Inverse and forward modeling of New York City public buildings for refurbishment strategies

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Abstract

Useful building performance indicators can be extracted from monthly energy data using inverse modeling approaches such as multiple linear change point models. It is, however, difficult to derive scenarios for strategic retrofit from building monitoring data, which would require a reasonable model description of the building and its technical systems to analyze performance when system components are exchanged or the building envelope is improved. In this work, methods are discussed to simulate building performance of the huge stock of New York public buildings by using 3D CityGML geometry data coupled to monthly energy balance models and calibrate the models using the monitoring data.

Introduction

Cities have a key role in fighting against climate change. The deployment of new intelligent technologies is seen as key factor in decreasing greenhouse gas emissions and improving energy efficiency of cities [Ahvenniemi et al. (2017)]. Commercial and residential buildings in the USA and Europe account for 40 % and 37 % of the total urban energy consumption [Perez-Lombard et al. (2008)], respectively. Therefore, it is necessary that cities are developing strategies to become sustainable. To get a clearer view on their own energy consumption and to derive strategies for demand reduction, many cities, regions and counties have started to initiate energy monitoring programs for their public building stock. Urban energy monitoring was initiated in the 1990s with the Earth Summit 1992 [Marsal-Llacuna et al. (2015)]. Energy monitoring programs are part of the implementation of national legal specifications and can be integrated in the urban land use planning [Ascione et al. (2012)], [Bialk et al. (2010)]. New York City developed the program "One City: Built to Last" in 2014 [NYC (2014b)]. The City of Stuttgart politically adopted its energy concept in January 2016 [StadtStuttgart (2016)]. Both programs have ambitious goals of reducing CO_2 emissions by 80 % until 2050 and contain specific measures for energy savings in public buildings, where the cities have direct control of refurbishment actions

Many cities have adopted sustainable building retrofit programs to strategically address the challenge of refurbishing large numbers of individual buildings. It is necessary to establish baseline consumption to determine the benefits of retrofit actions, detect errors in building operation and to develop strategic scenarios for refurbishment priorities [Ma et al. (2012)]. Available energy data, however, are often highly aggregated with no sub-metering data to distinguish between the different energy sources for cooling, heating, lighting and appliances. Nevertheless useful performance indicators can be extracted from monthly energy data using inverse modeling approaches such as multiple linear change point models [Kissock et al. (2002)]. This includes the determination of base load consumption, air leakages with high ventilation losses, wrong set points or too high volume flows of HVAC systems. Such change-point models allow to analyze building operation pre-/post retrofit and to assess the cost/benefit of the measures carried out.

To derive scenarios for strategic retrofit from building monitoring data requires a reasonable model description of the building and its technical systems. A condition for the building model is a proper description of the building geometry. Using building information modeling (BIM) is often mentioned in this context of sustainability and energy-based retrofitting [Khaddaj and Srour (2016)]. This method shows great potential of analyzing building over the whole lifecycle and is already used in the field of building thermal energy simulation [Bum Kim et al. (2015)]. Detailed building simulation models are useful to analyze the operation and thermal performance of buildings. They can support online fault detection and diagnosis up to model-based control of energy plants and building components. Using BIM for large scale applications on a city or city quarter scale, automated data capturing has to be implemented as well as the updating and maintenance of pre-existing BIM data. When modeling entire urban areas, it seems more appropriate to work with city scale geometry data, which today is often available in the CityGML data format and used in this work.

The calibration process of building models is a huge field in research. There are many efforts on calibrating building models so as to use them for evaluating retrofits on a macro-level. Calibration based on a Bayesian approach can unburden the calibration of normative energy models, because it can be done without deep modeling. But in the current stage, this method relies heavily on the judgement of experts [Heo et al. (2012)]. In order not to be dependent on the judgement of experts, evidence-based methodologies to calibrate whole building-energy models are suitable. Here a source hierarchy for evidences is set. The parameters are only changed, if the source of the new parameter is more reliable. This is a very accurate, but time intensive calibration model. For this kind of calibration at least monthly measured data from the building are required, but hourly measured data would be even better [Raftery et al. (2011)].

A pattern-based automated calibration method was developed to adjust monthly energy balance model parameters. The method allows to correct universal and seasonal biases, i.e. overall under or overestimation of energy demand or seasonal dependence of errors. A rule-based model calibration is then done, for example a universal overestimation of electricity and underestimation of gas consumption suggests that lighting power density is too high [Sun et al. (2016)]. An energy retrofit analysis toolset for such rule based automated calibration was developed for commercial buildings in the US based on EnergyPlus modeling. The main drawback of the method is that there is no automatic EnergyPlus model generation available for every building, so that only a limited number of seven prototype buildings were used for the analysis [Hong and Piette (2015)].

In the approach of our paper, the real geometry of each building is used from the CityGML data and a monthly energy balance model is automatically created using the real surface orientations for solar gain calculations, the real building volumes for ventilation losses and gains etc. The public building stock of New York City retrieved from an urban geometry LOD1 CityGML model is used in this work and first calibration exercises were done on five exemplary buildings.

Energy use intensity comparison

When comparing building energy use intensity worldwide, the indicators must match to make results comparable. As buildings mostly use several types of energy, from electricity to natural gas, oil, or steam to renewable heat from biomass, for a rating such as the US Energy Star consumption has to be expressed in a single common unit. In the US site energy is used to describe heat and electricity consumed in a building, while source energy includes all conversion losses from the primary energy, i.e. the raw fuel, to the site, which are energy conversion, transmission, and delivery to the building. In Europe site energy corresponds to final energy and source energy to primary energy.

For non-residential buildings the US Energy Information Agency (EIA) releases regular commercial buildings energy consumption surveys. The last release from 2015 covers 6700 commercial buildings with consumption data referring to the year 2012. The total average site energy consumption for all commercial buildings is 252 kWh/m^{2}a. Office buildings are very close to the average building consumption with 245 kWh/m^{2}a.

To convert this site energy into source or primary energy, the mix of fuel sources needs to be known. For office buildings 70 % is electricity, 22 % natural gas, 6 % district heat, and 2 % oil. Using the Energy Star Source to Site ratios of 3.14 for electricity, 1.05 for natural gas, 1.2 for district heat or steam and 1.01 for oil, the total office building source energy use intensity is 618 kWh/m^{2}a. In New York the median office building source EUI is 601 kWh/m^{2}a with a large fluctuation [NYC (2014a)].

Using the same Energy Star conversion factors for the European office buildings, a typical source EUI for an old office building in Germany with a heating demand of 104 kWh/m^{2}a and an electricity consumption of 54 kWh/m^{2}a would be around 278 kWh/m^{2}a or 55 % lower. The best German office buildings today built with high insulation standards, efficient lighting and electrical appliances have site EUI of 45 to 60 kWh/m^{2}a, corresponding to source EUI of about 120 kWh/m^{2}a. This is five times lower than the average US office building today. To explain and reduce the difference in consumption is a strategic aim of the authors.

Monitoring data analysis

Five public buildings in New York City with available monthly consumption of electricity and heating fuel were included in the analysis, three courthouses and two office buildings. Due to data protection the building names Courthouse A to C and Office A and B are used. Based on the monitored consumption, the Building Performance Laboratory of the City University of New York used inverse modeling procedures to determine the heating and cooling setpoints and the heating and cooling dependency on ambient temperature levels.

The building's site energy is in the same range as the average US office buildings (between 200 and 300 kWh/m^2), of which 50 to 70 % is used for electricity, the rest for heating fuels. As only 11 to 24 % of this electricity is used for cooling, a very high electrical baseload of 96 to 137 kWh/m^{2}a remains. This baseload electricity is more than double compared to non-refurbished office buildings in Germany, which typically do not have air handling units and distribute heat via closed loop water radiator circuits. The ventilation and lighting systems in the buildings should be a first focus of efficiency measures.

To better understand the building performance and the impact of refurbishment measures, forward modeling is used. As it is costly and time consuming to model a large number of buildings, for example the public building stock of New York, the modeling procedure has to be automated. In this work available CityGML 3D models of the New York building geometry were used to extract building geometry and associate building physics and usage parameters.

3D City Modeling

Two 3D models of the New York City building stock are available in level of detail one (LOD1) and in LOD2, respectively. The data are provided by the New York City Department of Information Technology and Telecommunications in the Open Geospatial Consortium's CityGML data format. The original files which contain approximately one million buildings are huge (more than 12 Gigabyte).

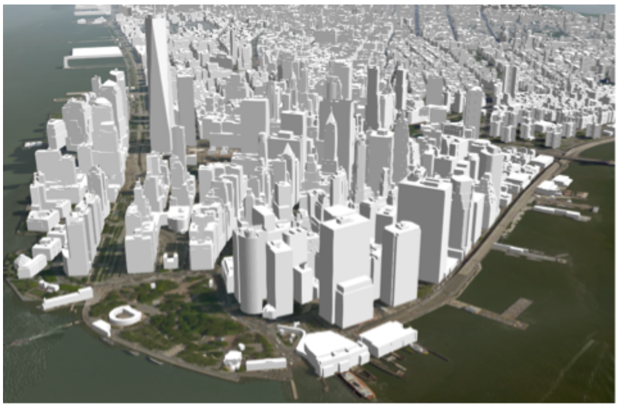

Figure 1: 3D model used to extract the geometry of the public buildings used in the analysis.

Based on CityGML, the urban energy simulation platform SimStadt [Nouvel et al. (2015)] was developed by the Stuttgart University of Applied Sciences in the framework of a project funded by the German Federal Ministry of Economic Affairs and Energy. It has a modular, extensible workflow-driven structure and can handle all LODs.

Through its graphical user interface, the parameters can be modified and assessed. The results can be visualized in different ways with graphs or maps. Several multi-scale energy analyses can be performed, such as heating/cooling demand calculations, building refurbishment scenarios or solar potential, supporting urban planners and city managers with defining and coordinating low-carbon energy strategies for their cities.

A simplified radiosity algorithm developed by (Robinson and Stone, 2005) can be used in SimStadt to model complex urban shading. The radiant external environment can be described by two hemispheres, discretized into a certain number of patches of known solid angle. Then, the radiant exchanges between each surface and its associated occluded patches are solved. It can be applied to districts or cities where obstructions and shadowing influence the incoming solar radiation.

Average shading losses for each façade orientation and roof of Manhattan were calculated for Midtown Manhattan. It could be shown that average monthly losses were 30 % on roofs and up to 55–65 % for façades depending on orientation.

SimStadt provides a Region Chooser tool which uses Google Street Maps in order to define a closed polygon. All building objects within the polygon are extracted and saved to a new CityGML file.

The goal of this work is to extend the capabilities of the building monitoring and inverse modeling approach, which follows the DOE building re-tuning protocol. This is achieved by modeling each building with its 3D geometry and to use the model for scenario calculations. A major challenge is that many parameters needed for the building model are usually not known. This includes the building physics parameters (mainly U-values of building envelope and total energy transmittance or g-value of the glazings), the ventilation and infiltration rates as well as the internal gains and schedules.

Beside geometry, every building object in CityGML has two important attributes, namely the year of construction and the usage category of the building. SimStadt provides two libraries with physical and usage default data. These data form the basis for a later simulation of the building.

The monitored buildings investigated in this study were modeled with the monthly energy balance method based on the German standard DIN V 18599 (which is very similar to DIN EN ISO 13790). The monthly heat demand Q_h of a building or a building zone is basically calculated as the difference between heat sinks Q^- and heat sources Q^+ multiplied by their monthly utilization factor η, i.e.

$$Q_\mathrm{h} = Q^- - \eta\, Q^+$$

The main heat sinks are transmission losses through walls and windows and ventilation losses. Main heat sources are solar gains and gains due to internal loads and appliances. On the other hand, the energy need for cooling Q_c is calculated by

$$Q_\mathrm{c} = (1 - \eta)\, Q^+$$

The calculations are carried out for an average day in each month, taking into account different boundary conditions for different days within the month (e.g. working days, weekends or holiday periods).

As our goal is to work with large scale urban data sets derived from laser scanning flights, only the external geometry of a building is given in a typical urban CityGML data set. Usually there is little information of different usage or thermal zones of a building, although an automated subdivision of the building volume in stories is possible and has been tested by the authors assuming standard room heights. Especially in large non-residential buildings, simultaneous heating and cooling might occur resulting for example from dehumidification and reheating. However, as no evidence of simultaneous heating and cooling could be found from the monitoring data (rather constant baseload and no cooling electricity increase at low ambient temperatures), we considered it a reasonable assumption to treat each building as one thermal zone.

The measured monthly heating/cooling energy values are then used to calibrate the building model. The main free parameters are window fraction and transmission coefficients, internal gains, ventilation rates and mean envelope U-values. The solar irradiance can be accurately calculated for each building element using the 3D city model with or without shading and is an input to the monthly energy balance model together with the mean ambient temperature. The best fit parameters of the monthly energy balance equation with transmission and ventilation losses and internal and solar gains are then determined from the measured monthly energy values.

The building models can then be used to calculate retrofit scenarios for a large number of buildings.

The method is tested on five examples of the public building stock of New York City, where monitoring and change-point inverse modeling was carried out for 500 facilities, about 100 retrofit projects and a range of solar installations.

Courthouse A

Courthouse A was built between 1899 and 1907. The eight and a half story structure is constructed as a granite masonry with a steel-framed structure. The building also has two levels below ground, a basement and a sub-basement. The gross floor area of the building is 19,742 m^2. According to the CityGML file, the footprint area of the building is 2,809 m^2 with a height 47.8 m, so that the total volume of the building is 134,303 m^3. Since the building has a flat roof, the volume from the LOD1 CityGML file should be close to the real volume of the building.

The audit report [Engineers (2014)] says that Courthouse A uses steam purchased by Con Edison primarily for space heating (96 %) and domestic hot water (4 %). The average annual steam consumption is 3,232 MWh. The annual average electricity consumption is 1,514 MWh. Courthouse A uses electricity for lighting (30 %), ventilation (20 %), space cooling (20 %), space heating distribution (7 %), and other miscellaneous (23 %). The energy audit results in an electricity demand for cooling of 302 MWh annually. From five years of monthly energy data measurements, the heating consumption was 5,275 MWh, i.e. much higher than the energy audit data. A careful analysis showed that this data included heat supplied to another building. Subtracting this consumption, the dashboard gave 3,572 MWh heating energy or 180 kWh/m^2a for the Courthouse A, i.e. comparable to the energy audit data. Also the total dashboard electricity data after correction was similar to the audit at 1,490 MWh. Subtracting the baseload of 1,158 MWh from the electricity demand resulted in an electricity demand for cooling of 332 MWh or 16.8 kWh/m^2, very similar to the audit data of 328 MWh.

The SimStadt simulation model—based on the German physics and usage parameter defaults—shows a space heating demand of 2,630 MWh or 133 kWh/m^2a and space cooling demand of 1,675 MWh (85 kWh/m^2a). Figure 2 shows the measured and simulated monthly values over a period of five years.

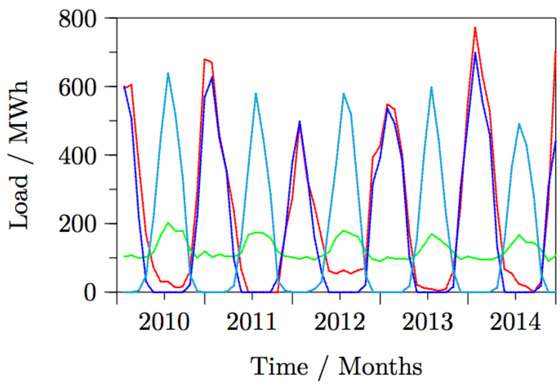

Figure 2: Measured heating (red) and electricity consumption (green) und calculated heating (blue) and cooling (cyan) data for the Courthouse A.

In order to have a fair comparison, the months have been calculated with the true monthly means of ambient temperature, measured at the Central Park weather station. The measured consumption data were converted to heating demand assuming a heating system efficiency of 80 %. The heat demand calculations show an almost unbelievably good agreement between measured and simulated data. Interpretation of the cooling data is more complicated. First, the measured electricity consumption includes all electrical loads of the building, meaning that the base load needs to be substracted first to obtain the electricity demand for cooling. Also a COP of the chiller has to be assumed to convert cooling electricity into cooling demand. A realistic COP for the chiller type in Courthouse A would be 3.0, resulting in a demand of only 996 MWh, i.e. 60 % of the simulated demand. The analysis showed that the cooling load is not just satisfied by an electrical chiller in the building, but gets chilled water from a dual temperature water loop from a plant located in a different building so that a comparison between measured and simulated cooling load is hardly possible.

Figure 3 shows the same data as Figure 2. The representation of heating and cooling demand is the basis for the inverse modeling approach. While the measured heating consumption was converted to demand

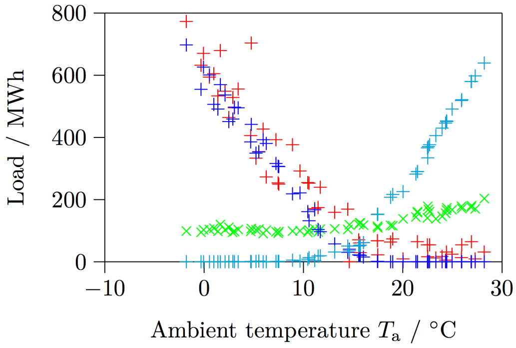

Figure 3: Comparison of measured and simulated data of the Courthouse A.

assuming a 80 % system efficiency, the cooling consumption plotted has not been converted to demand with a COP and shows measured electricity consumption for cooling.

Courthouse B

Courthose B is four stories high, has two side wings and includes a usable basement. Each floor has an area of approximately 1,000 m^2, a basement of 2,300 m^2 and approximately 5,559 m^2 of total space. Figure 4 shows the 3D CityGML model of the Courthouse in LOD1 and LOD2 geometry. As can be seen, the LOD1 volume is extremely overestimating the true volume of the building, which then results in a highly overestimated gross floor area of 20,500 m^2.

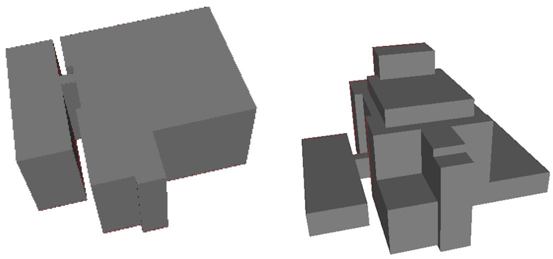

Figure 4: Courthouse B in LOD1 and LOD2.

According to an audit, the courthouse annually uses 504 MWh electrical energy, of which about 36 % are used for lighting, 33 % for cooling (166 MWh), 16 % for ventilation, 11 % for pumps and 4 % for other electricity. The energy intensity is 391 kWh/m^2a for site energy and 618 kWh/m^2a for source energy. Space heating is operated by two steam generators in the cellar level. For space heating, about 1,665 MWh (steam usage) and from that, 1,099 MWh (demand) are needed per year according to the energy audit or 1,782 MWh demand, according to two years of measured data. The steam generators have an efficiency of about 66 %. The simulated demand using the LOD1 model is 1,582 MWh per year. The difference is mainly the result of a wrong heated volume derived from the simple LOD1 model, which wrongly extruded low side parts of the building. After adjusting this parameter from 64,000 m^3 to 37,800 m^3 and the floor area from 20,500 m^2 to 5,509 m^2, the U-value from the walls from 1.2 to 1.0 and the U-value from the windows from 3.2 to 3.5 W/m^2K, the simulated heating energy demand is 1,085 MWh (198 kWh/m^2, which means a difference of only 1.2 %.

After substracting the baseload electricity of 278 MWh from the total dashboard electricity consumption of 519 MWh, the resulting electrical energy for cooling of the building is 241 MWh per year, i.e. 45 % higher than in the energy audit. With the original volume and parameter assumptions from SimStadt, the cooling energy demand is 985 MWh. After the corrections of volume and building parameters the Courthouse would need 680 MWh (thermal cooling) per year with the calibrated parameters for volume, floor area and U-values. With assumed COP of 3.0 for the chillers, this corresponds to 227 MWh electric, i.e. only 6 % lower than the consumption.

Courthouse C

The building was constructed in 1973 and has 12 floors above ground and two floors below. Most of the floors are used as offices and court rooms. The courthouse has a concrete construction with a granite-like finish. The CityGML geometry data shows a simplified model of the building construction. The CityGML data does not cover the top floors, so the real geometry has been reconstructed from Google Earth information.

With the original SimStadt assumptions, the heating energy demand simulated is 3,050 MWh (68 kWh/m^2a) and cooling demand is 1,971 MWh (44 kWh/m^2a). To validate the results, the Energy Audit and Retro-Commissioning Assessment of Courthouse C were used.

With the adjustments of geometry and building characteristics, the heating demand is 21 % lower than the reported consumption value (4,042 MWh from the energy audit report or 4,343 MWh from 2 years of metering data). The building is connected directly to the steam network of New York City without heat exchangers. Assuming 10 % losses in the direct steam use, the difference between metering and simulation reduces to about 10 %.

For cooling the measured annual electricity consumption from two years of metering data is 937 MWh (632 MWh from the auditing report). Assuming a COP of 3.0 for the central cooling unit, the audit results correspond rather very well to the simulated cooling energy demand of 1,971 MWh, while the dashboard data would overestimate the demand, unless the COP would be lower.

Office A

Office A has five original stories and two additional ones. It was completed in 1846. According to the

Table 1: Parameters which most influence the simulated heating and cooling demand (Office A).

Parameter	Heated building volume [m³]	U-value walls [W/m²K]	U-value windows [W/m²K]	Heating setpoint temp. [°C]	Air change rate [1/h]	Floor area [m²]	Cooling setpoint temp. [°C]
SimStadt default	101148	1.22	2.5	21	0.99	36953	24
Adapted	108800	1.01	3.52	22	0.75	23800	22
Parameter difference	7 %	-17 %	29 %	5 %	-25 %	-75 %	-4 %
Energy demand difference	4.6 % (qh)	-3 % (qh)	2.5 % (qh)	8.3 % (qh)	-16.5 % (qh)	6.5 % (qh)	26.9 % (qc)

Table 2: Parameters which most influence the simulated heating and cooling demand (Office B).

Parameter	Heated building volume [m³]	Floor area [m²]	U-value walls [W/m²K	U-value windows [W/m²K	Window Area in % of the wall area	Usage days per year [d/yr]
SimStadt default	16340	5229	1.22	3.2	33%	250
Adapted	15226	4872	1.60	4.8	25%	365
Parameter difference	-7 %	-7 %	31 %	50 %	-25 %	46 %
Energy demand difference	-2.2 %	-1 %	8 %	17 %	-2.4 %	6 %

energy audit the total site energy is divided into 38 % ventilation, 7 % lighting, 13 % cooling, 24 % heating, and 18 % other electricity.

The gross floor area is 22,489 m^2 with a building height of 32 m. The LOD1 CityGML model gives a volume of 101,148 m^3. When comparing this volume with the real building geometry an internal patio has to be substracted with the approximate dimensions of 40 m length and 15 m width.

The simulation with the simple LOD1 CityGML geometry gives a heating energy demand of 1,933 MWh and energy demand for cooling of 1,351 MWh. To validate the results the Office A Energy Audit and Retro-Commissioning Assessment was used, which gave a measured heating energy consumption of 1,229 MWh. The metered data from two years of monitoring (2013 and 2014) gave an average consumption of 1,533 MWh.

The audit report gives a cooling energy consumption of 679 MWh electrical, while the two years of monitored electricity for cooling is only 361 MWh. Depending which of these values is true, this would correspond to a cooling COP between 2.0 and 3.8.

To identify the most influencing parameters, different model configurations were used. In the first scenario the U-values from [Deru et al. (2011)] were used to calibrate the model.

Besides the building envelope the sensitivity of the HVAC parameters were studied. It shows that internal gains and the minimal air change rate are the most influential parameters for the heat energy demand. Reducing the cooling setpoint lower than the default values, the cooling demand increases significantly.

Office B

This office building was built in the early 20th century. It consists of nine floors above ground and one floor below ground with a total of 5,481 m^2. Two façades to the street form the front of the building with a window area of 34 %. The façade to the backyard has a few small windows and a window area of 24 %. The third façade is the connection to the neighboring building. About 39 % of the building's energy consumption are used for heating, 19 % for site cooling, 9 % for ventilation, 21 % for lighting, 4 % for DHW and 8 % for other consumers like a data center or plug devices. Natural gas is the fuel source for 90 % of the building's heating consumption needs, the rest is oil. Three dual-fired steam boilers located in the basement with new powerflame burners provide the heating. From the audit report in 2011, 698 MWh natural gas and 80 MWh oil was used for the space heating. The metered data from the summer 2013 to 2015 gave a heating demand of 810 MWh (147 kWh/m^2). Most of the building is cooled with approximately fifty window AC units. Only the data center on the second floor has multiple air conditioning units. According to the energy audit, the electrical usage was 924 MWh. The cooling portion is about 33 % of this usage, about 308 MWh/a. Subtracting the baseload from the total electricity of the dashboard data the resulting cooling electricity was 197 MWh, i.e. significantly lower.

According to the simulation in SimStadt, the building would have a demand of 331 MWh cooling and 482 MWh heating energy. Comparing this demand with the measured consumption, this results in a heating system efficiency of 60 % and a cooling COP of 1.7.

With a heating efficiency of 80 % the audit report consumption corresponds to a heating demand of 621 MWh and with a cooling COP of 1.4 for the window units a cooling demand of 231 MWh.

Discussion

Comparing the results of all forward simulations based on the monthly energy balance, significant influence factors on the simulation results can be detected. One main error source of the input values from the CityGML files is the heated volume, which is related to the LOD1 or LOD2 geometry. The correction of volume is the most important improvement for the simulated results compared to the consumption data. Influential geometries such as patios or low-lying east or westwings are not taken into account.

A further source of uncertainty for the monthly energy balance are the U-values of the walls and windows. They will be adapted to local New York Standards during the next months. It is not expected that the impact is significant, as the buildings analyzed are rather compact with low surface to volume ratios.

The user behavior and thus building energy variables such as heating and cooling setpoints/setbacks, internal gains and air change rates are imported into the model from a typical German office building usage library. Since standard values are used as a basis, a further improvement in the simulations results would be obtained by adapting these default European values to more realistic New York settings. Sensitivity studies of the monthly energy balance showed that mainly air change rates and heating/cooling temperature setpoints influence the energy demand.

A major unknown is the system efficiency of the heating and cooling plant. The better the local knowledge about plant types, age, maintenance status is, the more realistic is the conversion between simulated energy demand and measured consumption.

Conclusion

To analyze energy optimization potentials of large portfolios of buildings such as the municipal building stock of New York City, efficient procedures are required to determine the status quo and analyze refurbishment options. In this work, the building stock of New York was modeled based on a CityGML 3D model to describe the urban geometry in detail. From the 3D model individual buildings can be easily extracted. Data bases for building physics characteristics and schedule information are then used to parametrize a monthly energy balance method. Monitoring data sets from the New York Building Performance Laboratory and from energy audit reports were then used to calibrate the building models. Care has to be taken when using monitoring data, as there are significant differences between energy audits and monthly consumption data. In some cases the consumption data included additional buildings or additional heating or cooling supply was provided by energy networks from other buildings. To use a realistic 3D geometry for volume and surface area calculations, it is important to use LOD2 models, especially when the buildings are not compact. The most important parameters for the forward models are good estimates of air change rates, temperature set points, building usage schedules, and U- and g-values of the building envelope.

The toolset opens new ways to the municipal administration to systematically analyze their building stock performance and determine the potentials for energy savings and retrofit actions.

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