BIM-based interoperable workflow for energy improvement of school buildings over the life cycle

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Abstract –

Simulation and predictive models to verify the energy performance of new or retrofitted existing buildings strongly need tuning procedures based on energy monitoring in the operational phase, thus to avoid performance gap concerns. The value chain of an uninterrupted information for energy models based on design data (e.g. for new buildings) or on paper documents and additional surveys (e.g. for existing buildings) is crucial to perform a reliable design optioneering process. The present research applies a BIM2BEM approach to provide a public administration with a model for facility management (i.e. BIM) and a model to assess energy improvement and check the choices (i.e. BEM), as a pilot project on school buildings renovation. Schools are frequently out-of-date buildings in harsh need of structural and energy refurbishment and public administrations require consistent economic evaluations considering the payback time of the proposed solutions. Additionally, O&M (Operation & Maintenance) costs should be included in a life cycle evaluation of the buildings. Two schools with different layouts and configuration adopted as case studies to compare energy simulation to actual consumption. The workflow empowers the energy simulation results highlighting the accuracy of energy modelling in different situations and it introduces possible tuning strategies to decrease uncertainty.

Keywords –

Predictive models; energy retrofit; BIM, interoperability.

1 Introduction

Nowadays, digitalization of design processes is BIM-based and allows an uninterrupted information chain [1] promoting a consistent energy model based on design data through BIM2BEM (Building Information Model to Building Energy Model) procedures enabled by gbXML interoperable format [2]. Furthermore, the possibility in existing cases to compare the predicted results with actual energy consumptions is imperative to identify suitable tuning criteria for energy models that always differs from real use [3]. The proposed BIM-based framework could empower in the whole life cycle an accurate evaluation of the building changes that are key factors to manage the asset and to guarantee the economic feasibility of renovation strategies [4]. The research aims at investigating how to use the BIM methodology for existing building management and how to implement energy retrofit strategies based on performance analysis by means of dynamic simulations accomplished through BEM. The main innovation and value is the interoperability of the models that allows to guarantee the conformity of the information in the design and evaluation environments. The possibility to extract the energy model from the BIM model is a step towards an optimized workflow that is not currently implemented in the practice when design and energy evaluation are always running on parallel tracks [5]. The performance gap that affect the energy simulation in comparison with actual performance in the running phase often heavily affects reliability of the models and time and cost are wasted to understand where is the misleading factor. Many factors collaborate on performance gap, however variability of occupancy, weather data, modeling assumptions and real performances of the building referred to designed and modeled ones are the main issues to be addressed [6]. The possibility to reduce the discrepancy of information and to define the reliability of simulation models is thus fundamental for AEC sector and to reach the nZEB goals. Different uses of the buildings are more or less prone to these errors and educational facilities are a very interested field of application because of the relevance of the thermal behavior of the building related to comfort conditions and learning performance of the users. At national level the school building stock is highly inefficient, as the 75% has been realized before energy laws [8][9] and thereby it is outdated and in need of retrofit and structural interventions [13] [14]. In the paper a new methodological approach is proposed defining BIM model for existing buildings and translating data to BEM models. A comparison of energy simulation and real consumption is used to understand the reliability of the model in different building configurations and to define tuning procedures that can be based on sensing and IoT.

2 Methods and tools

The use of the BIM methodology in combination with BEM energy analysis software for existing buildings is implemented in order to carry out preliminary analyses for renovation strategies and maintenance interventions to improve performance and reduce energy consumption. The data transmission between the two digital environments is guaranteed by interoperability which is the ability of a system to cooperate and exchange information with other different systems in a more or less complete and error-free way with the aim of optimizing resources reliably even between non-homogeneous information systems, both in software and hardware. This issue is becoming increasingly important when we talk about BIM-oriented design. The interoperability between BIM and BEM is a quite new issue and there are not many operational suggestions available for relocating data from architectural to energy models [7]. The data transfer process makes possible to keep the value chain of the information reducing discrepancies and possible inconsistencies contributing to exacerbate the performance gap, and increase time and cost of the realization.

2.1 Workflow

The analysis path uses Autodesk Revit as BIM authoring tool and IES VE as BEM dynamic simulation software (Figure 1). The architectural spaces defined in Autodesk Revit are defined as bounded analytical spaces and thus translated as thermal zones in the BEM. Analytical spaces are objects used to define and analyze of volumes that have thermal characteristics and specification allowing to store information about that thermal zone (e.g. occupancy rate, ventilation rate, temperature set points, etc.) to perform static and dynamic analyses on heating and cooling loads. The BIM model adapted for energy simulation should be enriched with data about thermal characteristics of the envelope, thermal specification for loads and parameters of the thermal zones and plants efficiency and typology. In this way it is possible to enable load calculation in the BIM environment or dynamic simulation in further simulation environments (directly into Green Building Studio or through *.gbXML file in IES VE, Design Builder, etc.). In the present research a workflow BIM2BEM through gbXML is adopted to eventually simulate the thermal behavior of two case studies.

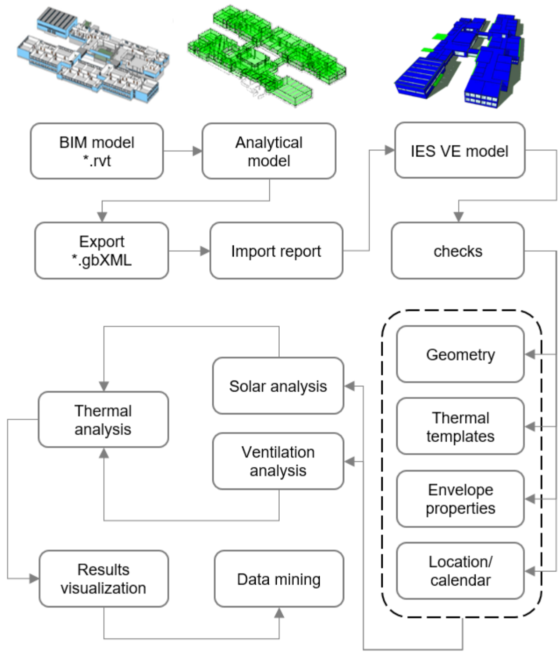


Figure 1. Workflow for interoperability BIM2BEM.

2.2 Scope and research problem

In the case studies the BIM methodology has been proposed to the public client (the Municipality of Seregno, Northern Italy) in order to manage the existing school building stock. The BIM2BEM path has been adopted to simulate different condition of the schools during time (and with refurbishments adopted in comparison with original situation) and to evaluate the advantages of different design options for further energy retrofit strategies (design optioneering). The information coming from the BIM database have been translated into the BEM simulation model to perform dynamic simulations. It is also possible to go back to enrich the BIM model with BEM calculated values for thermal spaces enabling a bi-directional information flow. In the present research the main scope was map the interoperability process and to test the reliability of energy model in comparison with energy consumption data through a data mining process.

2.3 Data mapping

The interoperability process needs a strong control and detailed data mapping to assure consistency of the model with the real conditions of the building spaces. The importing process through gbXML file is accompanied by an IES VE report showing the encountered problems and the measures taken by the software to fix them. The report also lists the presence of architectural holes in the external envelope, making impossible to carry out the energy analysis. The report is thus a first step to evaluate the process, however, a specific data mapping has been defined through *error sheet* to guide the process for further implementation of the methodology (Figure 3Figure 2).

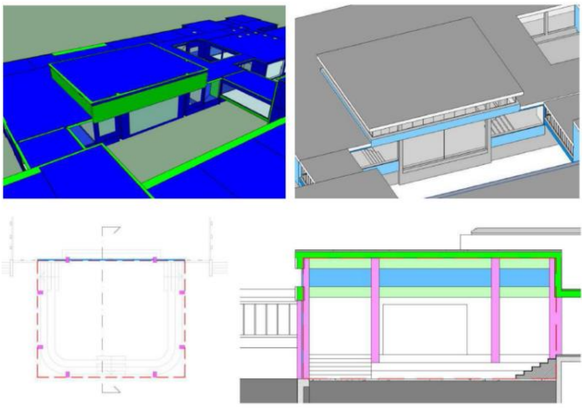


Figure 2. Specific data mapping of the import errors through BIM2BEM and suggestions for the simplification of the energy model.

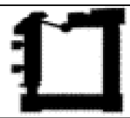
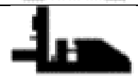
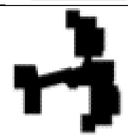
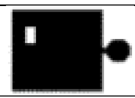
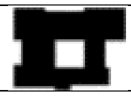
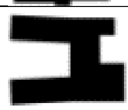
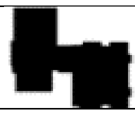
3 Case studies

The research started with the analysis of the educational facilities in the municipality of Seregno, northern Italy where 11 educational facilities dating from 1900 to 1987 are located. The municipality of Seregno is located near to Milan in the province of Monza and Brianza and it is one of biggest cities strongly developed between ’80s and ’90s. the greatest part of the expansion of the city dates in the ’90s and the quality of construction about energy performance cannot be considered high due to the low level of insulation introduced by the national energy laws in 1976 [8] and 1991 [9]. The thermal transmittance that can be assumed for public buildings realized in that period ranges between 0.8 and 0.6 W/m^{2}K for vertical opaque envelope and 3.5 W/m^{2}K for transparent surfaces. Nevertheless, the school buildings have been previously realized as reported in Table 1, this means lower values that can be assumed about 1.1 W/m^{2}K for opaque envelope and 5.7 W/m^{2}K for transparent surface where no retrofit occurred [10]. The school building stock in Seregno is representative of the characteristics of the 62,000 national schools, that have a total annual energy consumption is about 11’630 GWh (i.e. 70% for heating and 30% for electricity). The specific heating and hot water consumption for public schools is about 180 kWh/m^{2}year whereas the requirement for new construction is less than 40 kWh/m^{2}year, according to current standards [11] and EU Directives [12]. The community of Seregno has 44,875 inhabitants. Given the high density of population, a growing number of schools have been developed over the years, both public and private, and currently the following structures are located in the territory:

- n. 9 nurseries;
- n. 3 kindergartens;
- n. 7 primary schools;
- n. 6 secondary schools of first grade;
- n. 7 secondary schools of second grade.

Among these 32 structures, 11 public schools where energy bills were available have been selected.

Table 1 School Facilities in Seregno, Northern Italy.

n.	Year	School Level	Floor configuration
1	1900-1920	Primary (Stoppani)	
2	1920-1940	Primary (Cadorna)	
3	1965	Secondary (Mercalli)	
4	1969	Kindergarten (Nobili)	
5	1970	Secondary (Manzoni)	
6	**1972**	**Primary (A. Moro)**	
7	**1973**	**Kindergarten (H.C. Andersen)**	
8	1974	Multilevel (Gianni Rodari)	
9	1975	Nursery (Aquilone)	
10	1976	Nursery (San Carlo)	
11	1987	Secondary (Don Milani)	

A first analysis has been focused on maintenance costs and BIM-based management strategies while for the present research, 2 case studies among these schools have been chosen to develop a detailed analysis in order to compare the dynamic simulation about thermal behavior with data on the actual consumption. The comparison aims at underlining the level of reliability of energy models and the discrepancy introduced by standard simulation setup compared to actual thermal behavior of the school buildings. The realization of the BIM model with different stages of evolution during time and with different architectural and retrofit development has been useful for the municipality to store information about the historical evolution of the assets. The interoperability path allows also estimating and verifying the energy consumption in the life cycle. Among the 11 schools two case studies has been selected considering the listed criteria:

- area > 1000 m^2;
- construction year;
- morphology;
- interventions occurred over time.

The two case studies are part of the same school complex, the "Aldo Moro" Comprehensive Institute: they are the Primary school “Aldo Moro” (n. 6 in table 1) and the kindergarten “H.C. Andersen” (n. 7 in table 1). It is worthy to note that the 82% of the school is configured in blocks with a distribution corridor, and one or two sides of classrooms. There are only two cases in which a different use and a more complex organization of the space can be guessed. The corridor-classroom distribution is the main traditional configuration that can be found in the national school building stock. A new concept of school related to pedagogic needs is addressed by the two different cases (n.5, n.7 in Table 1). The traditional primary school A. Moro has been simulated in two versions describing the upgrade introduced in the last 2 years regarding envelope retrofit to be compared with energy bills and the complex school kindergarten “H.C. Andersen” has been simulated in the original configuration and with the following extension, (i.e. 1/4 of the space was added during refurbishment).

3.1 Traditional school with a distribution corridor and one side of classrooms

The primary school “A. Moro” presents a traditional distribution of the educational spaces and it has been retrofitted by improving thermal resistance through an insulation layer for the opaque envelope and substituting the windows to increase thermal performance of the transparent envelope. The building has two main blocks in which different uses are hosted. The north side hosts the classrooms section while in the south block the gym, offices, auditorium and canteen are located (Figure 3).

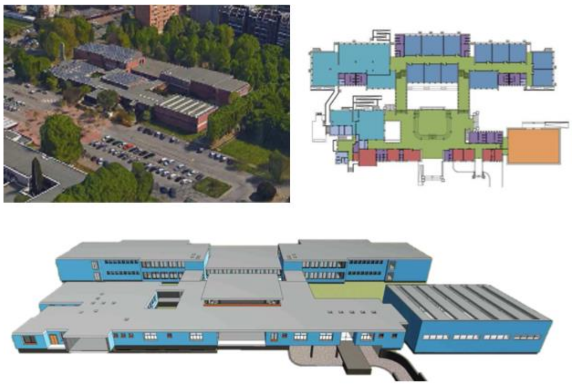


Figure 3. View of the Primary School “A. Moro”, floor area with functional spaces and BIM model.

The modelling process started with a detailed BIM model which included the two stages of implementation of the school: the original envelope configuration and the refurbished one. The refurbishment focused on the envelope increasing the energy performance of transparent and opaque envelope. Specifically the interventions have been: the windows replacement and the increased resistance of the opaque envelope by adding a polystyrene insulation layer.

3.2 Complex school with classrooms around a hall used as informal educational space

The kindergarten “H.C. Andersen” is the most significant complex school in the list of table 1. It has an L shaped ground floor, which has been extended with a fourth squared pavilion giving a final compact squared shape to the whole school. The school has ne floor and as can be seen in Figure 4, the floor plan has the classrooms located in different sides facing a wide common space as connection and distribution. It has also a didactic role for social skills improvement because for children it is very important to exploit informal spaces and learn how to exchange information in a sort of indoor playground. Therefore, the school configuration is a square with a central common space with skylights to bring the daylighting in the central area. A BIM model with the first configuration (L shaped) and the updated configuration (Square shaped) allowed the translation of the information to the energy simulation software. Once all envelope stratifications had been arranged in the BEM model and the correct association of the delimiting building components for each thermal zone has been checked, it is needed also to verify that the envisioned use of the rooms as set out in Autodesk Revit has been maintained. The energy software assigns to the rooms the specific use, which is closer to that defined in the BIM model. The verification of a multiple selection of rooms can be performed through the building manager tool. The database manager is used to set customizable profiles of each thermal (i.e. 7.30 a.m. to 6.30 p.m. for the school spaces and 10.00 a.m. to 1.30 p.m. for the kitchen, Saturday, Sunday and public holidays have been excluded).

Figure 4. Aerial view of the kindergarten “H.C. Andersen”, floor area with functional spaces and BIM model.

3.3 Interoperability process assessment

For both the case studies, problems in the data transfer process have been faced starting with the partial loss of information of the bounding elements of the single thermal zones.

A complete interoperability process should allow the import into IES VE of all the setups defined in the Autodesk Revit model. A partial interoperability is still a good result nevertheless the goal is to develop a workflow that could be easily managed and automatically replicated. Thermal zone delimitation and settings, envelope constructions, use of the spaces, schedule and thermal plants are the fundamental information to be included in the thermal model. Many information are missed if specific modelling strategies are not adopted in the BIM model. As first the internal partitions such as walls, floors and roofs should have active the local delimitation parameter in order to create the correct thermal zone.

In order to overcome specific losses of information about material stratification a fixing downstream procedure can be adopted selecting in detail the element and checking the assigned material and possibly adjusting the stratification directly in the energy simulation software. If the envelope type is transferred from BIM to BEM, a step forward is to check the integrity of the correct layering of the opaque envelope because material layers with no thermal definition in BIM are lost in the translation. This can occur for example for plaster or some substrate.

The problem can be solved by editing the envelope layering adding or replacing the missing layers with existing materials in the libraries or creating new materials. The adjustment and bug-hunting process is a time-consuming hard task. When the model has been completed in all its parts and the correct link between the various elements has been verified the energy simulation can be successfully performed. The results of the energy simulations have been compared to the energy bills in the last three years to confirm the accuracy and measure the uncertainty of the predictive model referred to actual energy use.

4 Results

Energy simulation of the two case studies have been performed in the four configuration (i.e. two for each case study) simulation the existing situation of the schools, before the retrofit and before the extension.

The predicted energy consumption related to the envelope but also to the thermal plants specifications have been compared with the energy bills collected in the archive of the Seregno Municipality.

The main results of the research is thus to emphasize the potential of the optimization process introduced as methodology that uses BIM data to simulate the building energy performance and can be directly compared to existing actual data with a confidence interval to be estimated. The successfully application of the methodology enables and speed up the process providing reliable results and thus potentially consistent economic feasibility evaluations.

4.1 Energy evaluation of the traditional school

In the case of the "A. Moro" school, which has a traditional layout configuration, the energy gave monthly results according with the actual energy bills although a standard setting of the indoor space has been adopted. The standard setting includes data about internal gains, people density, ventilation rates, temperature set points and time schedule that are derived by commonly adopted value for the traditional building use. The more traditional distribution of school with spaces organized as commonly adopted since 1900 has less discrepancy compared to complex and innovative solutions and thus it can be expected that some parameters could not be equally fitting in the traditional and complex schools of the case studies.

Coming back to the "A. Moro" school, in Figure 5 the comparison between the original version and the retrofitted building is shown. The envelope solutions introduced clearly enhance the thermal behavior in the winter period. It is worthy to note that while the most complex "H. C. Andersen" school required to make conscious alterations to the templates changing from the standard data setting to a specific custom definition, for the traditional primary school no additional tuning was needed to obtain a result with an acceptable percentage gap between simulation and energy bill (Figure 6).

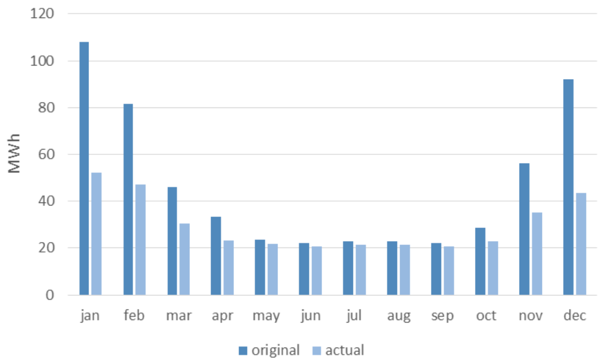
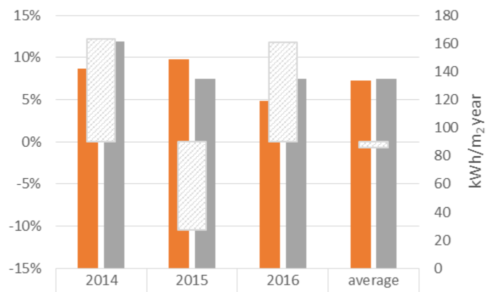


Figure 5. Primary school “A. Moro”: energy consumption simulation of in the original situation and the retrofitted version.



	2014	2015	2016	average
energy bill	141.97	148.86	118.91	133.885
energy consumption	161.68	134.74	134.74	134.74
percentage gap	12.2%	-10.5%	11.7%	-0.6%

Figure 6. Primary school “A. Moro”: actual energy bills compared to energy consumption simulation and the percentage gap between simulation and real data.

The acceptable uncertainty level is also due to the geometry of the spaces, which inevitably affects their use and also they have been designed with a specific vocation. Actually, the corridor facing the classrooms is not conceived as a place of permanence of the students, it is a simple element of distribution and connection and its size is not exceeding the tolerance of an aggregated energy use and setting. On the contrary, precisely because in the kindergarten "H. C. Andersen" there is neither a need nor an obligation to keep pupils in classes, the school has been designed with a central internal space conceived as a wide circulation space that is also a covered playground suitable for expression of sociality. Consequently the space is constantly used to host the different activities carried out in the school and the children have the possibility to relate with a different space that seem a square or an open space for events with a zenithal daylighting that is far from the traditional enclosed learning space of the classroom. Hence, the configuration of school building should also take into account the specific needs that the different types of pedagogic training require. The school is not indeed a kindergarten however in the setup of simulation and in the assumption the same standards are often supposed.

4.2 Energy evaluation of the complex school

The kindergarten “H.C. Andersen” increased its energy consumption in 2014 when the new section of the school has been realized. In Figure 7 the energy bills and in the original situation (L shaped building) and in the following three years are reported. The average value has been also added as currently adopted procedure to compare energy simulation to actual consumption.

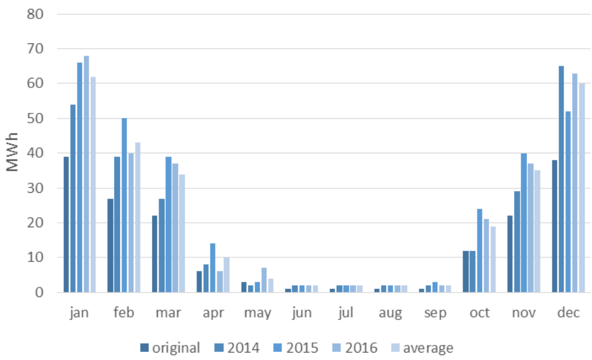
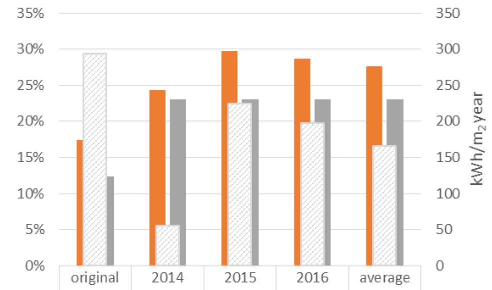


Figure 7. Kindergarten “H.C. Andersen”: energy consumption simulation of in the original situation and during the following three year of operation phase.

The first simulation using the BIM based data has been enriched in the BEM setup with standardized value of people density for the occupancy schedule, nevertheless the particular configuration of the central space defined a different scenario. For that reason the first result diverged from the energy bill of about 40% and therefore a fine tuning of the model have been performed. The standard people density equal to 0.5 people/m^2 adopted for standard school is suitable for classroom spaces however in the complex school case study the central space is used with a lower density that is not comparable to the standard value however educational activities take place. The schedule of use were also re-defined to address this different occupancy rate into the space. Furthermore, a higher temperature compared to the standard value, due to the children presence and the space in which the fan coils are not effective into heating the core part of the school has been established. With this fine tuning procedure and measures the percentage of discrepancy decreased to less than 20% compared to the three years average value of the energy bill (Figure 8). A detailed assessment of users' flow has not been introduced in this stage of the research however could be interesting in future research development. Could be useful to stress that the level of the school and the methods of use are not too flexible, although obviously some uncertainty of the results is linked to the variability of occupant attendance to the classes.



	original	2014	2015	2016	average
energy bill	174.38	243.86	297.19	286.92	275.99
energy consumption	123.07	230.36	230.36	230.36	230.36
percentage gap	29.4%	5.5%	22.5%	19.7%	16.5%

Figure 8. Kindergarten "H.C. Andersen": actual energy bills compared to energy consumption simulation and the percentage gap between simulation and real data.

5 Conclusion

The aim of the research was to explore the possibilities of comparing building consumption directly to predictive models realized through an interoperability BIM2BEM process. The digital twin of the building allows creating an archive of the retrofit interventions and a database for the asset management in the life cycle. The BIM model also permits the transfer of the stored information to other platforms adopted for specific energy assessment and simulations. Through the BIM2BEM interoperability path, an uninterrupted information chain is created generating additional value and ensuring process consistency. By means of predictive models, adjusted and customized during the different phases of the building's life cycle, it is possible to evaluate the design optioneering in an analytical way enabling conscious choices based on results whose accuracy must be verified and double checked.

It is particularly important to give reliability to the process in order to verify the simulation results to critically understand the thermal behavior of buildings. It is very important to ensure the accuracy when approaching existing buildings the need to be upgraded. In fact, the economic feasibility of the retrofit interventions is strictly related to the accuracy of energy savings that can be predicted in the design phase. Too often the energy intervention are not supported by reliable energy calculation and declared NZEB are not NZEB, are not that efficient and the goal is unattended. In the school is also crucial to assure that indoor conditions will be comply with standard comfort level to implement and support learning performance and users' development. Finally, a complete interoperability process needs to be ensured in order to promote reliability and to improve the information management in the BIM2BEM process. The manually implemented part is an adjustment which decreases the level of detail of the BIM in order to reduce the errors in the BEM. This process requires accuracy and simplification not involving crucial elements to assess the thermal behaviour of the building.

Acknowledgments

The authors would like to mention and thank Arch. Manuel Mancosu and Arch. Laura Canonico for the setup of the models and the fundamental work on the simulation process. The research starts from the work of Eng. Federico Gulino, where documentation about the Seregno school building stock has been collected and analyzed. A special thank goes to the Municipality of Seregno for the support and cooperation in collecting data and availability of materials.

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