	★★★	68 %	68 %		
1946 - ...	Echangeur de chaleur	Local	Réseau CAD par défaut	5	★★★	32 %	32 %		
1946 - ...	Compteur électricité	Local	Réseau électrique	1	★★★				100 %

Figure 3. The web interface of the MEU platform, here showing the main energy carrier used for heating in each building and the possibility to define any number of energy conversion systems to provide the energy services.

each surface of the scene, direct from the sun, diffuse from the sky and reflected by other surfaces. The results of this model, together with predictions of long-wave radiation exchange, are input to a thermal model. This model determines the thermal exchange through building envelopes and computes the heating and cooling energy needs to maintain predefined temperature conditions inside. Finally, ECS providing heating, cooling and electricity can also be defined.

As input, a complete physical description of the scene as well as climatic data are needed for the simulation. The climatic data includes hourly temperature, wind and irradiance values, together with the geographic coordinates and the definition of far field obstructions (which is used by the radiation model). The building models describe the envelope of each building (the thermal properties of each facade, the layered composition of the walls with thermal inertia and transmittance properties, the proportions of window openings and the physical properties of the glazing) as well as the infiltration rate and the presence of occupants and heat gains.

CitySim is used in the MEU platform to compute heating and cooling demands only. It was transformed for this purpose into a web service, also including the estimation of electricity and DHW annual demands based on the SIA norms [12]. The central MEU web service prepares the input model based on the data available in the database, calls the CitySim web service and retrieves the simulated energy demands to save them in the database.

IV. CASE STUDY MODEL

The verification study considers three case study urban areas, located in the Swiss cities of Neuchâtel, La Chaux-de-Fonds and Martigny. Still in its verification phase, the platform has, to date, not been used in other countries. This section describes the data sources used to create the models, and gives some specific insights on each of the urban zones. The default data chosen to complete these models is discussed in the next section.

A. *Data sources*

The models created for this project are based on cadastral data defining buildings' footprints, and possibly their type (allocation). The footprints are combined with data from the national building register including the address, period of construction, number of floors and optionally space heating and DHW supply systems. These were completed with a large amount of default data to form the physical model of the building (see Section IV-C).

The monitored consumption of electricity, gas and heat from the district heating network (DHN) were obtained through the local energy providers. Part of the fuel oil (supplied by various companies) consumption values were provided by the cities, based on contacts with building owners. The model is completed with locally measured meteorological data for the year corresponding to monitored consumption data.

The concerned municipalities' help permitted to slightly simplify the collection of data. Nevertheless, the combination of the various sources into a coherent model remained a time-consuming task, accounting for several weeks of work for each case-study model.

B. *Case study urban zones*

The three cities are located in the western part of Switzerland, but cover quite different climatic conditions. Figure 4 shows the buildings' footprints and their construction period.

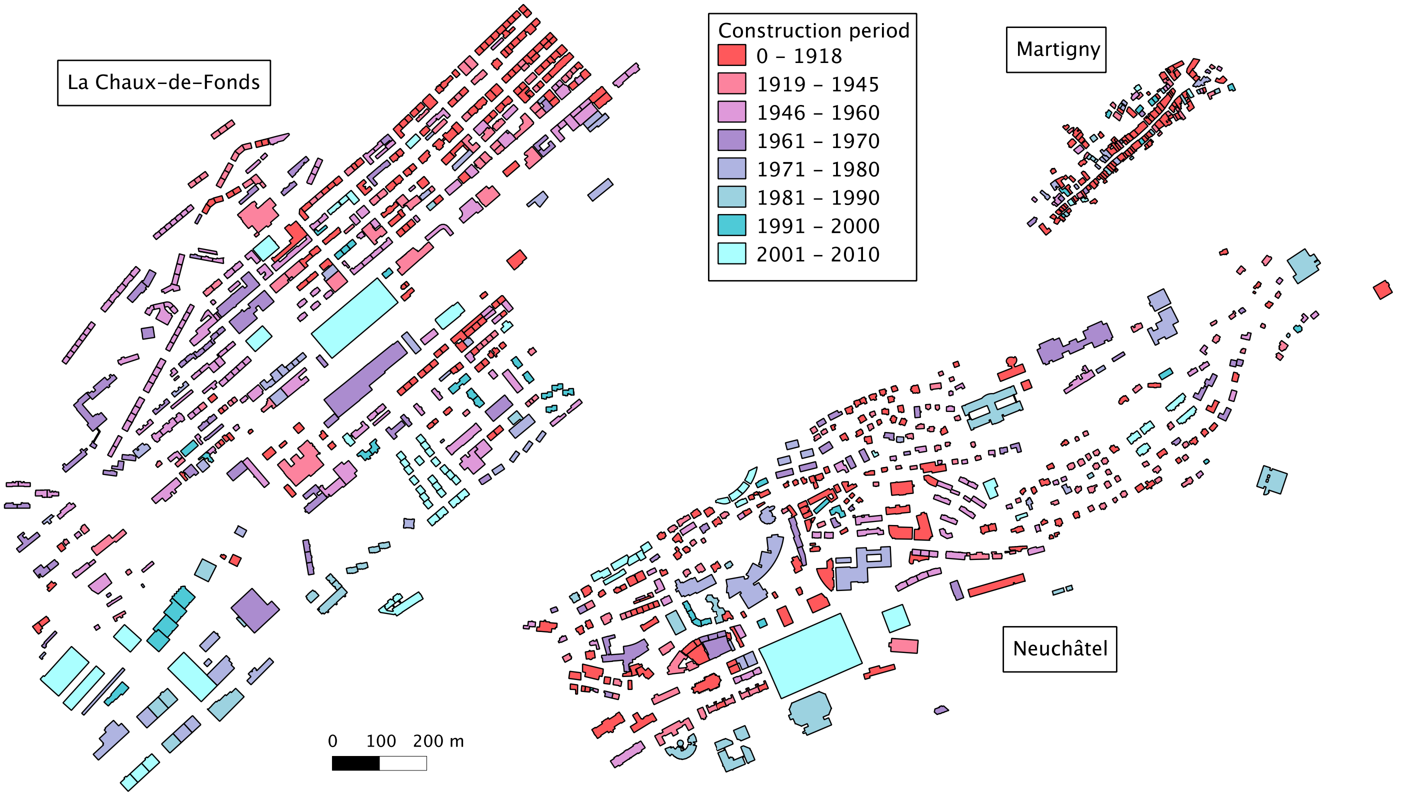


Figure 4. Maps of the three case study areas, showing the buildings' construction period (colours available online).

1) La Chaux-de-Fonds (CdF): Located in the Jura sub-alpine mountain range, La Chaux-de-Fonds (alt. 1000m) is a UNESCO World Heritage Site for its watchmaking industry-driven urbanism mixing housing and workshop at the heart of the city. The case study area covers the main part of the city center and is composed of 600 buildings. It includes mostly multi-family houses and industrial or workshop buildings, heated through a district heating network (DHN), gas or oil.

The model was up to some extent verified with the help of the energy office and energy supplier of La Chaux-de-Fonds, producing the highest confidence level case study model. Energy consumption data for the year 2011 (3853 degree-days[1]) was provided for electricity, gas and the DHN as well as for oil, although part of this data was extrapolated from other years.

2) Neuchâtel (Nch): Neuchâtel is located in the Swiss plateau, between the Alp and the Jura mountains. The case study area is a part of the city center, covering a slope between a lake and the first shoulders of Jura (alt. 430m-500m), and composed of approx. 400 single-family houses, multi-family houses, commercial buildings and other types of buildings. This most heterogeneous case study area is also heated with gas, oil and DHN.

Digital surface and terrain models (DSM and DTM) were available for the creation of the model, providing individual building's average altitude and height. The model was less intensively checked than that of CdF, but can rely on monitored gas and DHN consumption data for the year 2008 (3166 DD).

3) Martigny (Mrt): Martigny (470m) is located in the Rhone valley in the western part of the Alps range; the case study area is a very compact housing neighbourhood of approximately 200 buildings west of the city center. Unlike the two other case study areas, a large share of the buildings are heated with electricity, the others using mostly oil or gas. Monitored consumption values are available for 2010 (3116 DD). The model is however the least verified, and an unknown part of the buildings might use a wood stove for complementary space heating. The case study was still included in our analysis for representativeness, although the results obtained with it were considered with a lower weight.

C. Default data

As mentioned above, in order to obtain a microsimulation model at this scale of a few hundred buildings, numerous default values and rules were used. Only a very limited amount of data was considered as compulsory to create the case study models: the buildings' footprint, period of construction, main allocation (type) and number of floors (although the use of more available data was always possible).

For this verification study, default values were first chosen based on the information available to us, through published

---

[1] Using $\bar{T}_d$ the average temperature of day d, the degree-days (DD) were computed as $DD = \sum_{d=1}^{365} \left\{ 0 \text{ if } \bar{T}_d > 12; \quad 20 - \bar{T}_d \text{ if } \bar{T}_d \leq 12 \right\}$

Table I. DEFAULT PHYSICAL PROPERTIES OF THE BUILDINGS: VENTILATION RATE n_{VENT} [H^{-1}], WALL U-VALUE U_w [W/M^{2}K], ROOF U-VALUE U_r [W/M^{2}K] AND GROUND K-VALUE K_g [W/M^{2}K]. DEFAULT WALL TYPES ARE DESCRIBED OUTSIDE TO INSIDE, THE VARIOUS VERSION BEING SLIGHTLY BETTER OR LESS INSULATED.

Period	Wall description	Version 1				Version 2				Version 3			
		U_w	U_r	K_g	n_{vent}	U_w	U_r	K_g	n_{vent}	U_w	U_r	K_g	n_{vent}
Before 1918	Rough-stone wall	1.41	1.9	2.8	0.70	0.90	0.70	1.4	0.60	0.94	0.50	1.0	0.60
1919 - 1945	Rough-stone wall	1.41	1.9	2.8	0.70	0.90	0.70	1.4	0.60	0.94	0.40	0.9	0.60
1946 - 1960	Rough-stone, air gap, brick	1.35	1.4	2.3	0.60	0.98	0.70	1.5	0.60	1.35	0.85	1.5	0.75
1961 - 1970	Brick, air gap, brick	1.14	1.3	2.0	0.55	0.91	0.65	1.3	0.55	1.03	0.70	1.3	0.70
1971 - 1980	Brick, insulation, brick	0.58	0.70	1.3	0.50	0.67	0.60	1.1	0.50	0.86	0.70	1.2	0.65
1981 - 1990	Ins., armed concrete	0.42	0.40	0.63	0.40	0.62	0.43	0.68	0.45	0.90	0.65	1.0	0.60
1991 - 2000	Ins., armed concrete	0.29	0.28	0.42	0.35	0.44	0.31	0.49	0.40	0.69	0.55	0.85	0.55
2001 - 2010	Ins., armed concrete	0.21	0.20	0.28	0.30	0.36	0.25	0.35	0.40	0.51	0.45	0.70	0.55

work as well as surveys or informal knowledge transmission. Given the limited available knowledge regarding the existing building stock's physical properties and energy supply situation, the first version (Version 1) of the model was not expected to provide a good match with monitored data, but rather a basis for the definition of more adapted but still realistic default values. The objective of such a crude model is not to obtain precise individual building energy demands, but representative average results.

Regarding the simulation of energy demand, energy consumption studies show that the most influent parameters are the dimensions of the building, its age and its type (allocation) [17], [18]. The dimensions of the buildings are obtained through their footprints and number of floors. The default values are thus attributed based on the buildings' period of construction and type. Sensitivity analyses performed with CitySim, in accordance with [19], show that after dimension-related parameters, the most influent parameters for the simulation of heating loads are the set point temperature, the ventilation rate and the insulation thickness (or more generally the outer surfaces' properties), followed by internal heat gains and climatic conditions.

The closest measured climatic data was obtained through a national database. Swiss norms recommend the use of a heating set point temperature of 21 ˚C for housing and administrative buildings' thermal simulations. This important parameter can vary considerably depending on the occupants preferences, but cannot be refined based on the data available to us. Together with electricity and DHW needs, internal heat gains are estimated based on norms.

As for dimension-related parameters, the simulation uses a 3D flat-roof model based on the cadastral footprint of the buildings and their number of floors. The fractions of façades that are shared between heated buildings are considered to be adiabatic. The DSM and DTM data of Neuchâtel's case study corresponds to an average height of 2.73 m per floor as recorded in the register of building. This value is used to estimate the unknown heights of buildings, while a treated floor area to footprint ratio of 0.8 per floor is assumed. The heated volume is further estimated considering 20 cm thick slabs and 10% of the volume occupied by furnitures.

The ventilation rate and construction properties are more uncertain and will thus be the focus of our analysis. The ventilation rate parameter represents the building's air volume change per hour in usual conditions. It strongly depends on the air-tightness of the envelope, the existence of an HVAC (heating, ventilation and air conditioning) system and the occupants' stochastic behaviour regarding ventilation (window opening to avoid overheating is considered separately in CitySim simulations). Although one of the most influential parameters for the simulation, it is thus one of the least accessible. Studies on the air tightness of buildings present a large range of results, corresponding to infiltration rates ranging from 0.1 to 1 h^{-1} [20]–[22]. We thus chose default values for the ventilation rates based on two considerations: most studies show that the infiltration rate of older buildings is 2 to 4 times higher than that of more recent buildings, and Swiss norms recommend a minimum total ventilation rate of 0.3 h^{-1} for comfort and health purposes. The original default values are shown in the "Version 1" part of Table I (the versions 2 and 3 are discussed further on).

Table II. DEFAULT WINDOW TO WALL RATIO α_{win} [-], WINDOW AREA U-VALUE [W/M^{2}K] AND WINDOW AREA G-VALUE [-], BASED ON THE AVERAGE OBSERVED WINDOWS PROPERTIES. THE VALUES CONCERN THE FULL WINDOW AREA, INCLUDING AN AVERAGE OF 25% OF FRAME.

Period	α_{win}	Version 1		Version 2 & 3	
		U_{win}	g_{win}	U_{win}	g_{win}
Before 2000	0.25	2.3	0.47	2.0	0.5
2000 - 2010	0.35	1.3	0.49	1.7	0.5

Regarding the physical properties of the envelope, the construction default parameters must represent the average state of all buildings of each construction period, as the available data does not include information about past thermal retrofitting of buildings. Further, the unknown existence of non-heated attics or cellars complicates the estimation of their thermal resistance (ground K-value and roof U-value). Nevertheless, a first version of default values was based on typical period-specific construction characteristics determined with the help of experimented local architects, and are also shown in Table I.

Windows ratio, U-value and g-value, estimated based on a visual survey of approximately 500 buildings in Zürich, are shown shown in Table II. The calculated U-value and g-value also depend on the hypotheses made regarding the typical glazing properties.

Considering the supply side, wherever monitored consumptions of gas, fuel oil or district heating are available, gas boilers, fuel oil boilers and heat exchangers respectively are defined in the corresponding buildings. It is assumed that these produce space heating, as well as DHW if the building register announced the same energy carrier for both services. The consumption values are then affected to these systems. This

Table III. DEFAULT ENERGY CONVERSION SYSTEMS EFFICIENCY η.

Technology	Version 1 & 2	Version 3
	η [-]	η [-]
Heat exchanger	0.93	0.97
Gas boiler	0.85	0.79
Oil boiler	0.85	0.77
Electric boiler	0.93	0.93
Wood boiler	0.65	0.65
Heat pump (COP)	3.4	3.1
Electricity meter	1.0	1.0

method showed its limits as numerous buildings of Neuchâtel appear to use gas only for cooking, their consumption being clearly incompatible with either space heating or DHW demands.

The lower confidence data of the building register was used to complete the supply picture with other ECS for both space heating and DHW when information was available for buildings without consumption data. At this point, using maps of the f_2 factor, buildings without monitored data for heating that are semi-detached from buildings with a high consumption value were considered to be heated by the same centralised ECS and thus connected to that ECS. Fuel oil boilers were eventually defined in buildings without any other ECS.

An electricity meter providing electrical services was also defined in each building, and associated with the electricity consumption obtained through the energy provider. The electricity consumption of electrical boilers was assumed to be included in the total monitored electricity consumption.

The technology models used to simulate the ECS are quite simple and use the default efficiencies shown in Table III, based on the Swiss norm SIA 2031 [23]. When two or more ECS are defined to provide the same service, it is supposed that each meets the same share of the demand, except for solar thermal panels that are often sized to provide approximately 65% of the annual DHW demand. These default shares can be adapted during the simulation based on the monitored data.

V. DEFAULT DATA CALIBRATION AND MODEL VERIFICATION

The calibration and verification of the model focused on the housing and administrative buildings, which seem the most predictable building types. Other types of buildings are expected to have more varying energy demands, which are barely correlated to the rough data at our disposal. The limited number of such buildings in our case studies also limits the possibilities to perform statistically relevant analyses.

Each case study model was simulated with the MEU platform, first using the Version 1 default values. This section analyses the results using the f_2 factor. Representing the discrepancy between simulated values and monitored data, it provides insights regarding the default values' adequacy as well as indications on other possible model errors. Two improved default values versions were then defined, simulated and analysed.

A. Version 1 simulations

Most of the least reliable default values concern the space heating demand simulation and are attributed based on the construction period. The logarithmic discrepancy factor f_2 for the heating demand is plotted against those periods in Figure 5 for all housing or administrative buildings of each case study.

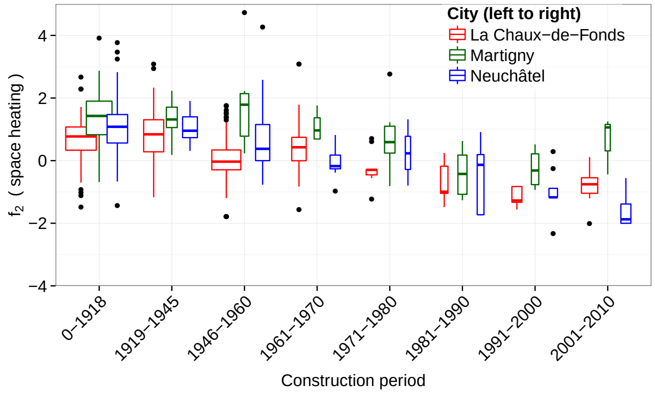


Figure 5. Discrepancy factor of the heating demand as a function of the construction period for the Version 1 simulations. The width of the boxplots is proportional to the square root of the number of observations. Positive f_2 values corresponds to simulated values greater than monitored values, and vice-versa. A zero f_2 value represents a perfect match between simulated and monitored values. Four points outside the range of the graph were ignored. (Colours available online.)

First of all, it must be noted that the largest proportion of buildings in our case studies were built before 1960 (Table IV); the results concerning more recent buildings are less reliable as a result of their limited number. The dispersion of the discrepancy factor is quite high, with a few buildings for which the simulated value was more than 4 times smaller or 16 times greater than the monitored value. However, the interquartile range is between 1 and 2 units of the f_2 factor's scale, which corresponds to ratios of 1:2 to 1:4.

More interesting at this stage is the average value of the f_2 factor, showing that our model globally overestimated the space heating demand of older buildings and underestimated that of more recent constructions. In other words, the thermal efficiency of old buildings was underestimated, while that of recent buildings was overestimated. Surprisingly, the energy use per square meter for heating, represented in Figure 12 and discussed later in Section VI, does not evidence a decrease of the energy consumption with time, except for buildings built after 2000. This goes against our first choice of default values, which supposed a decreasing thermal efficiency for old buildings.

In the case of Mrt, either the heating demand was even more generally overestimated, or the monitored consumption values used for the comparison are too low, which would be coherent with the existence of a non-negligible number of unmodeled wood stoves, the consumption of which could not be taken into account.

B. Version 2 simulations

Based on the previous observations, a second set of default values (Version 2) was defined. The life-time of windows being considerably lower than that of buildings, it was estimated that

Table IV. NUMBER OF BUILDINGS OF HOUSING OR ADMINISTRATIVE TYPE WITH MONITORED HEATING CONSUMPTION. "ALL" GIVES THE TOTAL NUMBER OF BUILDINGS OF HOUSING OR ADMINISTRATIVE TYPE.

Period	CdF	Nch	Mrt
Before 1918	102	47	72
1919 - 1945	44	24	13
1946 - 1960	92	22	8
1961 - 1970	23	12	4
1971 - 1980	13	3	12
1981 - 1990	6	4	9
1991 - 2000	11	8	6
2001 - 2010	29	11	3
Total	320	131	127
All	411	338	155

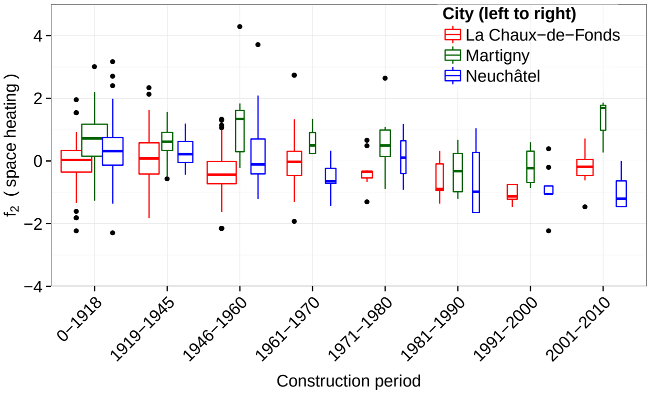


Figure 6. Discrepancy factor of the heating demand as a function of the construction period for the Version 2 simulations. Four points outside the range of the graph were ignored.

the quality of glazing and frame materials was more uniform than previously estimated (Table II). The overall quality of the envelope was revised, based on the hypothesis that the simplest insulation measures for old buildings, and thus the most likely to be widespread, concern primarily the roof and ground. The ventilation rate of old buildings was also reduced, keeping in mind the following remarks:

- To our knowledge, no study regarding air-tightness or ventilation rates of Swiss buildings is available.
- Measurements usually concern the air-tightness of the envelope; the estimation of an average ventilation rate based on those measurements still involves numerous hypotheses (among other regarding wind conditions) that were not taken into account in this work.
- For very leaky buildings, improving the air tightness is possibly easier to accomplish than other energy-efficiency measures.

Conversely, the overall quality of more recent buildings was slightly reduced, among other by diminishing the estimated insulation thickness.

The results of the second simulation, shown in Figure 6, slightly improved the match between simulated and monitored values, but the trends observed in the first simulation remain.

At this point, the correlation between the discrepancy factor and the technology used for heating was also investigated, but no significant trend could be observed (Figure 7). Nevertheless, and although information regarding the average efficiency of existing energy conversion systems is very scarce, the default efficiencies of the heat exchangers, oil boilers and gas boilers were modified the Version 3 to better represent the average quality of installed ECS. Regarding the DHN, according to a local specialist heat exchanger efficiencies are currently of the order of 99%. This value was only slightly decreased to 97% to account for heat losses after the heat exchanger. Losses occurring during heat production and in the distribution network are considered elsewhere, i.e., at the corresponding nodes in the graph model, and were also set according to the local energy provider's data. By contrast, the original hypotheses regarding gas and oil boilers efficiencies were probably too optimistic, as they correspond to values given by the norm [23] for correctly sized condensing boilers. Regarding conventional boilers, the norm proposes an annual efficiency of 80%, and less in case of bad sizing. An official document regarding the sizing of boilers also mentions typical annual efficiencies of 70 to 85% [24]. Globally, the overall space heat production efficiency in Switzerland is estimated at 78% by [25]. Moreover, the efficiencies are traditionally computed based on the lower calorific value of the substance in Europe [26] (the convention used by the documents cited above is unspecified), while the efficiencies considered in our simulation refer to the higher calorific value. Finally, the efficiencies used in two large scale studies of Swiss energy consumption [27] [28], once converted to refer to the higher calorific value based on [29], are reproduced in Table V. Based on these observations, the default efficiencies of the main technologies were adapted in the third version to the values presented in Table III.

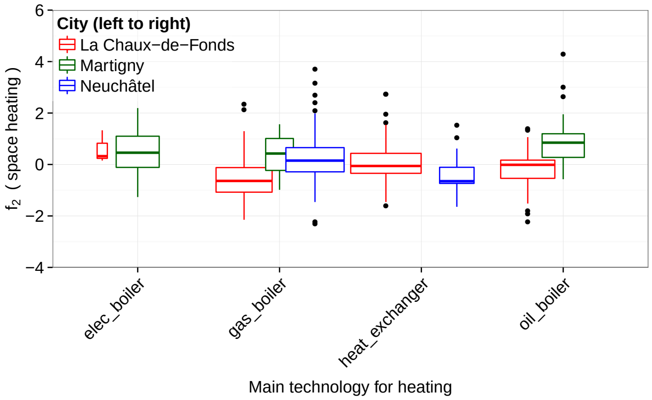


Figure 7. Discrepancy factor of the heating demand for the Version 2 simulations, per technology used for space heating. Four points outside the range of the graph were ignored.

Table V. AVERAGE ANNUAL EFFICIENCIES OF HEAT PRODUCTION FOR EXISTING PLANTS IN 2005 ACCORDING TO TWO STUDIES REGARDING THE SWISS BUILDING STOCK.

Technology	[27]	[28]
Gas	0.79	0.79
Fuel oil	0.77	0.77
Wood	0.64	0.64
Heat pump (COP)	3.3	2.7

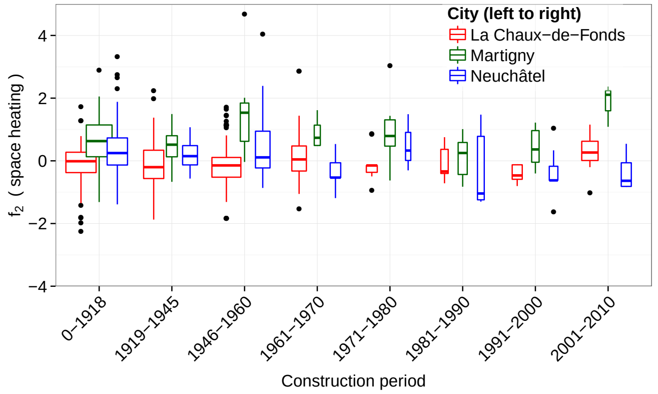


Figure 8. Discrepancy factor of the heating demand as a function of the construction period for the version 3 simulations. Four points outside the range of the graph were ignored.

C. *Version 3 simulations*

In addition to the ECS efficiencies modifications, the default properties of buildings were also adapted again, with the overall same hypotheses as before regarding pre-1960 constructions. For more recent constructions, the envelope's quality was lowered again, but most importantly the ventilation rate was substantially increased. We thus make the hypothesis that the usual ventilation habits clearly exceed the minimal recommended ventilation rate of 0.3 h^{-1}.

The simulation of all case studies with the third version of default values leads to the discrepancy factor for space heating showed in Figure 8. This third version intends to represent the most equilibrate hypotheses that can be made regarding the unknown parameters of our simulation, based on the available information and monitored data. A more refined calibration of the model for buildings built after 1960 would require a larger number of buildings to be relevant.

With this better calibrated space heating energy demand simulation, the f_2 factors for the DHW and electricity demands were also investigated. Both energy demands are estimated based on the building type; Figure 9 shows the f_2 factor per type for all services. The average electricity and DHW consumption of housing and administrative buildings was quite well estimated by the simulation based on norms, while other building types show, as expected, much less predictable trends.

VI. DISCUSSION

Considering the case studies of CdF and Nch only, half of the housing and administrative buildings' f_2 value for space heating is comprised in the interval (-0.40, 0.43), meaning that the simulated heating demand of half the buildings was comprised between 76% and 132% of the monitored values. This can be considered as a good result for such a crude model, although the results for individual buildings cannot be trusted. The quality of the results for DHW is similar, while the interquartile range for electricity is (-0.30, 0.45). The simulation of other building types is much less reliable, and the results of the case study of Martigny remain uncertain.

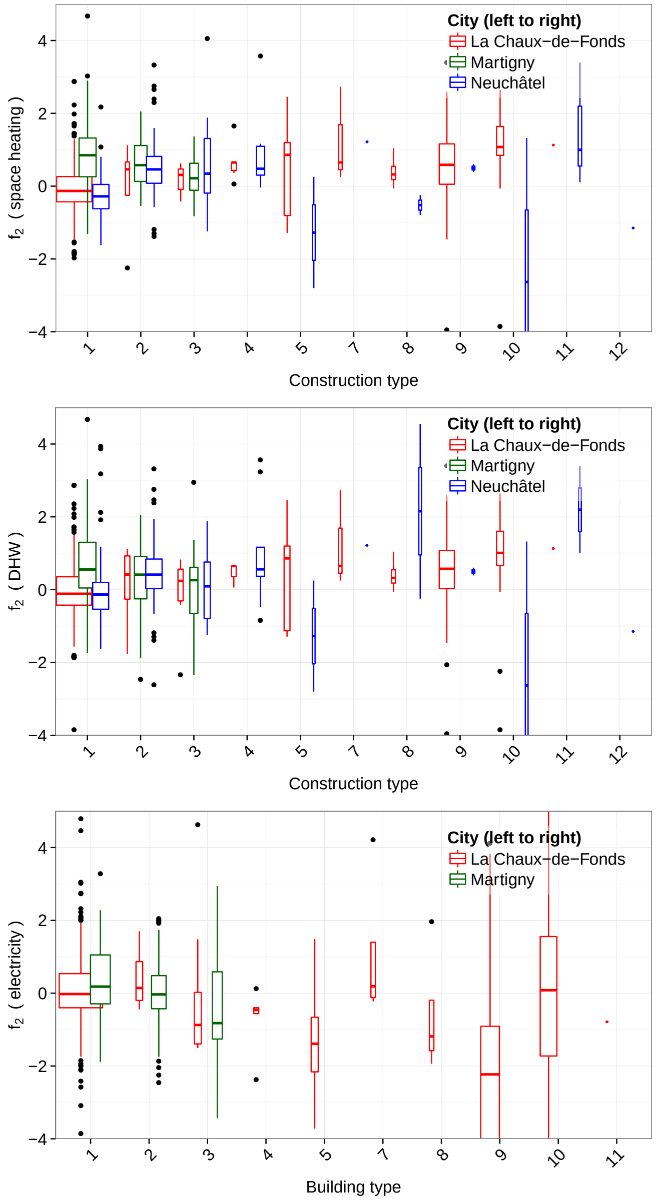


Figure 9. Discrepancy factor for the space heating, DHW and electricity services demands as a function of the building type in the version 3 simulations. Space heating and DHW show similar f_2 trends, as both are provided by the same ECS in most buildings. Allocation types: 1 apartment building, 2 individual home, 3 administrative, 4 schools, 5 sales, 6 catering, 7 meeting venues, 8 hospital, 9 industries, 10 warehouses, 11 sports installations, 12 indoor swimming pool.

The origin of the remaining discrepancies are numerous, but difficult to take into account. The space heating demand of individual homes is slightly overestimated when compared to apartment buildings, although the available data is not conclusive. Otherwise, the f_2 factor did not exhibit any significant correlation with the other available parameters that were tested (treated floor area, form factor, number of floors).

Among the inaccessible factors, the stochastic influence of occupants behaviour is known to be of high importance, practically limiting the precision of the results even with a very well calibrated physical model. However, numerous other sources of imprecision are known, in particular regarding space heating demand simulation:

- Many uncertainties regarding the correct attribution of monitored data remain. Visual representations of the f_2 factor help to spot likely errors, but more information is often needed to resolve them. For instance, adjacent buildings with high and opposed f_2 factor hints for a shared use of the energy consumption, but this often cannot be confirmed without on-site surveys.
- The existence of other ECS such as solar thermal panels and wood stoves is usually not documented and could not be assessed for this study. Aerial photography might prove to be a valuable source for the localisation of solar technologies, whereas the location of other technologies might remain very hard to assess without extensive surveys.
- The cadastral footprint of buildings used for the creation of the 3D model does not always represent the simulation relevant part of the building: some have been found to include adjacent garages, while buildings with a complex shape are simplified to the point where the 3D model and treated floor area estimation might not have any relevance at all. The use of the correct roof shape (instead of the simplified flat-roof model currently used) could also improve the simulation results' quality.
- The unknown refurbishment status of buildings is likely to account for an important part of the dispersion of the f_2 factor for all but the most recent buildings.
- Construction techniques are quite variable even for the same period, and further might depend on the region, although the difference between the three case studies simulated here with the same default values are not conclusive in this regard. The case study of Mrt, where a better thermal efficiency of buildings could be hypothesised based on the f_2 factor, is actually supposed to be a quite low energy efficiency neighbourhood.

Any attempt to further improve the calibration of the model without first addressing these uncertainties would not be pertinent. However, as the creation of models at this urban scale is likely to often suffer of the same limitations, it is interesting to document the precision of such models. The results obtained for buildings with monitored energy consumption also help to evaluate the reliability of the simulation on other buildings.

The simulated and adapted total space heating demands are shown in Figure 10, confirming for the case study of Mrt that either the space heating demand is overestimated, or the related consumption is underestimated. CdF and Nch total space heating demands are underestimated by 15.5% and 10.4%, although their average f_2 factors correspond respectively to a 5% underestimation and a 13% overestimation. Figure 11 shows that the highest space heating demands are indeed most frequently underestimated, and have an order of magnitude close to the difference between the total simulated and monitored values. Unlike regular statistical variations, the unpredictable demands of a few big energy consumers can thus have a strong impact on the overall results.

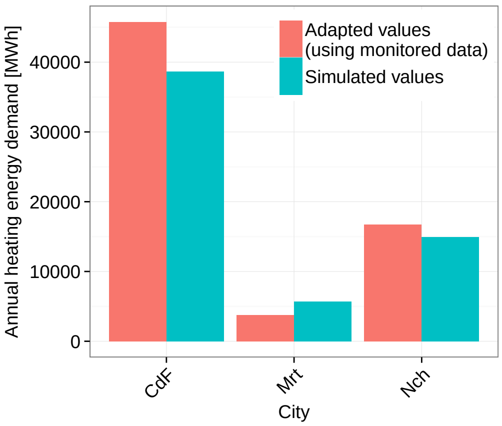


Figure 10. Annual space heating demand for housing and administrative buildings with monitored consumption.

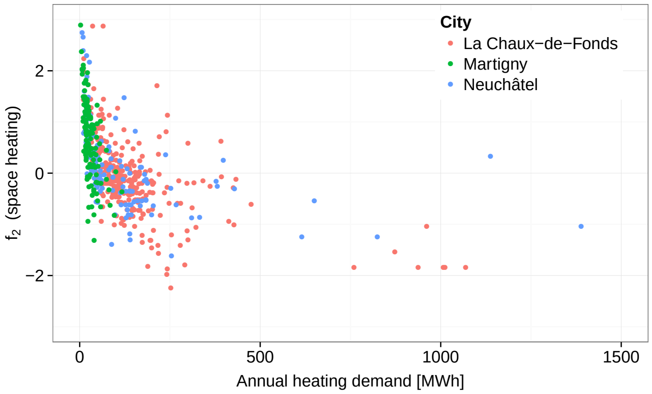


Figure 11. Correlation of the f_2 factor with the heating demand, as adapted based on monitored values. Four points with annual heating demand lower than 100 MWh and $f_2 > 3$ are outside the range of the graph.

Plotting the final energy use for heating versus the construction period of the buildings (Figure 12) does not reveals a clear decrease with time, except for the most recent buildings (built after 2000). All case studies present more or less the same trend, with only a marginal number of old buildings showing a clearly higher energy consumption for heating. The three partner cities have been promoting energy efficiency for some time and have all obtained labels in this domain [30]; nevertheless, Martigny's case study zone in particular is considered to have quite a low energy efficiency. On the other hand, the small number of recent buildings and possible errors in their modelling might have created a bias, which would require a broader study to be correctly explored.

VII. CONCLUSION AND FUTURE WORK

The calibration and verification work presented in this paper improved and assessed the quality of the urban energy flow

Figure 12. Final energy consumption for heating, per year and per square meter, for housing and administrative buildings with monitored consumption, as a function of the construction period.

simulation performed by the MEU platform. The platform intends to provide a flexible tool for the energy management at the scale of a neighbourhood, based on the limited available data sources and providing default values to supplement their low level of detail. The platform's combined management of simulation results and monitored data proved to be a powerful tool both to improve the model's quality and to perform verification studies.

The validity of the results at the scale of individual buildings was explored in detail, focusing on the housing and administrative buildings. The correct simulation of average buildings was demonstrated, while individual results remain, as expected, less reliable. The remaining discrepancies between simulated and monitored values can be attributed to the influence of the stochastic behaviour of occupants, but also to the limitations of the model regarding, among others, the attribution of monitored values, the unknown refurbishment status, the possible existence of other ECS, and the crude 3D model used for the simulation. Nevertheless, this study's results will already help improve the platform's reliability.

The aggregated results at the scale of a few hundred buildings shows that the total space heating demand is underestimated by 10% to 16% by the simulation for the two reliable case studies. This result highlights that a better match at the level of individual buildings does not necessarily yield a correct aggregated value, as some unpredictable high energy consumers can have an important impact. The possibility to simulate other buildings types with a satisfactory accuracy based on similarly low level-of-detail data remains to explore.

The research of realistic default values leads to new hypotheses regarding what can be considered as standard ventilation rates or as typical construction properties, but the lack of knowledge in this area makes the verification of those hypotheses difficult. A large scale but detailed assessment of existing buildings' physical properties would thus be a contribution of great value for the simulation of buildings' energy demand and for studies regarding the potential of energy-efficiency measures.

Finally, this study also evidenced interesting results regarding the energy use of our three case study areas. The most surprising observation is the low difference in energy consumption for space heating among buildings built before 2000. Note however that the individual renovation status of buildings is not known, and thus the role of recent refurbishments cannot be assessed. An analysis on a larger number of buildings built after 1960 would also be necessary to confirm the trends observed here.

ACKNOWLEDGMENT

The authors would like to thank the Swiss Federal Office of Energy (project number 102775) and all funders and partners of the MEU project, for providing most of the data used in this project, and for their help and availability to control the models and discuss the simulation results.

REFERENCES

[1] D. Perez, C. Vautey, and J. Kämpf, "Urban energy flow microsimulation in a heating dominated continental climate," in *Proceedings of SIMUL 2012, The Fourth International Conference on Advances in System Simulation*, 2012, pp. 18–23.

[2] L. Swan and V. Ugursal, "Modeling of end-use energy consumption in the residential sector: A review of modeling techniques," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 1819–1835, 2009.

[3] J. Keirstead, M. Jennings, and A. Sivakumar, "A review of urban energy system models: Approaches, challenges and opportunities," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6, pp. 3847–3866, 2012.

[4] L. Shorrock and J. Dunster, "The physically-based model BREHOMES and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock," *Energy Policy*, vol. 25, no. 12, pp. 1027–1037, 1997.

[5] J. Snäkin, "An engineering model for heating energy and emission assessment – The case of North Karelia, Finland," *Applied Energy*, vol. 67, no. 4, pp. 353–381, 2000.

[6] A. Egan, "Three case studies using building simulation to predict energy performance of australian office buildings," in *Proceedings of the eleventh international IBPSA conference, Glasgowleventh International IBPSA Conference*, 2009, pp. 896–903.

[7] Y. Shimoda, T. Fujii, T. Morikawa, and M. Mizuno, "Residential end-use energy simulation at city scale," *Building and environment*, vol. 39, no. 8, pp. 959–967, 2004.

[8] D. Robinson, F. Haldi, J. Kämpf, P. Leroux, D. Perez, A. Rasheed, and U. Wilke, "CitySim: Comprehensive micro-simulation of resource flows for sustainable urban planning," in *Proceedings of Building Simulation*, 2009.

[9] A. Strzalka, J. Bogdahn, V. Coors, and U. Eicker, "3D City modeling for urban scale heating energy demand forecasting," *HVAC&R Research*, vol. 17, no. 4, pp. 526–539, 2011.

[10] D. Perez and D. Robinson, "Urban energy flow modelling: A data-aware approach," *Digital Urban Modeling and Simulation*, pp. 200–220, 2012.

[11] EcoInvent, "EcoInvent Center, Swiss Center for Life Cycle Inventories," http://www.ecoinvent.ch, last checked : 03.12.2013, 2013.

[12] Société suisse des ingénieurs et des architectes, "Swiss norm 380/1 : L'énergie thermique dans le bâtiment," SIA Zurich, 2009.

[13] P.-A. Haldi and D. Favrat, "Methodological aspects of the definition of a 2kW society," *Energy*, vol. 31, no. 15, pp. 3159–3170, 2006.

[14] D. Robinson, A. Rasheed, J. H. Kämpf, M. Bruse, K. Axhausen, F. Flourentzou, M. Batty, F. Haldi, and D. Perez, *Computer Modelling for Sustainable Urban Design: Physical Principles, Methods and Applications*, D. Robinson, Ed. Routledge, 2011.

[15] S. Coccolo, J. H. Kaempf, and J.-L. Scartezzini, “Design in the desert. A Bioclimatic project with urban energy modelling,” in *Proceedings of Building Simulation 2013: 13th Conference of the International Building Performance Simulation Association*, France, 25-30 August 2013.

[16] A. Cifuentes Cuéllar, “Simulation urbaine d’un quartier de logement social à Bogotá, Colombie (Master thesis),” EPFL, Solar Energy and Building Physics Laboratory, 2012.

[17] T. Olofsson, S. Andersson, and J.-U. Sjögren, “Building energy parameter investigations based on multivariate analysis,” *Energy and Buildings*, vol. 41, no. 1, pp. 71–80, 2009.

[18] L. Perez-Lombard, J. Ortiz, and C. Pout, “A review on buildings energy consumption information,” *Energy and Buildings*, vol. 40, no. 3, pp. 394–398, 2008.

[19] D. G. Sanchez, B. Lacarrière, M. Musy, and B. Bourges, “Application of sensitivity analysis in building energy simulations: Combining first- and second-order elementary effects methods,” *Energy and Buildings*, 2012.

[20] F. d’Ambrosio Alfano, M. Dell’Isola, G. Ficco, and F. Tassini, “Experimental analysis of air tightness in mediterranean buildings using the fan pressurization method,” *Building and Environment*, vol. 53, pp. 16 – 25, 2012.

[21] W. R. Chan, W. W. Nazaroff, P. N. Price, M. D. Sohn, and A. J. Gadgil, “Analyzing a database of residential air leakage in the united states,” *Atmospheric Environment*, vol. 39, no. 19, pp. 3445–3455, 2005.

[22] A. Parekh and P. Eng, “Development of archetypes of building characteristics libraries for simplified energy use evaluation of houses,” in *Proceedings of the 9th International IBPSA conference*, 2005, pp. 921–928.

[23] Société suisse des ingénieurs et des architectes, “Swiss norm 2031 : Certificat énergétique des bâtiments,” SIA Zurich, 2009.

[24] SuisseEnergie, “Dimensionnement des chaudières à mazout et à gaz,” Swiss Federal Office of Energy, 2000.

[25] E. Jochem, G. Andersson, D. Favrat, H. Gutscher, K. Hungerbühler, R. von Rohr, D. Spreng, A. Wokaun, and M. Zimmermann, *Steps Towards a Sustainable Development: A White Book for R & D of Energy Efficient Technologies*. Novatlantis, 2004.

[26] Université catholique de Louvain (Belgique), Département de l’Énergie et du Bâtiment Durable., “Energie+ version 7,” http://www.energieplus-lesite.be/index.php?id=10396, last checked 27.03.2013, 2013.

[27] P. Hofer, “Der energieverbrauch der privaten haushalte, 1990-2035: Ergebnisse der szenarien i bis iv und der zugehörigen sensitivitäten bip hoch, preise hoch und klima wärmer,” Swiss Federal Office of Energy SFOE, Tech. Rep., 2006.

[28] H. Wallbaum, N. Heeren, M. Jakob, M. Gabathuler, N. Gross, and G. Martius, “Gebäudeparkmodell sia effizienzpfad energie dienstleistungs-und wohngebäude-vorstudie zum gebäudeparkmodell schweiz–grundlagen zur überarbeitung des sia effizienzpfades energie,” Swiss Federal Office of Energy SFOE, Tech. Rep., 2009.

[29] R. Frischknecht, M. Stucki, K. Flury, R. Itten, and M. Tuchschmid, “Primärenergiefaktoren von energiesystemen,” ESU-Services GmbH, fair consulting in sustainability, Uster, 2008.

[30] G. Cherix, M. Finger, M. Capezzali, H. B. Püttgen, A. Chapuis, and A. Nour, “Action and influence of the multiple decision levels over the whole energy chain,” in *Proceedings of the 5th Dubrovnik Conference on sustainable development of energy, water and environment systems*, Dubrovnik, 2009.