Urban Energy Flow Microsimulation in a Heating Dominated Continental Climate

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***Abstract*—A new energy management platform has been developed and tested on a 600 building urban zone of the Swiss city of la Chaux-de-Fonds. This simulation framework for energy-efficient systems simulates the buildings' energy demand, infers the production of the energy systems connected and simulate the complete supply and demand side energy flow picture. The platform is designed to use measured consumption data if available, and intended to produce correct estimates of the average energy demands of housing and administrative buildings if not available. This article discusses the first results obtained for the buildings' heating demands and their comparison with measured values. Two examples of energy efficiency scenarios are also presented. They show that the energy savings associated with building insulation can reach more than 12% of the total energy consumption in buildings in the zone studied.**

Keywords- energy flow simulation; simulation and measurement comparison; urban simulation; heating demand simulation; energy demand and supply.

I. INTRODUCTION

Despite the raising awareness of the problems linked to the widely unsustainable modern energy use, much improvement is still needed to reduce the resource consumption. Buildings in urban zones can be accounted for a large part of the energy use (20% to 40% of the total final energy consumption in developed countries according to [1]), and the urban population is increasing. It is thus a domain of interest for research to propose innovative energy efficiency measures and energy management tools.

Amongst the large amount 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] [5], 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 supply sides [6]. The advantage of this simulation approach is that it allows for the test of scenarios of various detail level, covering in a large part the options available to local politicians and energy departments

As discussed in [7], the amount of data involved in this kind of study, as well as its quality and longevity become important concerns. However, few publications in this domain intend to tackle this problem. The MEU platform presented in this study was developed while keeping 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 answering some of the data concerns related to this domain.

Section II gives an overview of the structure and simulation method of the MEU platform. Section III describes the model of the case-study neighbourhood, the default values and the origin of the data used. Section IV presents the results, first of the comparison between simulated and measured values, then about two energy efficient scenarios that were studied. Finally, Section V provides a concise conclusion of this paper.

II. THE MEU PLATFORM

The MEU platform models the urban energy flow as an oriented graph, with (currently) the following rules: *source* nodes (in a broad sense) are linked to *energy system* nodes or *network* nodes. The network nodes themselves are linked to other network nodes or energy system nodes, the energy system nodes in turn linked to other energy system nodes or *building* nodes, seen as energy sink nodes. Measured energy consumption can be associated to any energy system node as its input flow. Energy demands for heating, hot water, electricity and cooling services are associated to each building node. An arbitrary number of connections link each of these demands with the energy system 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: it can be natural gas as well as 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. Network nodes are mainly characterised by a loss factor, whereas energy system nodes refer to a dedicated simulation model including any number of modifiable parameters. Building nodes include data about their address, location (footprint), allocation and a physical model used for the estimation of their heating and cooling demand with the simulation program CitySim presented below. Their

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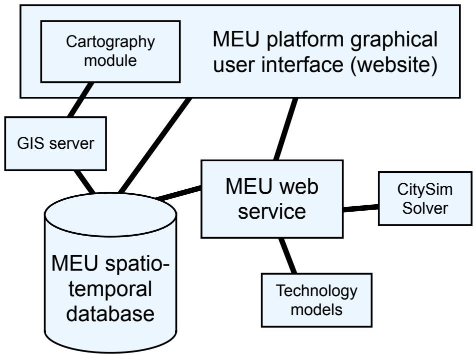

Figure 2. Web-based structure of the MEU platform

electricity and hot water needs are estimated using Swiss norms [8], based on their allocation and treated floor area.

A GIS-based web interface provides access and editing functionalities to the model through a map representation (Figure 1). The data is stored in a spatio-temporal PostgreSQL (opensource) database and can also be accessed directly. The simulation process takes the form of a dedicated web service. It includes calls to a CitySim web service for the estimation of energy demands, and to a technology model web service that simulates the production of an energy system based on its consumption or vice-versa (Figure 2). These are combined in a simulation process consisting in:

- Estimating the whole annual energy flows based on the simulated demands;
- Scaling this first estimate to match the measured consumption values available, saving both original and scaled values for later analyses.

A. *CitySim*

The urban energy use simulator CitySim [9] was developed at EPFL based on multiple physical models coupled together. 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 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 determinates the thermal exchange through buildings' envelopes and computes the heating and cooling energy needs to maintain predefined temperature conditions inside. Finally, energy systems 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 include 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, the proportions of window and the physical properties of the glazing), as well as the infiltration rate and, when possible, the presence of occupants.

CitySim is used in the MEU platform to compute heating and cooling demands only. It was transformed for this purpose into a web service, called by the central MEU web service. The MEU web service prepares a simple input model based on the data available in the database and save the results simulated by the CitySim web service.

III. Model

The input model used in this study is composed of both real data and default values, which are presented here.

A. *Data sources*

The chosen neighbourhood is located in la Chaux-de-Fonds in Switzerland (alt. 1000m), a UNESCO World Heritage Site for its watchmaking industry-driven urbanism mixing housing and workshop at the heart of the city. The model created for this project is based on cadastral data defining buildings' footprints. The footprints are combined with data from the national building register including the address, period of construction, allocation if housing, number of floors and optionally space heating and hot water supply systems. These were completed with a large amount of default data to form the physical model of the building (see Section III-B).

The energy consumption data of gas and heat from the district heating network (DHN) were supplied by the local energy provider for the years 2009, 2010 and 2011. Part of the fuel oil (supplied by various unknown companies) consumption values were provided by the city, based on contacts with building owners. Where measured consumptions of gas, fuel oil or district heating were available respectively gas boilers, fuel oil boilers and heat exchangers were defined in the corresponding buildings. It was assumed that these produce space heating, as well as hot water if the building register announced the same energy carrier for both services. The consumption values were then affected to these systems.

The lower confidence data of the building register was used to complete the supply picture with electrical boilers for domestic hot water in the buildings with measured consumptions but where the register announced electricity as the energy carrier for the production of domestic hot water. The register was also used to create other energy systems for both space heating and domestic hot water when information was available for buildings without consumption data. At this point, buildings without energy system for heating that are semi-detached from buildings with a high consumption value were considered to be heated by the same centralised energy system and thus connected to that energy system. Fuel oil boilers were eventually defined in buildings without

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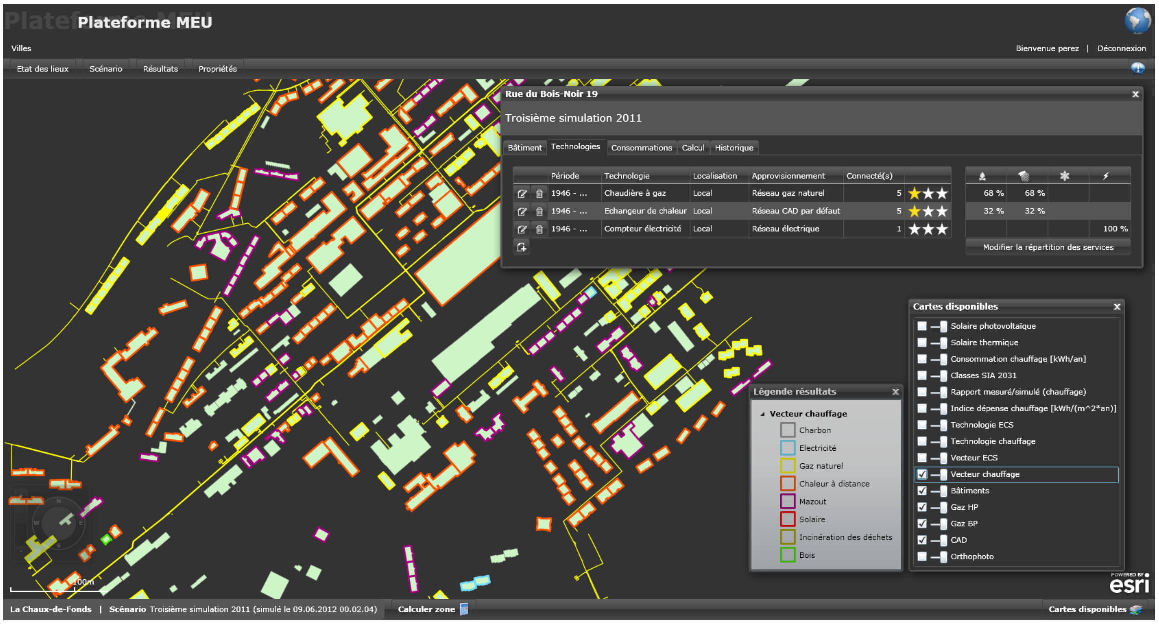

Figure 1. The web interface of the MEU platform, here showing the main energy carrier used for heating in each building and the possibility to define any number of energy systems to provide the energy services.

any other energy system. 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 electricity consumption measure.

The model is completed with measured local meteorological data for the years 2009, 2010 and 2011, which are used for the CitySim simulation.

B. Default data

As mentioned above, in order to obtain a microsimulation model at this scale of a few hundred buildings, numerous default values where used. The objective of this first crude model is, therefore, not to obtain precise individual building energy demands, but statistically adequate results.

Most of the default physical parameters used for the buildings, shown in Table I, are independent of construction period or allocation, which is an admittedly rough hypothesis. However, the default wall types (Table II) are attributed based on the construction period, and the set point temperature depends on the building's allocation (Table III).

The technology models used for the energy systems are crude; the wood, gas, oil and electrical boilers have an efficiency of respectively 0.65, 0.85, 0.85 and 0.93. The electricity meters have an efficiency of 1 and the heat exchangers of 0.93. The heat pumps have a fixed COP of 3.4.

When two or more energy systems are defined to provide the same service, it is supposed that each meets the same share of the demand, an hypothesis that can be adapted during the simulation based on the measured data.

Facades' windows ratio	0.3
Windows U-value [W/m^{2}K]	1.4
Windows g-value	0.7
Windows openable ratio	0.5
Ground K-value [W/m^{2}K]	3
Roof U-value [W/m^{2}K]	0.3
Short wave reflectance of surfaces	0.4
Infiltration rate [h^{-1}]	0.4

Table I
DEFAULT PHYSICAL PROPERTIES OF THE BUILDINGS

Period	Description	U value [W/m^{2}K]
Before 1945	Rough-stone wall	1.64
Before 1945*	+ inner insulation	0.19
1946 - 1960	Rough-stone, air gap and brick	1.46
1946 - 1960*	+ gap and outer insulation	0.19
1961 - 1970	Double brick wall with air gap	1.14
1961 - 1970*	+ gap and outer insulation	0.19
1971 - 1980	Concrete, ins., reinforced concrete	0.57
1971 - 1980*	+ outer insulation	0.20
1981 - 1990	Insulation and armed concrete	0.42
1991 - 2000	Insulation and armed concrete	0.29
2001 - 2010	Insulation and armed concrete	0.21
1981 - 2010*	+ more outer insulation	0.19

Table II
DEFAULT WALL TYPES, DESCRIBED OUTSIDE TO INSIDE, AND THE INSULATED VERSION (WITH A STAR) USED FOR THE REFURBISHMENT SCENARIO

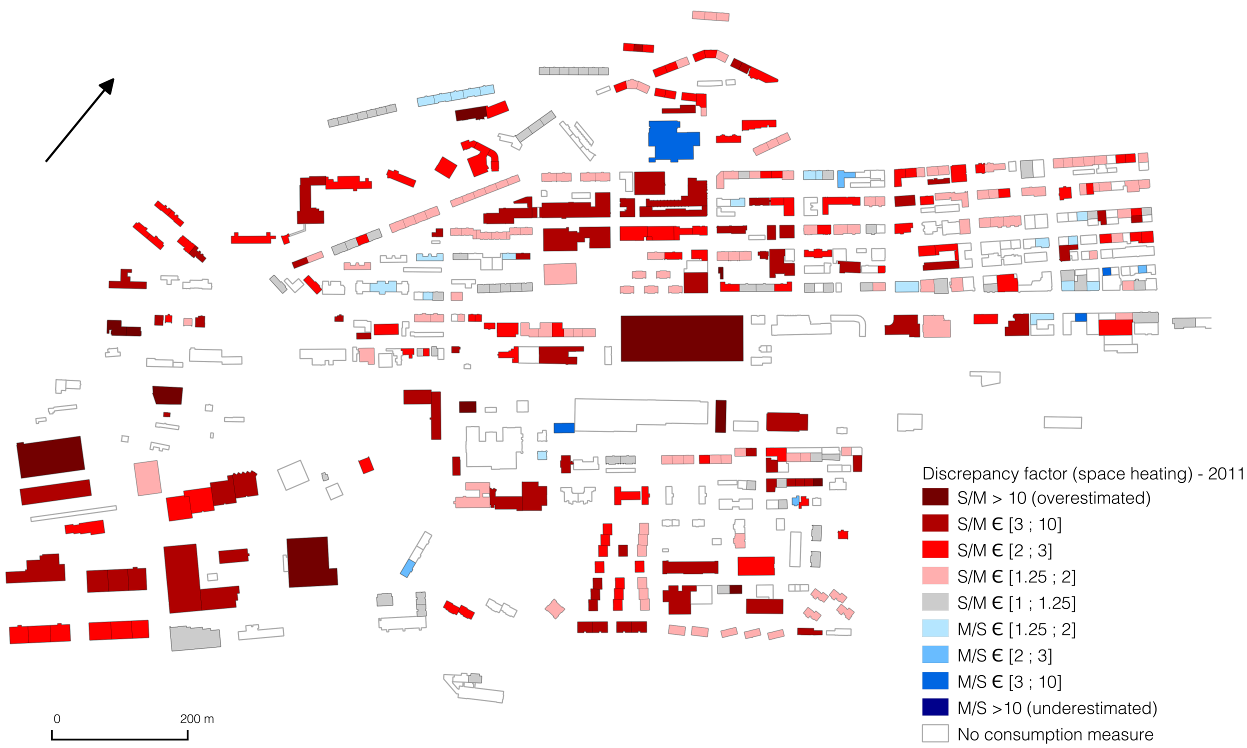

Figure 3. Discrepancy factor for the base case simulation. The ratio is defined with M for the measure and S for the simulated value in order to differentiate over- and underestimation.

Category	Electricity need MJ/(m^2·an)	Hot water need MJ/(m^2·an)	T min set point °C
apartment building	100	75	21
individual home	80	50	21
administrative	80	25	21
schools	40	25	21
sales	120	25	21
restauration	120	200	21
meeting venues	60	50	21
hospitals	100	100	23
industrie	60	25	18
stores	20	5	18
sports installations	20	300	18
indoor swimming pools	200	300	28

Table III
ALLOCATION-DEPENDENT DEFAULT VALUES

IV. RESULTS

The results cover two topics. First, a comparison of the simulated and measured values was performed. The second part of this section presents the results of two energy-efficiency scenarios.

A. Comparison between simulated and measured values

The first results confirmed that the approach described above could correctly represent urban energy flow. The scene includes several cases of centralised energy systems providing space heating and / or hot water 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 DHN during heavy load periods), and electricity meters providing both the electricity demand and an electrical boiler, which were correctly simulated.

The map-based representation of the discrepancy between the measured and simulated values allowed for simplified error location and efficient corrections of the model. As the discrepancies might originate from a wrong allocation of the measured consumption as well as from the simulated model itself, a symmetric discrepancy factor $D = \max(\frac{\text{measured value}}{\text{simulated value}}, \frac{\text{simulated value}}{\text{measured value}})$ was used, with values close to one representing a good match. The discrepancy factor over the scene after the correction of the obvious error is shown in Figure 3.

We observe a global over estimation of the buildings' heating demand, with a median discrepancy factor of 2. The most important sources for this difference are probably the following :

- The internal gains have not been considered in the model for now, which definitely results in an over

estimation of the demand for heating, although possibly not of that magnitude.
- The numerous default values used for the physical properties of the model might not be appropriate. Once the internal gains are accounted for, it will be possible to test for better adapted default values.
- Some of the measured consumption interpreted as covering hot water as well as space heating might actually correspond only to space heating. As the details about the energy systems installed in the buildings is not known and cannot be obtained without a large survey, this was defined with several assumptions.
- Finally, the default value approach adopted here is not expected to produce very close results for buildings which are not of housing or administrative allocation. The processes taking place in other allocation buildings are too various to be represented with this method, and the platform is intended to be used with real consumption data for these buildings. The discrepancy is also slightly better when excluding these "non-standard" buildings: the median of the discrepancy factor is at 1.8 over the housing and administrative allocation buildings.

The inclusion of internal gains in the simulation and the improvement of the default values used are thus high priority developments for the future.

B. Energy efficiency scenarios

Using the global energy flow picture discussed above, two energy efficiency scenarios where studied. The base case simulation results are known to be of limited quality; however the relative results of two simulations remain valid. The energy flow have been scaled to match the consumption measurements, and this scaling of the simulation results is used to study first scenarios presented here. The future improvements of the model will evidently improve the quality of the scenarios' results as well.

1) Refurbishment of high consumption building on the DHN: A known intention of the energy providers in la Chaux-de-Fonds and more generally in Switzerland, is to make the DHN denser. The objectives are to increase their efficiency as well as their profitability, while adapting to the decrease of heat demand following the recently prevailing refurbishment policies.

The MEU platform provides a map of the density of final energy used for each service (Figure 4), which allowed to easily spot a high consumption block of 5 buildings (over 400 kWh/m^2 per year). As the heating demand of these buildings was originally underestimated by the platform, the model was adapted for the base case to represent better the low quality of the envelope. The window U-value was set to 3 [W/m^{2}K], the roof U-value to 0.3 [W/m^{2}K] and the infiltration rate to 1.5, leading to a discrepancy factor lower than 1.25. In the scenario, the building was refurbished under

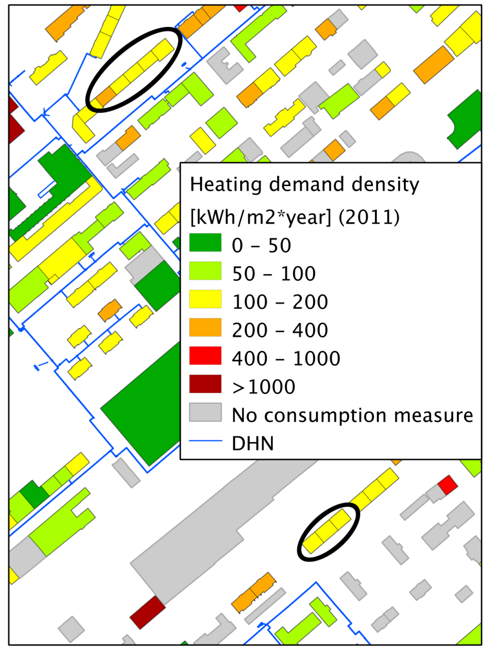

Figure 4. Heating energy use density and buildings that could be connected to the DHN with the energy saving of the first scenario

the swiss standard Minergie so that the average U-value of the envelope approaches 0.2 [W/m^{2}K] :
- The wall type was changed for the insulated version of 1946-1960 (see Table II).
- The window U-value was set to 1 [W/m^{2}K].
- The roof U-value was set to 0.2 [W/m^{2}K].

Applying the same discrepancy factor to scale the simulation results, the scenario leads to a 3.6 GWh decrease of the heating demand, or 65% of the original value. These buildings happen to be heated by the DHN for only 32% of their heat needs (interruptible DHN, completed by a gas boiler). The economy at the DHN level is still of 1.2 GWh per year, which would be sufficient to connect 7 other buildings close to the DHN (shown in Figure 4) and currently heated with oil furnaces.

2) Refurbishment of all buildings in the scene: A second scenario was defined to estimate the possible gains over the whole scene by refurbishing all buildings. The scenario was defined by setting the same window and roof U-values as in the first scenario in every building, and by insulating all facades according to Table II.

This scenario leads to the map of heating energy use density shown in Figure 5, and to an economy of 22.3 GWh of final energy, representing 12.2% of the total final energy used in the scene for the electricity, hot water, space heating and cooling services. All results have been scaled with the discrepancy factor where available. Moreover, the non-inclusion of the internal gains leads to an underestimation of the decrease of heating demand, as these gains become

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Figure 5. Heating energy use density in kWh/m^2 per year for the second scenario, as shown by the platform MEU.

proportionally more important when the buildings are better insulated.

V. Conclusion and Future Work

This first study performed with the MEU platform is first of all a proof of concept. It demonstrates the possibility to simulate demand and supply side urban energy flows at a large scale and on a building basis. This approach opens a wide panel of possibilities for more specific or detailed studies. The first results show that the current limitations of the MEU platform are not structural, but mostly concern shortcomings of the simulation input model. It requires some adjustments regarding the inclusion of internal gains for the heating demand simulation and the improvement of the default values used. Whereas the simulation of energy demands yet need improvements, a possibility to use them together with measured values was demonstrated.

The first scenario illustrates how the energy supply can be quite easily rationalised. The insulation of 5 low performance buildings liberating enough power on the DHN to connect and heat 7 other buildings close to the network and currently heated with oil furnaces. This is combined with an economy of more than 2.4 GWh of gas, the insulated buildings being heated by both gas and DHN.

The second scenario presented provides an estimate of the energy economy possible on a urban zone by insulating the buildings' envelope. It amounts to more than 12% of the final energy used in buildings (not including transportation). This result supports the suitability of policies encouraging energy efficient refurbishment of buildings as part of the general efforts to reduce the global energy consumption.

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