Application of a Simplification Algorithm for Urban Building Energy Modeling to Complex-Shaped Educational Buildings

Matteo Merli – Free University of Bozen-Bolzano, Italy – matteo.merli@stud-extra.unibz.it
Federico Battini – Free University of Bozen-Bolzano, Italy – federico.battini@natec.unibz.it
Giovanni Pernigotto – Free University of Bozen-Bolzano, Italy – giovanni.pernigotto@unibz.it
Andrea Gasparella – Free University of Bozen-Bolzano, Italy – andrea.gasparella@unibz.it

Abstract

To reduce greenhouse gases emissions related to the building sector and to make informed decisions about sustainable building design and urban planning, building energy simulation should be adopted as a supporting tool by designers and policy makers. However, since building simulation is extremely time-consuming, its application is limited in daily design work. This research aims at testing a new simplification algorithm proposed for Urban Building Energy Modeling to reduce the computational complexity of thermal models in favor of the simulation speed without compromising accuracy. The procedure was applied on two educational buildings of complex shapes located in Bolzano, Italy. Results show that the simplified models reduced the simulation time up to 135 times, with building level relative annual deviations lower than 6 %.

1. Introduction

In the building professional sector, Building Energy Modeling *BEM* can serve to design an energy efficient building or to verify its compliance with local, regional or national energy codes, as well as the actual energy performance. The former requires the use of *BEM* as an early design tool to support design tasks aiming at finding the best cost-effective solutions. At this stage of the design process, standard inputs and boundary conditions are conventionally used and a short calculation time is essential to compare multiple alternatives. The latter bypasses the analysis of different scenarios and focuses on the final simulation output, comparing it to a reference benchmark. In this case, the models are prepared in accordance with codes or technical standards, and a high degree of calculation accuracy is expected.

Overall, since accurate modeling procedures and iterative design processes require a large amount of time and computational resources, simplification workflows can be employed to speed up these kinds of simulations. However, most of the simplification techniques present in the literature have been developed for Urban Building Energy Modeling, *UBEM,* rather than *BEM*. Indeed, since *UBEM* is very computationally intensive, it is necessary to introduce such methods in order to perform urban scale simulations.

Even though *UBEM* is a relatively new field of study aiming at designing and optimizing urban energy systems and planning urban development, several tools, such as CitySim, SimStadt, umi, CityBES, URBANopt and TEASER, have already been released. Nonetheless, in recent years, different types of simplification algorithms intended to ease *UBEM* computing resources have been proposed. Different to the tools listed above, which fully comprise the *UBEM* workflow, these algorithms are only meant to replace the simulation stage.

In 2013, Dogan and Reinhart developed a fully automated and accelerated method capable of abstracting building massing into a meaningful group of simplified box-unit (shoebox) thermal models (Dogan & Reinhart, 2013), which they later named Shoeboxer (Dogan & Reinhart, 2017). In 2019, inspired by the idea of the Shoeboxer, Zhu et al. (2019) developed the Building Blocks Energy Estimation *BBEE* method for assessing building thermal demand at the district level by combining a *BBEE* algorithm and energy databases.

In this work, a new algorithm, developed by Battini et al. (2021b), which simplifies every building energy model into a representative simplified shoe-

Part of
Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2023. Building simulation applications BSA 2022. bu,press.
https://doi.org/10.13124/9788860461919

box, was tested at the individual building level. The aim is to evaluate the algorithm's performance in estimating the energy use and accelerating the simulation of complex-shape buildings by applying it to two educational buildings in Bolzano, Italy.

2. Methodology

The process followed in order to assess the performance of the shoeboxing algorithm on the buildings considered is made of several steps. (i) case study introduction and data gathering, (ii) detailed geometry and energy modeling, (iii) calibration against monitored temperature profiles, (iv) application of the algorithm, and (v) model simulation and comparison.

2.1 Case Study

The two case studies are two educational buildings located in Bolzano, Italy. The first one is a kindergarten, called "Positano", built in 2009, while the second one is a primary school, called "Langer", built in 2014. Fig. 1 shows the location of the two buildings in the city of Bolzano. As reflected in their year of construction, both buildings are located in the western part of the city, in which new neighborhoods have been built over the past few decades. Positano kindergarten is a three-storey building, one of which is underground, and it is located in a district in which it is surrounded by residential buildings of up to 6 floors in height.

Fig. 1 – Locations of the two buildings in Bolzano, Italy

On the other hand, Langer primary school, which has three floors above ground and one underground, faces high residential buildings from North-East to South and open agricultural areas to the west.

2.2 Detailed Building Energy Modeling

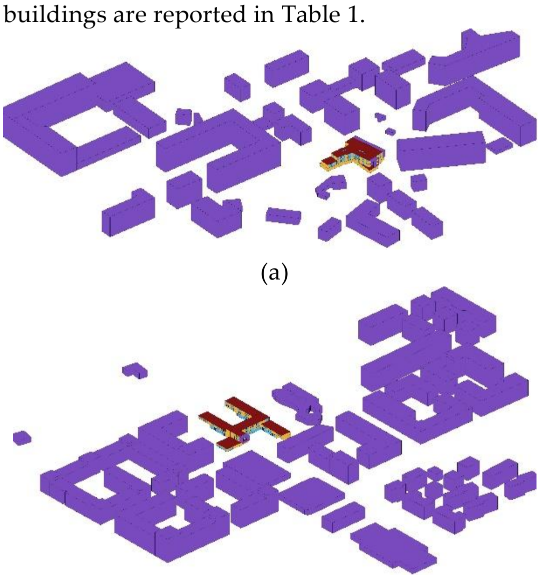
Rhinoceros3D and Grasshopper were used to model the buildings' geometry in compliance with the technical floorplan drawings provided by the Municipality of Bolzano, allowing a characterization of the outer shell with windows and external fixed shades, as well as the subdivision of the internal spaces into different zones. Multi-zonal building energy models were prepared according to two main factors: construction assemblies and use of space. Adjacent spaces with similar properties were merged into a single zone, i.e., a single massing model with no internal partitions. Since each level includes spaces with similar functions, Positano was modeled with one thermal zone per floor. On the other hand, Langer school was subdivided into 12 thermal zones, according to the different functions and shapes of the school.

To model the urban context, the geometries of surrounding buildings' up to 200 m distance away have been imported into Rhinoceros3D with the aid of Gismo, a Grasshopper plug-in which enables automatic generation of urban environment and terrain geometry through a connection with the OpenStreetMap website.

The conversion from massing models to thermal zones was conducted using Ladybug Tools, an open-source suite of plug-ins for Grasshopper, and the characterization of the energy models was automated thanks to eppy, a Python scripting language for EnergyPlus which allows rapid and selective modification of EnergyPlus input files.

The energy certifications provided by the Municipality of Bolzano were used to define the construction elements (opaque and transparent) making up the envelope of the buildings. Occupancy profiles, people density, plug loads and lighting power densities were provided by the school administrations or obtained during in-situ surveys. Since the city of Bolzano belongs to the climate zone E, the heating period was set from the 15th of October to the 15th of

April, in accordance with Italian law. For Positano, the heating setpoint was set to 21 °C, based on the real temperature data available. On the other hand, for Langer primary school, the heating setpoint was set equal to 22 °C, in accordance with the information received by the school administration. The daily schedules of occupancy were determined combining information from the schools' administration and suggestions based on technical standards, such as UNI CEN/TR 16798-6 (2018) and ASHRAE 90.1 (2013). The density of people per square meter was estimated using the technical standard UNI 10339 (1995). The infiltration rates were set equal to 0.17 ach, according to the results of a previous experimental study in which indoor conditions were monitored in a classroom at Positano kindergarten (Dugaria et al., 2021). The ventilation rates were initially estimated by means of the calculation proposed in the technical standard UNI 10339 (1995), while the ventilation schedules were obtained by estimating the window openings depending on the variation of CO_2 concentration detected by dedicated sensors. Thanks to already-performed monitoring campaigns, it was possible to have data from one sensor in one classroom for the ground and first floors in Positano and one sensor in one classroom in Langer. Moreover, in the primary school, all the thermal zones, except the classrooms and the hallway, are equipped with a controlled mechanical ventilation system. Thus, for these thermal zones, a decision was made to use the design ventilation rates and schedules reported in the energy certification. Finally, as regards the shades, a dynamic solar based control with a setpoint of 300 W/m² was hypothesized, in accordance with what was found by Roberts et al. (2022), limiting their activation to the period from February 15th to October 31st in both buildings. The values for the internal loads and controls for all the zones of both buildings are reported in Table 1.



(a)

(b)

Fig. 2 – 3D geometrical models of the buildings with context: (a) Positano kindergarten and (b) Langer primary school

Table 1 – Internal loads, HVAC system controls and shading control settings for type of zone in the two buildings

	Zone	Lighting power [W/m²]	People [people/m²]	Ventilation rate [ach]	Infiltration rate [ach]	Heating setpoint [°C]	Shading setpoint [W/m²]
Positano	Underground	5.71	0.1	2.82	0.17	21	–
	Ground	4.25	0.17	1.72	0.17	21	300
	First	5.24	0.26	1.86	0.17	21	300
Langer	Basement	1.5	0.08	1.5	0.17	22	–
	Hallway	2.65	0.12	1.64	0.17	22	300
	Canteen	2.55	0.6	3.36	0.17	22	300
	Classrooms	3.8	0.3	2.42	0.17	22	300
	Library	3.95	0.3	3.03	0.17	22	300
	Gym	2.4	0.2	2.87	0.17	22	300
	Auditorium	5	0.6	1.83	0.17	22	300

2.3 Calibration

Both models were calibrated against the real indoor air temperature data available for two kindergarten classrooms for the whole year 2019 for Positano and of one classroom from 11th April 2019 for Langer. The calibration was performed using the weather file of Bolzano from the year 2019 only on the zones for which data were available. For Positano, the ground and first floor were calibrated, while for Langer, the zone in which the monitored classroom is present. For the primary school, the result of the calibration was then applied to the other zones without mechanical ventilation.

The models were calibrated considering as variables the ventilation rate and people density. Both variables ranged from -50 % to +50 %, with a step of 10 %, starting from the nominal values computed according to standards. Table 2 reports all the values employed for the calibration for the zones considered. For each zone, a full factorial calibration was carried out, resulting in 121 simulated models for each case. The hourly Root Mean Square Error *RMSE* was computed between the simulated and monitored temperature during the period of interest for the calibration, i.e., the heating season, from the 15th of October to the 15th of April. Since for Langer no data were available for the first period of the year, the school's classroom was calibrated only considering the last months of the year.

In the present study, since no data were available about the heating system and its rated power, an ideal heating system characterized by an unlimited power was employed. For this reason, the simulated temperatures will always be greater or equal to the setpoint, even though the monitored temperature profiles can be lower. In order to cope with such discrepancies and to pick the most suitable combination of inputs from the calibration, the minimum seasonal *RMSE* was found. Then, all the combinations yielding a *RMSE* within 5 % difference from the minimum were considered. Among these combinations, the one with the lowest *RMSE* closest to the nominal ventilation rate was selected. In this way, it was possible to prevent choosing a combination with too low or too high a ventilation rate, which could undermine annual prediction accuracy for the heating demand. Indeed, since the simulated temperatures cannot be below the setpoint, changing the ventilation rate can lead to very limited improvements in the *RMSEs* of the temperature profiles, while having a huge impact on the heating demand.

2.4 Application of the Simplification Algorithm

Once the detailed building energy models were calibrated, the simplification algorithm was used to obtain as many shoebox energy models as the number of thermal zones making up the detailed models.

Table 2 – Ranges and values for calibration per zone

	Positano – Ground Floor										
	-50 %	-40 %	-30 %	-20 %	-10 %	0 %	10 %	20 %	30 %	40 %	50 %
Ventilation rate [ach]	0.86	1.05	1.25	1.44	1.63	1.72	1.82	2.01	2.2	2.4	2.59
People [people/m^2]	0.08	0.1	0.12	0.14	0.16	0.17	0.18	0.19	0.2	0.21	0.22
	Positano – First Floor										
Ventilation rate [ach]	0.93	1.13	1.34	1.55	1.75	1.86	1.96	2.17	2.37	2.58	2.78
People [people/m^2]	0.13	0.16	0.19	0.22	0.25	0.26	0.27	0.3	0.33	0.36	0.39
	Langer – Classroom										
Ventilation rate [ach]	1.21	1.48	1.75	2.02	2.29	2.42	2.56	2.83	3.09	3.36	3.63
People [people/m^2]	0.15	0.18	0.22	0.25	0.28	0.3	0.32	0.35	0.38	0.42	0.45

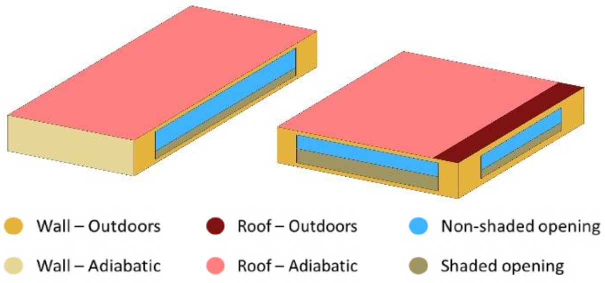


Fig. 3 – Example of shoebox models with boundary conditions

A comprehensive overview of the operations executed by the algorithm can be found in the work by Battini et al. (2021b). Nonetheless, the main steps can be summarized as follows:

1. Incident radiation analysis on the windows of the detailed energy model, subdivided for each cardinal direction by considering a ± 45° tolerance range. The ratio between the annual incident radiation on each façade and the one calculated for a reference box unit is set as shading factor in order to take into account the share of radiation obstructed by self-shading and external objects.
2. Shoebox generation based on three geometrical indicators employed to solve a system of equations, in which the three dimensions of the shoebox are the unknowns. The shoebox's apertures are generated according to the same window-to-wall ratio calculated for each orientation of the related thermal zones (± 45° tolerance range).
3. Calculation of the adjacent surface area portions for each thermal zone that are in contact with other thermal zones. Since the algorithm generates freestanding buildings, the inter-building partitions are treated as adiabatic surfaces, assuming no heat flow between touching thermal zones.
4. Shoebox aperture surface reduction according to the shading factor that was calculated for each orientation. The reduction is implemented by substituting a part of transparent surface with an opaque element having the same thermophysical properties of the window.

Once the shoeboxes were obtained, the same non-geometrical properties of the starting thermal zone were assigned to the related shoebox.

2.5 Detailed and Simplified Model Comparison

Different to the procedure followed in the calibration process, in which temperatures were used to compare the monitored and simulated profiles, the comparison between detailed and simplified models was performed on the heating needs. Although energy simulations commonly adopt Typical Meteorological Year (TMY) weather files, the same weather file with the climatic data of Bolzano for the year 2019 employed for the calibration was utilized to assess the algorithm's performance.
As regards heating needs, the comparison metrics selected for this purpose are: (i) the absolute difference of the annual energy needs, (ii) the relative difference of the annual energy needs and (iii) the *RMSE*, calculated with a time step of 1 hour. Since shoeboxes are generally smaller than the starting geometry, their heating demand was multiplied by a scaling factor to take into account the reduction of floor area that is part of the simplification process.

3. Results and Discussion

3.1 Calibration

Table 3 reports the outcomes of the calibration, in which people densities do not correspond to the ones computed from the standards, while the values for ventilation rates are the same. This is because, even though the lowest *RMSEs* obtained were the ones with the greatest ventilation rates, as stated in Section 2.5, values closer to the ones computed following the standards would have been chosen if within 5 % difference.

Table 3 – Calibration results

	Ventilation rate [ach]	People density [people/m²]
Positano – Ground floor	1.72	0.08
Positano – First floor	1.86	0.16
Langer – Classroom	2.42	0.25

Indeed, the *RMSEs* showed differences in the order of hundredths or thousandths of degree, hence negligible. The combination of inputs obtained from the calibration process was also used in the simplified models for the comparison.

3.2 Simplification Results

The annual energy demands for space heating are reported in Table 4.

For Positano kindergarten, the simplified model's total annual heating demand is equal to 30.13 MWh, 1.69 MWh more compared with the detailed model's results. In relative terms, the total deviation of the detailed model is equal to -5.62 % compared with the simplified one.

Regarding each thermal zone, the underground floor shoebox underestimates the heating demand, although only slightly, while the ground and first floor shoeboxes overestimate it by a deviation that does not exceed 2.06 MWh. As regards *RMSEs*, even though they are low for all floors, the underground floor shoebox shows the best performance in terms of hourly deviation from the detailed thermal zone's heating demand prediction.

For Langer primary school, the simplified model's total annual heating demand prediction is equal to 153.21 MWh, which is 7.05 MWh greater than the detailed model's predicted results. In relative terms, the total deviation is equal to +4.60%. Analyzing the results for each thermal zone, only the basement and the canteen underestimate the heating demand, while the rest of the shoeboxes overestimate the annual heating demand by a deviation that varies for each zone. Classrooms, gym and auditorium shoeboxes show the best performances, overestimating no more than 13.10 % in relative terms, or 0.88 MWh in absolute terms. The library's ground floor shoebox overestimates the predicted heating demand of the detailed model by 27.30 %, which is, however, one of the lowest heating needs (only 4.89 MWh). On the other hand, although the library's first floor heating demand is below average, it is characterized by a deviation of 6.20 %.

Table 4 – Heating needs prediction comparison

		Detailed - Heating [MWh]	Simplified - Heating [MWh]	Absolute difference [MWh]	Relative difference [%]	RMSE [kWh]
Positano	Underground	7.41	6.91	0.49	-7.16%	0.08
	Ground	9.05	9.18	-0.13	1.40%	0.79
	First	11.97	14.03	-2.06	14.68%	0.42
	TOTAL	28.43	30.13	-1.69	5.62%	0.89
Langer	Basement	19.91	17.97	1.95	-10.80%	0.33
	Hallway	33.03	36.25	-3.22	8.90%	0.61
	Canteen	10.71	10.62	0.08	-0.80%	0.31
	First Floor Classroom1	10.46	11.34	-0.88	7.80%	0.19
	First Floor Classroom2	8.15	8.42	-0.28	3.30%	0.06
	First Floor Classroom3	2.69	2.98	-0.29	9.80%	0.06
	Second Floor Classroom1	9.80	10.00	-0.20	2.00%	0.04
	Second Floor Classroom2	3.02	3.47	-0.45	13.10%	0.09
	Library Ground Floor	4.89	6.73	-1.83	27.30%	0.42
	Library First Floor	8.96	9.56	-0.59	6.20%	0.12
	Gym	22.29	22.92	-0.63	2.70%	0.25
	Auditorium	12.26	12.94	-0.69	5.30%	0.16
	TOTAL	146.16	153.21	-7.05	4.60%	1.38

Table 5 – Recorded simulation time and comparison

			Simulation time [s]	
Positano	Underground		4.01	
	Ground floor		5.16	
	First Floor		5.43	
	Simplified	Total	14.60	134.78x faster
	Detailed		1967.64	
Langer	Basement		3.97	
	Hallway		5.18	
	Canteen		4.83	
	First Floor Classroom1		4.83	
	First Floor Classroom2		4.85	
	First Floor Classroom3		4.51	
	Second Floor Classroom1		4.85	
	Second Floor Classroom2		4.79	
	Library Ground Floor		4.80	
	Library First Floor		4.88	
	Gym		5.19	
	Auditorium		4.83	
	Simplified	Total	53.54	8.18x faster
	Detailed		438.14	

The results of both case studies showed that shoeboxes can predict fairly well the heating needs of the detailed thermal zones. Moreover, for both buildings, the sum of the shoeboxes' predictions achieves high accuracy in estimating the global annual heating demand of the buildings detailed.

Even though results about temperatures have not been reported, the temperature profiles of the simplified models are generally underestimated throughout the entire year (i.e., leading to larger heating needs), with larger discrepancies in the summer period. This is mainly because, in general, the shoeboxing procedure leads to smaller thermal zones having a lower thermal capacity and it models the incoming radiation starting from a fixed obstruction ratio for the whole year. Indeed, in order to yield even more accurate results, the modeling of the external shadings should be improved since the surrounding context has a different impact on the air node heat balance during the year, i.e., it has a greater influence in summer (Battini et al., 2021a).

Table 5 reports the simulation runtime of detailed and simplified models. Regardless of the building considered, the shoebox simulation time takes between 3 and 5 seconds. Summing up the time required by the simplified models for each building and considering the simulation time of the whole building models, the simplified building models reduced the computing time of the energy simulation by 134.78 and 8.18 times for Positano and Langer, respectively. Such discrepancies in time reduction are due to the time required for the detailed models to be simulated. Indeed, the speed of the detailed model's simulation mostly depends on the shape of the thermal zones and the external shading objects. Even though Positano kindergarten is composed of only three thermal zones, all of them are characterized by a complex shape, while Langer primary school is mostly composed of parallelepiped-shaped thermal zones. Moreover, the number of surfaces representing the urban context in Positano is approximately 3.5 times the one in Langer.

4. Conclusion

In this work, a new simplification algorithm capable of properly estimating the energy use of complex-shape buildings reducing the simulation time was tested. The algorithm can convert every building of whatever shape and geometry into a representative shoebox energy model. The conversion involves the simplification of the building geometry, apertures and adjacencies, and the transformation of the buildings' obstructions into shading opaque elements.

To test the procedure at the individual building level, two educational buildings of complex shape located in Bolzano, Italy, were studied, i.e., Positano kindergarten and Langer primary school. Firstly, both buildings were modeled in detail in terms of geometry, construction assemblies, internal loads, schedules and surrounding context. Then, they were calibrated thanks to monitored indoor temperature data of the schools' classrooms considering the two variables characterized by the largest uncertainty: ventilation rates and people densities. Afterwards, the simplification algorithm was applied to obtain shoeboxes from the detailed thermal zones. Finally, detailed and simplified models were simulated in EnergyPlus using the same weather file and the simulation results were analyzed and compared. The comparison highlighted that, in both case studies, the simplification algorithm is able to convert complex-shape building thermal zones into shoeboxes that can predict their annual heating demand with high accuracy and through significantly faster energy simulations. In general, the heating needs are slightly overestimated by the shoeboxes, leading to total overestimates equal to 5.62 % and 4.60 %, for Positano kindergarten and Langer school, respectively. Since shoeboxes have proven to be more capable of predicting thermal behavior of the detailed building model in winter rather than in summer, the implementation of new solutions for managing the incoming radiation is needed as further research.

In terms of computing time, the simplified models' energy simulations were 135 and 8 times faster compared with the detailed ones for Positano and Langer, respectively.

The significantly faster simulations achieved by the shoeboxes, together with their high accuracy in predicting the detailed model's energy performance, allow this simplification algorithm for building level applications to be used.

Acknowledgement

This research was developed thanks to the Geology, Civil Protection and Energy Office of the Municipality of Bozen-Bolzano, within the framework of the Project IndAIR-Edu – "Indoor Air Quality and Ventilation Effectiveness in Educational Buildings" (CUP: I56C18000180005; Free University of Bozen-Bolzano, Faculty of Science and Technology, RTD call 2018).

References

ASHRAE 2013. *ASHRAE 90.1-2013. Standard energy standard for buildings except low-rise residential buildings.*

Battini, F., G. Pernigotto, and A. Gasparella. 2021a. "A parametric analysis of the impact of thermophysical, geometry and urban features on the energy demand of a simplified building shoebox model." In *Proceedings of Building Simulation 2021*, Bruges, Belgium

Battini, F., G. Pernigotto, and A. Gasparella. 2021b. "Development of a shoeboxing approach for Urban Building Energy Modeling." In *Proceedings of the VI International High Performance Buildings Conference at Purdue*, West Lafayette, IN, US.

Dogan, T., and C. Reinhart. 2013. "Automated conversion of architectural massing models into thermal 'shoebox' models." In *Proceedings of Building Simulation 2013*, Chambéry, France.

Dogan, T., and C. Reinhart. 2017. "Shoeboxer: An algorithm for abstracted rapid multi-zone building energy model generation and simulation." *Energy and Buildings* 140: 140-153. doi: https://doi.org/10.1016/j.enbuild.2017.01.030

Dugaria, S., G. Pernigotto, and A. Gasparella. 2021. "Indoor conditions in educational buildings: the case of Bolzano schools." In *ASHRAE Topical Conference Proceedings*, Athens, Greece.

Roberts, J. A., G. De Michele, G. Pernigotto, A. Gasparella, and S. Avesani. 2022. "Impact of active façade control parameters and sensor network complexity on comfort and efficiency: A residential Italian case-study." *Energy and Buildings* 255: 111650. doi: https://doi.org/10.1016/j.enbuild.2021.111650

UNI. 1995. *UNI 10339:1995. Air-conditioning systems for thermal comfort in buildings: general, classification and requirements. offer, order and supply specifications.*

UNI. 2018. *UNI CEN/TR 16798-6:2018. (2018). Energy performance of buildings - ventilation for buildings - part 6: Interpretation of the requirements in en 16798-5 -1 and en 16798-5-2 - calculation methods for energy requirements of ventilation and air conditioning systems.*

Zhu, P., D. Yan, H. Sun, J. An, and Y. Huang. 2019. "Building Blocks Energy Estimation (BBEE): A method for building energy estimation on district level." *Energy and Buildings* 185: 137-147. https://doi.org/10.1016/j.enbuild.2018.12.031