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Article

A Building Energy Efficiency Optimization Method by Evaluating the Effective Thermal Zones Occupancy

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Abstract: Building energy efficiency is strongly linked to the operations and control systems, together with the integrated performance of passive and active systems. In new high quality buildings in particular, where these two latter aspects have been already implemented at the design stage, users' perspective, obtained through post-occupancy assessment, has to be considered to reduce whole energy requirement during service life. This research presents an innovative and low-cost methodology to reduce buildings' energy requirements through post-occupancy assessment and optimization of energy operations using effective users' attitudes and requirements as feedback. As a meaningful example, the proposed method is applied to a multipurpose building located in New York City, NY, USA, where real occupancy conditions are assessed. The effectiveness of the method is tested through dynamic simulations using a numerical model of the case study, calibrated through real monitoring data collected on the building. Results show that, for the chosen case study, the method provides optimized building energy operations which allow a reduction of primary energy requirements for HVAC, lighting, room-electricity, and auxiliary supply by about 21%. This paper shows that the proposed strategy represents an effective way to reduce buildings' energy waste, in particular in those complex and high-efficiency buildings that are not performing as well as expected during the concept-design-commissioning stage, in particular due to the lack of feedback after the building handover.

Keywords: building energy efficiency; dynamic simulation and validation; post-occupancy evaluation; equipment operations and management

1. Introduction

1.1. Research Background

The reduction of energy use in the built environment through optimizing building energy efficiency is a strategic research challenge [1], in particular after the Fourth Assessment Report of the IPCC [2]. This international report comprises three working groups that deal with the scientific basis of global warming (Working Group I), its consequences (Working Group II), and options for slowing the trend (Working Group III). This latter section specifically deals with the global potential of building energy efficiency for mitigating global warming phenomenon. In fact, given that 36% of the global consumption is imputable to the built sector [3], the energy and environmental concerns around buildings becomes ever more urgent. The research efforts concerning building energy efficiency are continuously making progress through a wide variety of multiple issues. For example, without being exhaustive, important progress is being undertaken in the following fields:

(i) innovative strategies for energy conservation coupled with indoor comfort improvement [4];
(ii) advanced procedures for envelope system optimization [5,6] toward zero energy buildings;
(iii) elaboration of new high performing renewable energy plants, *i.e.*, PV panels, to optimize the building-plant integrated system performance and environmental impact [7];
(iv) increasingly detailed tools for simulating the thermal-energy performance of buildings and their components with respect to specific climatological contexts [8];
(v) development of the building occupants' awareness and its effect in energy saving [9];
(vi) elaboration of environmental strategies spanning the single-building boundary, for energy optimization of urban inter-building networks at neighborhood level [10–12].

The increasing building technology complexity has guided the research through the development of specific procedures to assess and verify effective operational performance [13], during the service life of buildings. Energy-saving measures applied to existing buildings were also considered as financial and environmental priorities, in order to achieve cost-effective energy and environmental improvements, and add value to the properties [14,15]. In this field sustainable strategies for optimizing the performance of the operational control system [16] have also increasingly assumed importance, especially in complex high-technology buildings. In fact, in such buildings, other traditional retrofit interventions (*i.e.*, envelope and plants' improvement and substitution, *etc.*) have represented important financial barriers to energy saving. Specific research has examined the topic of energy saving procedures through innovative control and management strategies, that could reach about the same efficacy as standard retrofit practice [17]. The research issue around the necessity to integrate supply and demand sides has produced important developments, leading to new research purposes based on the system thinking in design and management of buildings [18]. Smart and innovative buildings considered environmental, social, economic and technological factors. Thus the use of multi-attribute models for sustainability assessment of intelligent buildings was a key strategy to quantify the improvement of energy efficiency and occupants' satisfaction in [19].

Together with these energy efficiency techniques, a recent research effort arose from the evidence that buildings often do not perform as well as predicted [20], in particular those high-complexity buildings equipped with high efficiency energy systems. The continuous improvement of building technologies also highlighted the importance of Post-Occupancy Evaluation (POE), in order to bridge the gap between designers, building managers, and occupants after handover [21]. This same research by Menezes *et al.* [21] in particular showed that the combination of monitoring data about post-occupancy analyses with advanced simulation engines, is able to optimize the reliability of building energy prediction within 3% of actual consumption. It is evident that better predictions also improve energy analyses and saving procedures.

This articulated research background took into account the importance of occupants' feedback, that represents a key factor in order to comprehend and reduce building energy requirements [22,23]. To this aim, Gill *et al.* [24] correlated measured data about low-energy houses in the UK with occupants' surveys results. They found that occupants' behavior played a key role in increasing the gap between predicted and observed energy consumption. To analyze the same issue, another important research effort concerned the awareness and cooperation of occupants, in order to achieve the best results in terms of energy saving [25]. In particular Murakami *et al.* in [26] proposed a new system to control HVAC and lighting systems through implementation of occupants' requests. They found that an interactive control system based on occupants' requests was able to produce a 20% energy savings with respect to traditional air conditioning control strategies.

1.2. Motivation

Starting from this complex background, this research proposes a method that combines an energy efficiency post-occupancy evaluation with occupants' attitude assessments, in order to elaborate operational energy saving strategies for complex existing buildings.

The investigation criterion consisted of the belief that building service behavior and thermal zone function are often too far from the predictions at the design stage, especially in complex multipurpose buildings, that are largely subject to high variability of people's behavioral attitudes [27]. Only equipment commissioning is not enough to guarantee the best energy efficiency potential and occupants' satisfaction level. Also, even if continuous commissioning [28] is a strategic procedure to maintain the correct functionality of HVAC equipments, only technology monitoring is still not enough to address the maximum energy saving potential, while maintaining occupant satisfaction. Thus occupants' needs and their activity schedules should be taken into account to elaborate interactive post-occupancy control procedures, based on the effective building requirements during its service life.

The case study building was the university campus of Baruch College, built in Manhattan, New York, in 2001 (Figure 1). Both architectural and technological features showed the high quality level of the design and construction intervention. Despite that, a notable energy waste was registered. Such a waste was mainly imputable to the effective use of the indoor spaces, which was far from the forecast performed at the pre-occupancy stage. As previously mentioned, this kind of failure could be hardly reduced through traditional building retrofits, because both materials and equipments are already high quality solutions, difficult to replace by cost-effective solutions.

Figure 1. Localization of the case study building in Manhattan, NYC; (**a**) aerial view of the neighborhood; (**b**) aerial view of the block.

(**a**) (**b**)

1.3. Purpose of the Work

In this perspective, a post-occupancy analysis of complex multipurpose buildings' thermal-energy behavior is the main focus of this research, aimed at elaborating an energy optimization method consisting of rescheduling of the energy operations through the assessment of the effective users' occupancy of the building.

The research pivot was the study of the thermal-energy behavior of complex multipurpose buildings through in-field monitoring and dynamic simulation modeling, calibration and validation. The objective was to reduce the energy requirement of such buildings by optimizing the equipment operations for lighting, heating, cooling, ventilation, and all the appliances. The optimization was based on the effective post-occupancy evaluation of spaces' use, occupants' attitudes and their global comfort perception. In particular, the strategy for optimizing the energy and environmental performance concerned the rescheduling of the integrated electric equipment. This rescheduling implemented post-occupancy evaluations about the effective occupants' weekly attitudes within the building. To this end, an integrated procedure of: (i) numerical analysis, (ii) in-field monitoring, (iii) occupants' survey elaboration and (iv) setup-calibration-validation of a dynamic simulation model was carried out. The proposed procedure took into account: (i) building construction characteristics, (ii) technical equipment technology and main operations and (iii) building users' attitudes and needs related to the complex weekly schedules. In fact, given the relatively young service life of the building and its complexity, energy conservation strategies based on control and management of operations could represent effective and low cost strategies to be implemented in such cases.

2. Methodology

2.1. Workflow of the Activities

The proposed procedure is illustrated in the following flow diagram (Table 1).

Table 1. Methodology layout.

Sequence	Description of the phases
1	Choice of the appropriate building to achieve interesting through post-occupancy evaluation for energy savings [29]; ↓
2	Analysis of the building design documents to evaluate architectural and technological properties (*i.e.*, HVAC, lighting, heat water production, equipments data); ↓
3	Energy modeling and year-round dynamic simulation of the building base-case scenario (Scenario 0); ↓
4	In-field analysis campaign: indoor environmental measurements, occupants' surveys and interviews following the approach in [23]; ↓
5	Whole building model calibration and validation through monthly electricity bills; ↓
6	Data analysis and elaboration of the optimization strategy through post-occupancy experimental assessment; ↓
7	Dynamic simulation of the optimized scenatio (Scenario 1): year-round simulation of the case study model after the implementation of the proposed strategy; ↓
8	Analysis of results.

2.2. Choice of the Building

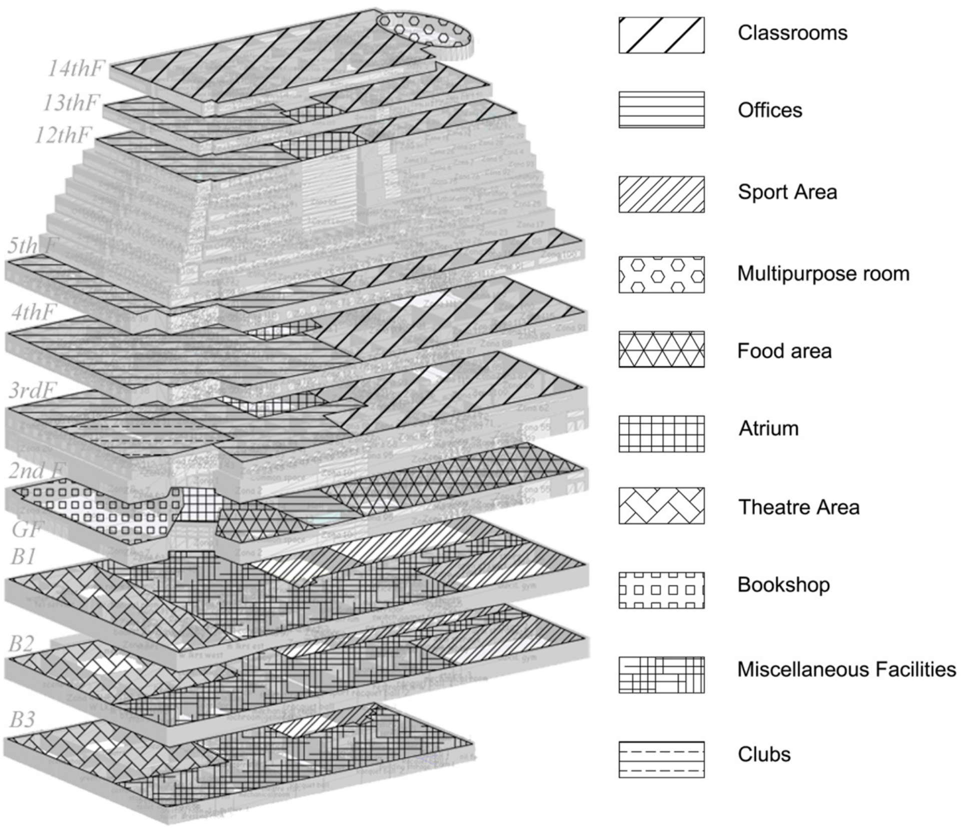
Looking at complex and relatively new buildings, important differences between pre-occupancy and post-occupancy scenarios are observed. Even if building design is becoming an ever more integrated procedure, there is still an important gap between design forecasts and effective building use [30]. With the purpose of bridging this gap, a multipurpose complex building, such as the one used in this case study, requires to be periodically monitored in-field. Such monitoring is fundamental in order to understand which are the main activities, their weekly timing and the yearly agenda. This information is necessary to schedule all the energy equipment and to reduce energy waste while maintaining the same occupants' perception about the indoor environment.

In this view, the choice of the building constitutes a fundamental step of the research when implementing such a field-based post-occupancy strategy. In fact the Vertical Campus of the Baruch College in Manhattan is an iconic building where multiple functions and different users operate every day. In addition, as reported in [4], the estimated annual energy requirements of this building fall within the highest energy range. Considering this, an integrated procedure to save energy related to post-occupancy evaluations about users' behavior represents an effective and relatively sustainable solution compared to traditional retrofits. In particular, an economically impactful retrofit solution, *i.e.*, the energy equipment renovation or interventions on the envelope, could represent an insurmountable barrier to the effective retrofit implementation, given also the relatively new age of the building, that was built on 2001. Looking at the further development of the research, the choice of the building is also aimed at assessing the impact of such field-based strategies at a city-scale, taking also into account potential inter-building effects in terms of energy policies [31,32].

2.3. Building Characterization

The Baruch College is a 73,019 m^2 multipurpose building that occupies an entire block (Lexington: 3rd Avenue and 24th–25th Streets) in Manhattan, New York. It represents the hub of the college. It is 72 m high and it has 14 floors and three basements. In the lower floors there are athletics and recreation spaces such as the Marvin Antonowsky Performing Arts Complex, the Rose Nagelberg Theatre and Engelman Recital Hall, gym and auxiliary gym areas, a swimming pool, racquet-ball courts, movies rooms, and some offices. The ground floor includes a food court, a kitchen, a cafeteria, a campus bookstore and a large, eight floors high, atrium. In the upper floors there are more than 100 high-technology classrooms and research facilities, faculty and administrative offices, conference rooms, lounge areas, and several students' centers, such as additional computer labs and multipurpose rooms (Figure 2).

Figure 2. Internal spaces layout of the building.



Due to this complexity and variety of devices, the Baruch College building (also named Newman Vertical Campus) was honored by the American Institute of Architects with the highest award that the College offers to an individual building [26]. The architectural characterization of the internal and external walls, the ceilings, the roof and the transparent envelope are described in Table 2, and the main energy equipment schemes are reported in Figure 3.

Table 2. Architectural modeled details and thermal properties of the envelope.

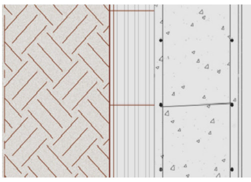
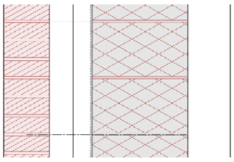
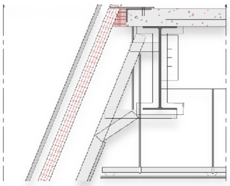
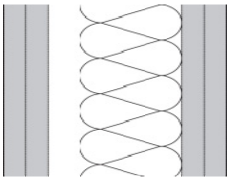
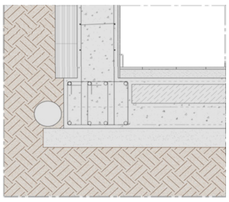
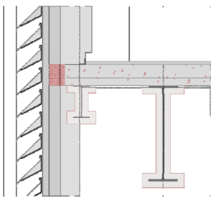
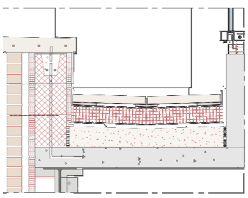
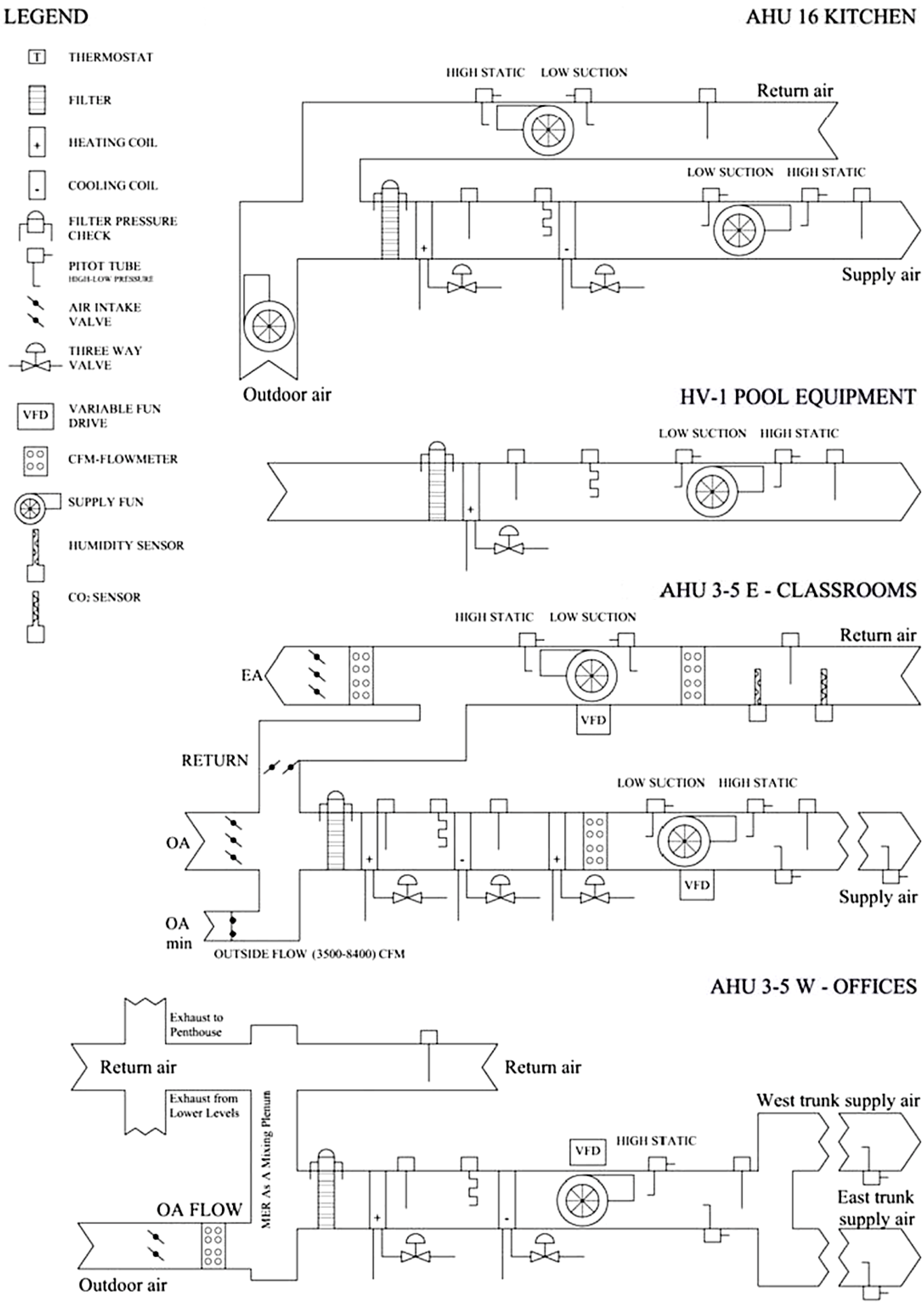
Architectural Element	**AutoCad Architectural Element (Out:left-In:right)**	**Layers Materials description and thickness (from other side)**	**Thermal proprieties Transmittance U; Thermal capacity Ct**
External Wall Basements		1. Bitumen felt layers 20 mm; 2. Ethylene propylene EPDM 20 mm; 3. Aerated brick 160 mm; 4. Reinforced Concrete 500 mm; 5. Mineral wool 100 mm; 6. Gypsum plaster 10 mm	U = 0.27 W/m^2 K; Ct = 14.9 kJ/m^2 K
External Wall from Ground Floor to 5th floor		1. Brick 200 mm; 2. Air gap 80 mm; 3. Bitumen 4 mm; 4. Concrete paviour 200 mm	U = 0.44 W/m^2 K Ct = 168.3 kJ/m^2 K
External Wall 6th Floor to 14th floor		1. Aluminum sheet 15 mm; 2. Air layer 50 mm; 3. Elastomeric foam 50 mm; 4. Air layer 360 mm; 5. Gypsum plasterboard 20 mm	U = 0.41 W/m^2 K Ct = 18.5 kJ/m^2 K
Internal Partitions from B3 floor to 14th floor		1. Gypsum plasterboard 15 mm; 2. Gypsum plasterboard 15 mm; 3. Air layer 90 mm; 4. Gypsum plasterboard 15 mm; 5. Gypsum plasterboard 15 mm	U = 0.34 W/m^2 K Ct = 33.9 kJ/m^2 K
Ground Floor		1. Reinforced concrete 250 mm; 2. Bitumen felt/sheet 4 mm; 3. Reinforced concrete70 mm; 4. Bitumen felt/sheet 4 mm; 5. Concrete tiles 40 mm	U = 0.16 W/m^2 K Ct = 178.4 kJ/m^2 K
Internal Ceiling		1. Linoleum 4 mm; 2. Elastomeric foam 4 mm; 3.Cast concrete 200 mm	U = 1.68 W/m^2 K Ct = 191.1 kJ/m^2 K
Roof		1. Linoleum tile 4 mm; 2. Cement screed 50 mm; 3. Concrete reinforced 50 mm; 4. Pur 130 mm; 5. Concrete very lightweight 200 mm; 6. Concrete reinforced 100 mm	U = 2.12 W/m^2 K Ct = 230.2 kJ/m^2 K

Figure 3. Main thermal equipment schemes.



2.4. Building Modeling and Energy Simulation of the Case Study

The building modeling started with the analysis of the same building in terms of layout of indoor spaces and functions (Figure 2), technical details (Table 2), and energy equipments (Figure 3) with the corresponding schedules and control system. The building layout and the thermal-energy characterization were modeled through a graphical interface in order to be imported into the EnergyPlus [33] engine. The dynamic simulation was performed using the typical meteorological year weather file of New York [34] as boundary conditions. All the thermal zones were modeled through characterizing all the partition materials (Table 2). The energy equipment for cooling, heating, ventilation (Figure 3), and all the miscellaneous features such as lighting systems, cooking stoves, computers, office supplies, gym equipment, and toilet and looker rooms' facilities were characterized through the dynamic simulation engine. In particular, the analysis and modeling procedure consisted of the following steps [35]:

i. Preliminary assessment of design documents: drawings and reports about architectural, mechanical, electrical, and functional systems;
ii. Description of building geometry layout within the physical modeling interface;
iii. Elaboration of the energy model through the characterization of the building architectural elements (external walls, ceilings, roof, internal partitions, doors and windows, *etc.*) and their thermal properties (Table 2);
iv. Description of the building thermal equipment and utility supplies within the energy model, characterizing each thermal zone with its equipment for the final analysis of consumption;
v. Assessment of the control systems and characterization of the actual schedules, to realistically represent the base case scenario, that is a pre-occupancy based scenario;
vi. Elaboration of the base case scenario (Scenario 0) consisting of the continuous operation of the overall energy equipment, to maintain temperature and CO_2 levels under the limit values all over the year;
vii. Energy simulation of the base case scenario;
viii. In-field post-occupancy analyses consisting of: temperature and CO_2 levels monitoring, occupants' participation to surveys and interviews;
ix. Elaboration of the optimized scenario model (Scenario 1), thanks to the information collected in phase viii;
x. Calibration and validation of the model through whole building electricity monthly bills [36–38];
xi. Simulation of the year-round performance of the optimized scenario;
xii. Analysis of the results: evaluation of the potential benefits of such post-occupancy based strategy.

2.5. Post Occupancy Evaluation through in-Situ *Analysis*

The effective understanding of the occupants' attitudes at the college was determined through periodical visits to the campus (three times a week during the period between September and December 2011), where both spot measurements and people surveys were carried out, following the approach described in [39]. These guidelines about surveying methodology [39] allowed us to define the environmental variables to consider, such as: (i) when the survey should be given, (ii) how often, (iii) the sample size, (iv) the number of groups (*i.e.*, students, professors, visitors, technicians were considered in this study). The effective involvement of 80 overall college users consisted of the participation in interviews and questionnaires aimed at understanding their attitudes and requirements about campus life within the building. In particular, following the method proposed by Zalejska-Jonsson in [23], the questionnaire was divided into three main parts: part 1 concerned questions about age, origin, role within the campus and some background data; part 2 regarded people's perception about indoor thermal, acoustic and lighting indoor conditions, during the course of the year; part 3 included investigation about occupants' attitudes, activities' weekly schedules and main needs. The questionnaire was proposed to the occupants through paper formats, waiting for their filling for approximately 15–20 min. Each question had multiple choices structure, and there is a comment box below, aimed at allowing the occupants to explain their attitudes, perceptions, and requirements (Table 3).

By collecting all the data and organizing the main results, this proposed survey allowed us to understand:

(i) the overall perception about thermal-acoustic-lighting characteristics within the most visited indoor spaces such as classrooms, cafeteria, fitness areas, atrium, swimming-pool area, 8^{th} floor lounge area;
(ii) possible sources of dissatisfaction and the relative causes;
(iii) location of the most used indoor thermal zones for spending free time and main activities that the students used to do in that time;
(iv) principal activities and sport facilities used by each participant.

Data collection about comfort perception showed that the 34% of participants declared themselves to be experiencing good global comfort conditions, without noting any specific sources of dissatisfaction. The main cause of discomfort derived from the overall survey was too much noise (41% of the participants), but acoustical comfort optimization was not considered in this phase of the research. The second cause of discomfort was represented by the sensation of cold in the classrooms (21% of the participants). Given the investigation of professors' opinion as well, it was found that it actually represented a specific strategy to maintain students' attention during lessons, thus it was not due to any thermal equipment failure. It was also found that, in students' opinion (23 people), the lighting level was too low in the connection areas, especially because students were used to also occupying connection areas for chatting, meetings and so on. This highlighted an overall inappropriate use of these areas, especially during students' free time. Both in the ground floor and the 8^{th} floor, where the biggest lounge areas are located, there is an overall good comfort perception. Such a perception showed that the appropriate spaces for spending free time provided satisfactory comfort conditions, in the occupants' opinion.

The second in-field analysis consisted of the experimental measurements of several parameters characterizing the indoor environment, such as: air temperature, CO_2 levels, and relative humidity of the thermal zones. This activity was aimed at registering eventual improper functioning within the occupied thermal zones. All the thermal zones of the buildings were monitored during periodical visits from September 2011 to December 2011. No anomalous condition was registered. In fact all the thermal zones registered environmental control parameters within the ranges. Also, the monitoring was performed during the usual activity schedule for each thermal zone, and at different times during the day (morning, lunch break, afternoon), in order to take into account several occupancy scenarios. There was no alarm activation of AHU Basic control functions such as: (i) supply air reset, (ii) CO_2 control with respect to the acceptability range 700–1200 ppm, (iii) carbon monoxide control, (iv) damper control, (v) VFD control/operation, (vi) outside air volume monitoring, (vii) safety utilities, (ix) pre-heat process. Table 4 represents the monitoring results of the main thermal zones of the building.

Table 3. Questionnaire submitted to the Vertical Campus respondents (Baruch College, 55 Lexington Avenue at 24th Street, NY, USA).

Contact information (optional)	First Name and Family name (optional)					
Background information:						
Are you male or female?	M	F	*What is your age?*	17–21	21–30	More than 30
Do you live in the City?	YES	NO	*Where do you come from (US or extra-US)?*			
About Vertical Campus, indoors:						
Overall, how would you rate the VC indoor environment?	Too cold	Too hot	Too noisy	Too dark	Comfortable	I do not know
In particular:						
About classrooms	Too cold	Too hot	Too noisy	Too dark	Comfortable	I do not know
About caffetteria	Too cold	Too hot	Too noisy	Too dark	Comfortable	I do not know
About fitness area	Too cold	Too hot	Too noisy	Too dark	Comfortable	I do not know
About atrium	Too cold	Too hot	Too noisy	Too dark	Comfortable	I do not know
About connection areas	Too cold	Too hot	Too noisy	Too dark	Comfortable	I do not know
About swimming pool area	Too cold	Too hot	Too noisy	Too dark	Comfortable	I do not know
Other places (please, specify which)	Too cold	Too hot	Too noisy	Too dark	Comfortable	I do not know
About your Life in Vertical Campus (VC):						
What is your main activity at the Vertical Campus?	Studying	Teaching	Meeting people	Administration	Technical support	Other (…)
If you are a Student, approximately, how much time do you spend in classrooms every day?			1–2 h/day	3–4 h/day	5–6 h/day	>6 h/day
Do you usually play sport at VT?	YES	NO				
If yes, what kind of sport?	Fitness	Racketball	Swimming	Volleyball	Basket	Other (…)
Approximately how much time do you spend playing sports at VC every week (in hours)?			1–3	4–7	7–14	More than 14
Where do you mainly spend your time when you finish your classes?	Corridors	Classrooms	Lounge areas	Cafeteria	Fitness centre	Abroad
Do you usually spend your free-time alone or with friends at VT?	Alone	In small groups (<3 people)		In large groups (>3 people)		
What is your role at VC?	Student	Professor	Technician	Visitor	Other (…)	
What is the most crowded place at VT?	Corridors	Classrooms	Lounge areas	Cafeteria	Fitness centre	Nowhere
How satisfied are you with those crowded places (if there are)?	Very Satisfied	Somewhat Satisfied	Undecided	Somewhat Dissatisfied	Very Dissatisfied	
Personal opinion:						
Is there anything that you would like to change, to improve VC liveability?		YES	NO			
If YES, what and why would you like to improve?						
Thank you your time!						

Note: These data will be used to a work (about master thesis) by two Italian Student.

Table 4. Thermal zones monitored indoor parameters.

Thermal Zone	Floor Positioning	CO_2 Levels (ppm)	Air Temperature (°C)	Relative Humidity (%)
Pool	Basement 3rd	1007	24.5	55.8
Theatre	Basement 3rd	792	22.5	14.5
Recital Hall	Basement 3rd	887	21.8	21.4
Gym	Basement 3rd	928	21	22.5
Auxiliary Gym	Basement 3rd	1036	29	25.3
North Atrium	Ground floor	891	20.5	16.8
Court Atrium	Ground floor	865	20.6	18.3
South Atrium	Ground floor	1044	17	14.9
Cafeteria	Ground floor	922	20.6	17.3
Court Servery	Ground floor	784	21.6	9.1
Kitchen	Ground floor	806	21.6	12.8
Court Lounge	8th floor	881	23	16.8
Court Lounge 2	8th floor	880	22.9	16.8
Office 215	8th floor	850	22.9	16.1
Laboratory 160	8th floor	839	22	15.6
Lecture Room	14th floor	959	20.6	21.7
Multipurpose Room	14th floor	815	20.7	15.5

Note: values refer to November 18th, 2:30 p.m.–4:30 p.m.

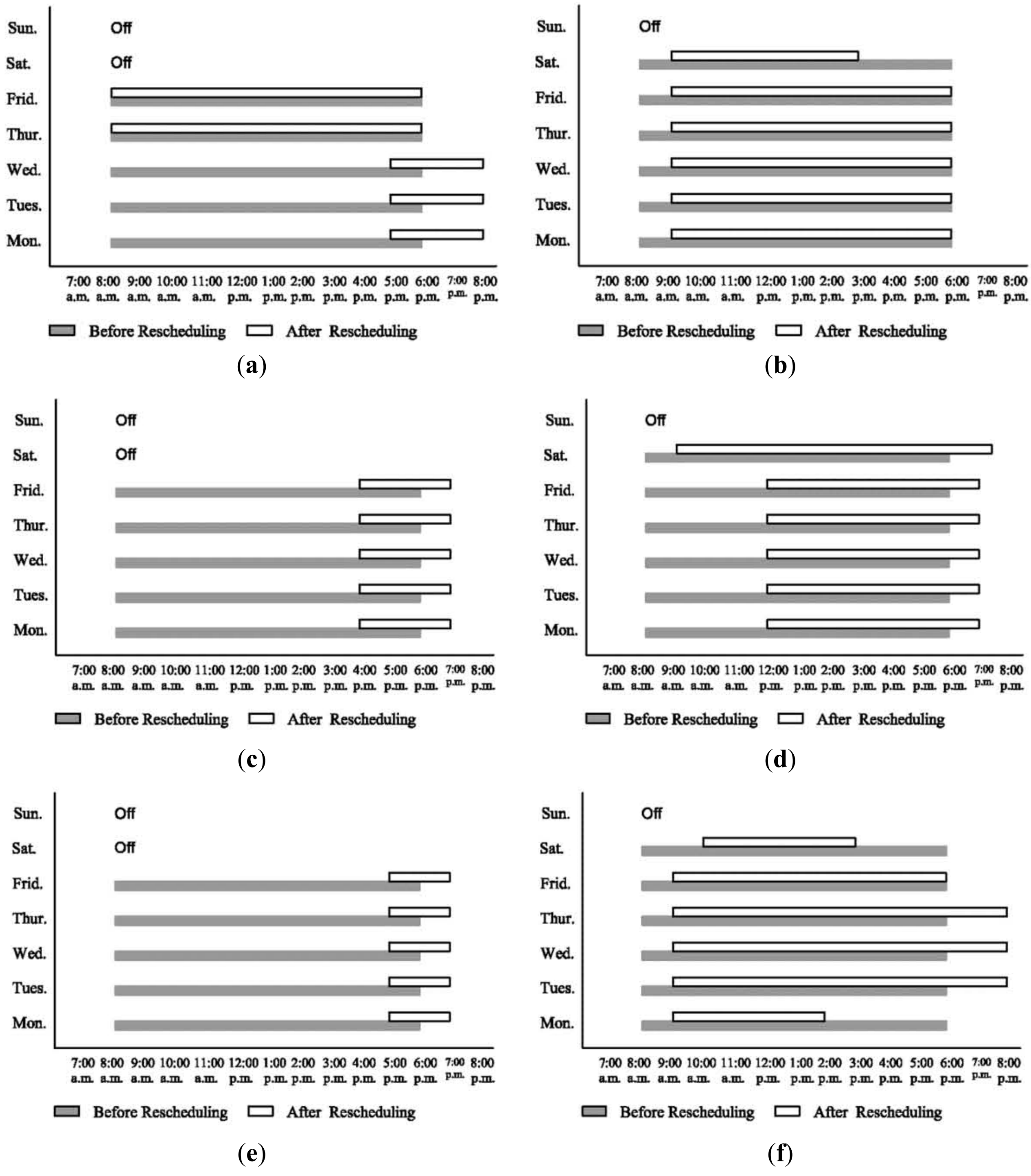
3. Energy Optimization Strategy

The analysis of the monitored data and of the walkthrough inspection results suggested that the campus equipment and control system were working according to the temperature and air quality set-points. Thus the overall analysis inspired by the Post-occupancy Review of Buildings and their Engineering (PROBE [30]) highlighted the lack in feedback between the predicted building occupants' attitudes and the effective use of the thermal zones. This was an important reason why a high energy requirement was observed for the building, especially if the case study building is compared to the building stock information collected by Howard *et al.* in [40].

In order to implement this data and to elaborate a methodology for saving energy, a post-occupancy strategy based on occupants' attitudes analysis and overall equipment rescheduling was proposed. This same proposed methodology had also the important role to implement an optimization solution only based on occupancy patterns, after verifying the operative conditions of the energy plants and their correct technological functionality, as is the purpose of the work.

Combined analysis of thermal and Indoor Air Quality (IAQ) conditions and occupants' opinions, guided the overall field-based rescheduling. In particular, the collected information was useful to discover if students usually occupied appropriate spaces, in particular during their free time. Focusing for example on the classrooms, it was found that all these zones were always maintained under comfort conditions, even when there were no ongoing lessons (constant CFM, cubic feet per minute, ventilation rate and temperature level). In fact, during the walkthrough building inspections, each classroom was occupied by a couple of people for independent study, sprawling the energy requirement all over the campus. In these cases, the optimization intervention consisted of turning off the class equipment when there were no lessons, guiding the students to spend their time in the appropriate lounge areas or multipurpose rooms. Also, the information collected through the interviews, allowed a large schedule reduction in the theatre area, that was usually only used during the weekends and just a few days before the shows. All the modifications, coherently with the post-occupancy evaluations, consisted of the proposed optimization strategy reported in Figure 4.

Figure 4. Occupancy analysis and electricity equipment weekly re-scheduling. (**a**) Theatre; (**b**) Classrooms—Lecture rooms; (**c**) Offices; (**d**) Club rooms (Gym, *etc.*); (**e**) Raquetball rooms; (**f**) Bookstore.



The re-scheduling operations were elaborated coherently with the effective monitored occupancy that represents the optimized scenario. The proposed optimization strategy did not impact the indoor thermal comfort and IAQ target in all the thermal zones during the appropriate occupants' activities. In fact the proposed strategy assumed that occupants should be guided to occupy those areas that are specifically dedicated to each activity, in order to avoid important energy waste produced by incorrect use of the campus facilities.

The base case scenario (Scenario 0), elaborated through pre-occupancy evaluation, consisted of the same continuous operation control setup all over the campus, in order to maintain the target ventilation rates and the indoor air temperature set-point at 72 °F (22.2 °C) in winter and 78° F (25.56 °C) in summer. Its weekly operation consisted of: (i) Monday to Friday: 6:00 a.m.–8:00 p.m.; (ii) Saturday: 6:00 a.m.–12:00 p.m.; (iii) Sunday: off. Given the mentioned inspection of the building, the new optimized energy equipment re-scheduling (Scenario 1) consisted of turning off all the equipment within those thermal zones where there were not appropriate activities, *i.e.*, when the campus users should not be allowed to stay for saving energy purpose. The operational control rescheduling was carried out for each thermal zone, as described in Figure 4. Thus, after analyzing the effective occupants' attitudes within each thermal zone typology (*i.e.*, classrooms, offices, *etc.*), these operational schedules were modified coherently with the in-field post-occupancy analysis of the overall building.

4. Whole Building Model Calibration and Validation Procedure

Dynamic simulation was used to predict and describe year-round building thermal-energy performance [41], coupled with spot measurements and occupancy in-field analysis. Even if the reliability of Building Energy Simulation (BES) techniques is always improving, important studies showed that the gap between effective and predicted energy requirement was still too significant (from 0.25 to 2.5 in [42]) to be considered a rigorous research tool. The Vertical Campus model and calibration was elaborated following [43,44]. The initial model (before the iterative revision process) was built as described in Section 2.4. The source hierarchy principle [44] was applied considering: (i) spot measured data (indoor air temperature and CO_2 concentration); (ii) surveys and physical verification (walkthrough inspections, photographs, geometry and architecture relief); (iii) interviews of occupants and building operators; (iv) material properties datasheets; (v) operation and maintenance manuals; (vi) as-built documentation (architectural and mechanical drawings, wall configurations, windows properties, electric equipment data and schedules); (vii) ASHRAE 55 standard [45] and simulation engine references. The ASHRAE Guideline 14 [36] defined different monthly or hourly acceptable limits for calibration in terms of Mean Bias Error (MBE) and Cumulative Variation of Root Mean Squared Error (CVRMSE). In this work, given the utility bills monthly documentation, the reference limit corresponded to 1% for both MBE and CVRMSE.

The model met the defined acceptance criteria after two iterations based on the progressive aggregation of the classroom and offices floor thermal zones. In fact, classrooms and offices represented a sort of macro-areas with open spaces from 4th to 13th floor. Thus the function of the internal partitions could be neglected, given the occupancy peculiarities and the uneven use of these areas. As specified above, students and professors occupied these areas for very few hours respect to the forecasted operational schedules. Therefore, these areas were randomly occupied for most of the time: all the doors were open and the energy consuming equipment ran continuously, even if there were no people inside and no activities were scheduled.

The first model iteration overestimated the energy requirement with a MBE equal to 8, the second iteration had MBE equal to 6; and the last definitive iteration presented 0.06 in terms of MBE and 0.09 in terms of CVRMSE. Thus it respected both the criteria described in [44]. Thus, this last model was chosen to characterize the whole Vertical Campus' thermal-energy behavior.

5. Discussion of Results

5.1. Potential Energy Saving for each Floor

Following the in-field post-occupancy analysis, this section reports the main results of each floor characterization, before and after the optimization. The primary energy requirement of each floor, for each month, corresponds to the overall electricity need. Thus cooling, heating, hot water generation, ventilation, lighting, and auxiliary equipment (pumps, *etc.*) are considered.

Figure 5 represents the monthly primary energy requirement for electricity related to each representative floor of the campus, where lighter lines describe the optimized scenario (Scenario 1), and black lines correspond to the actual scenario (Scenario 0). These results show the importance of the effective occupants' requirements and the building "agenda" during the week in terms of energy saving potential. In fact the areas where there is the maximum energy saving are those thermal zones which energy plants always run (classrooms and teachers' offices), even if there are no students courses or professors' activities occurring. In particular, the main results show that:

- from the 4th to the 13th floor: thanks to the real use analysis of classrooms (east side) and offices (west side), the predicted energy saving is up to 38% in January for the 13th floor (32% at 8th floor, 28% at 11th floor, and 27% at 6th floor);
- ground floor and basement 2 have almost negligible energy savings, given the few rescheduling operations allowed;
- basement 1 and basement 3 have very large energy saving potential due to the wrong facilities' operation of sport clubs and theatre areas. The predicted savings are up to 16% and 10% in January for basement 3 and 1, respectively.

To identify energy requirement sources of each floor, the annual results are represented in Figure 6. Energy requirements for heating represent the overall main contribution in each floor, especially in classrooms and office areas that have lower indoor thermal gain than ground floor or basements with sport facilities. The only exceptions are the ground floor and second floor, where the glass atrium represents a good source for solar heat gain, together with kitchen and restaurant facilities. In basement 3, room electricity and auxiliary equipment assume a very important role, given the presence of amenities and sport facilities,. Coherent with previous analysis, typical floors with classrooms and offices present very similar electricity consumption, and the main energy saving contribution is produced by the reduction of the heating system operation time.

Attention should also be paid to the variation of energy saving trends during the course of the year. In fact the more effective results of this methodology are obtained at the same time of severe climatological conditions, such as January-February in winter and July-August in summer.

This methodology assumes an important value also enlarging the perspective of inter-building energy peak demand, because it contributes to the reduction of blackout risks during those critical periods for electricity system.

Figure 5. Monthly energy requirement comparison between actual and optimized scenarios of representative floors.

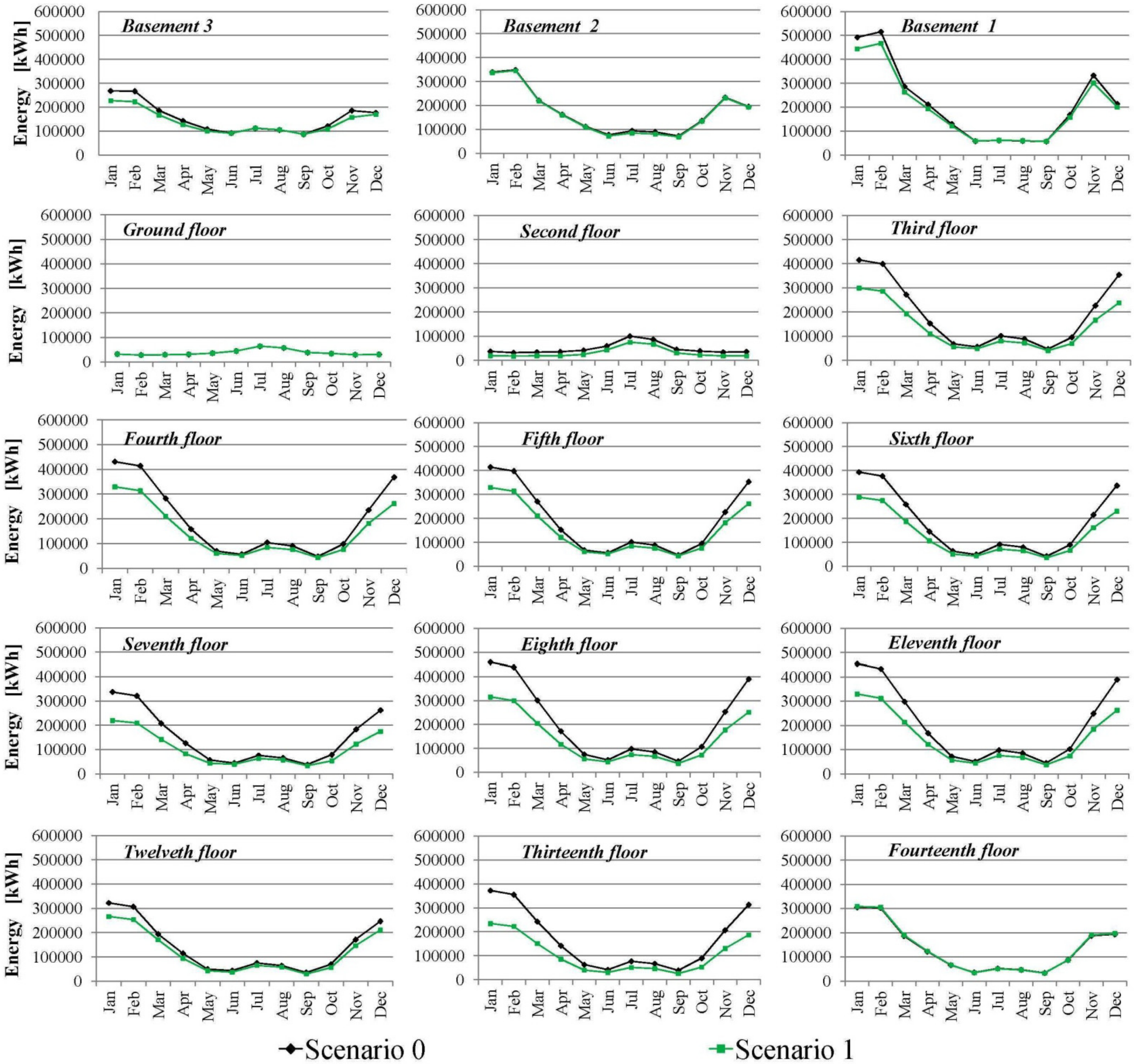
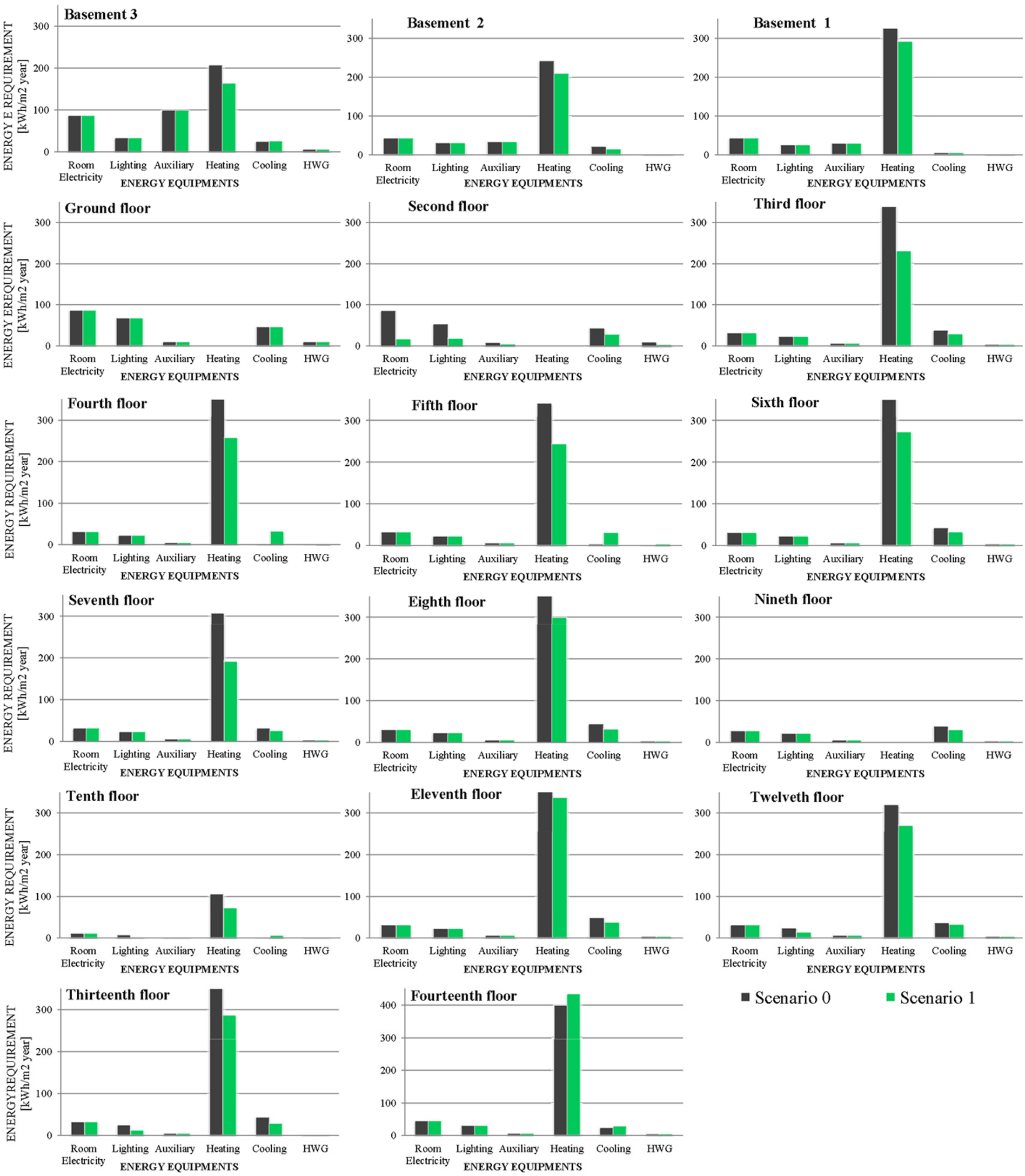


Figure 6. Year-round energy requirement comparison between Scenario 0 and Scenario 1, for each floor, and for each electricity equipment typology.

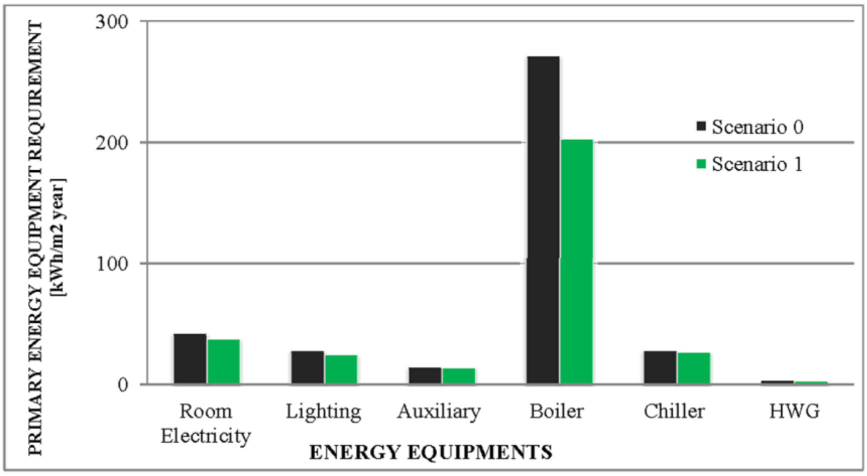


5.2. Whole Building Assessment

The analysis of the overall energy predicted impact of the study is represented in Figure 7, where primary energy requirements of the whole campus are reported in terms of kWh/m^2 per year, before and after the optimization strategy.

The implementation of the proposed methodology predicts an overall year-round energy savings of 25% for heating, 7% for cooling and auxiliary, 14% for lighting and 14% for room electricity. An almost negligible effect is registered for heat water generation, given the lowest variation of toilets and sport facilities operations. Finally, the proposed strategy predicts to reduce the yearly primary energy requirement of the multipurpose building from 385.8 kWh/m^2 year to 306.7 kWh/m^{2}year.

Figure 7. Whole building energy requirement comparison between actual and optimized scenarios.



6. Conclusions and Future Development of the Research

In this paper an in-depth methodology, based on post-occupancy field-based energy analysis, dynamic simulation and validation, occupancy monitoring and user surveys, was proposed and applied. The final purpose was to elaborate effective and low-cost strategies for saving energy after understanding the actual occupancy and operations of complex buildings. To this end, the proposed method was applied to the University Campus of the Baruch College in Manhattan, New York City. It represents a sort of microcosm building, built in 2001 with a high quality level of design and construction. The purpose was to discover how effective such a field-based low cost strategy could be in order to reduce that energy waste specifically produced by the "performance gap" between forecasted and effective indoor building behavior. After modeling, simulating and validating the actual scenario, the indoor environment condition was periodically monitored from September to December 2011. Building occupants such as students, teachers and technicians were also involved into the research to discover their real weekly attitudes within the building. The monitoring showed that all the energy equipment was operating in the predicted way, maintaining all the indoor parameters (air temperature and CO_2 levels) within the specified ranges. However the equipment's operation seemed to be very far from the effective occupants' requirements, which were observed through periodical visits and user surveys. Therefore a field-based optimization strategy was proposed consisting of electricity equipment rescheduling, coherently with the campus users' attitudes and the building management guidelines. Through modeling and simulating the optimized scenario, important primary energy savings were predicted. In particular the proposed methodology was able to achieve an average monthly overall energy saving of 20.5% for heating, cooling, lighting, auxiliary sources, room electric equipment. In fact the overall primary energy requirement for electricity decreased from

385.8 kWh/m^2 year to 306.7 kWh/m^2 year, calculated through a calibrated and validated dynamic simulation model.

Finally the research results suggest that the proposed low-cost energy saving method could become strategic in the future. In particular, the efficacy increases if this strategy is applied to those relatively new existing buildings that already have high performance materials and technologies, where other improvement interventions are thus not cost-effective. The same proposed strategy could represent an important solution in order to control and re-schedule the overall energy equipment of complex buildings, where the operation and control system are not already commissioned through post-occupancy evaluation. Also, these field-based procedures, if applied to a group of complex buildings in a dense urban context such as the Manhattan area, could produce important energy savings results at the inter-building and urban scale as well.

An important future development of the research will consist of the implementation of the proposed strategy, in order to quantify the effective energy saving and evaluate the impact on occupants' satisfaction.

The proposed analysis at building scale will be also applied to interesting energy-consuming neighborhoods, in order to evaluate the whole potential energy saving of dense urban areas, *i.e.*, the Kips Bay in Manhattan, NY, where the Vertical Campus and many other educational buildings are located.

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References

1. Chwieduk, D. Towards sustainable-energy buildings. *Appl. Energy* **2003**; *76*, 211–217.
2. Intergovernmental Panel on Climate Change. *Climate Change 2007: Synthesis Report*; IPCC Fourth Assessment Report; IPCC: Geneva, Switzerland, 2007; No. 104. Available online: http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm (accessed on 12 November 2012).
3. U.S. Green Building Council. Available online: http://www.usgbc.org/Default.aspx (accessed on 12 June 2012).
4. Chen, S.; Huang, J. A Smart green building: An environmental health control design. *Energies* **2012**, *5*, 1648–1663.
5. Domínguez, S.; Sendra, J.J.; León, A.L. Towards energy demand reduction in social housing. *Energies* **2012**, *5*, 2263–2287.

6. Wei, G.; Turner, W.D.; Claridge, D.; Liu, M. Single-Duct Constant Air Volume System Supply Air Temperature Reset: Using Return Air Temperature or Outside Air Temperature? In *Proceedings of the Second International Conference for Enhanced Building Operations*, Richardson, TX, USA, 14–18 October 2002. Available online: http://txspace.di.tamu.edu/bitstream/handle/1969.1/5165/ESL-IC-02-10-01.pdf (accessed on 9 July 2012).
7. Cotana, F.; Rossi, F.; Nicolini, A. Evaluation and optimization of an innovative low-cost photovoltaic solar concentrator. *Int. J. Photoenergy* **2011**, *1*, 1–10.
8. Asdrubali, F.; Cotana, F.; Messineo, A. On the evaluation of solar greenhouse efficiency in building simulation during the heating period. *Energies* **2012**, *5*, 1864–1880.
9. Peschiera, G.; Taylor, J.E.; Siegel, J.A. Response-relapse patterns of building occupant electricity consumption following exposure to personal, contextualized and occupant peer network utilization data. *Energy Build.* **2010**, *42*, 1329–1336.
10. Pisello, A.L.; Taylor, J.E.; Xu, X.; Cotana, F. Inter-building effect: Simulating the impact of a network of buildings on the accuracy of building energy performance predictions. *Build. Environ.* **2012**, *58*, 37–45.
11. Xu, X.; Taylor, J.E.; Pisello, A.L.; Culligan, P. The impact of place-based affiliation networks on energy conservation: An Holistic model that integrates the influence of buildings, residents and the neighborhood context. *Energy Build.* **2012**, *55*, 637–646.
12. Bo-ot, L.M.; Wang, Y.H.; Chiang, C.M.; Lai, C.M. Effects of a green space layout on the outdoor thermal environment at the neighborhood level. *Energies* **2012**, *5*, 3723–3735.
13. Wang, Z.; Wang, L.; Dounis, A.I.; Yang, R. Multi-agent control system with information fusion based comfort model for smart buildings. *Appl. Energy* **2012**, *99*, 247–254.
14. Ouyang, J.; Ge, J.; Hokao, K. Economic analysis of energy-saving renovation measures for urban existing residential buildings in China based on thermal simulation and site investigation. *Energy Policy* **2009**, *37*, 140–149.
15. Popescu, D.; Bienert, S.; Schützenhofer, C.; Boazu. R. Impact of energy efficiency measures on the economic value of buildings. *Appl. Energy* **2012**, *89*, 454–463.
16. Yu, Z.; Haghighat, F.; Fung, B.C.M.; Zhou, L. A novel methodology for knowledge discovery through mining associations between building operational data. *Energy Build.* **2012**, *47*, 430–440.
17. Claridge, D.E.; Liu, M.; Deng, S.; Turner, W.D.; Haberl, J.S.; Lee, S.U.; Abbas, M.; Bruner, H.; Lee, B.V.S.U. Cutting heating and cooling use almost in half without capital expenditure in a previously retrofit building. European Council for an energy efficient economy. In *Proceedings of European Council for an Energy Efficient Economy (ECEEE) 2011 Summer Study*, Niagara Falls, NY, USA, 26–29 July 2011; Volume *4*, pp. 74–85.
18. Kolokotsa, D.; Rovas, D.; Kosmatopoulos, E.; Kalaitzakis, K. A roadmap towards intelligent net zero- and positive-energy buildings. *Sol. Energy* **2011**, *85*, 3067–3084.
19. Alwaer, H.; Clements-Croome, D.J. Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings. *Build. Environ.* **2010**, *45*, 799–807.
20. Bordass, B.; Cohen, R.; Standeven, M.; Leaman, A. Assessing building performance in use 3: Energy performance of the Probe buildings. *Build. Res. Inform.* **2001**, *29*, 114–128.

21. Menezes, A.C.; Cripps, A.; Bouchlaghem, D.; Buswell, R. Predicted *vs.* actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Appl. Energy* **2012**, *97*, 355–364.
22. Deuble, M.P.; de Dear, R.J. Green occupants for green buildings: The missing link? *Build. Environ.* **2012**, *56*, 21–27.
23. Zalejska-Jonsson, A. Evaluation of low-energy and conventional residential buildings from occupants' perspective. *Build. Environ.* **2012**, *58*, 135–144.
24. Gill, Z.M.; Tierney, M.J.; Pegg, I.M.; Allan, N. Low-energy dwellings: The contribution of behaviours to actual performance. *Build. Res. Inform.* **2010**, *38*, 491–508.
25. Balaras, C.A. Energy Retrofit of a Neoclassic Office Building Social Aspects and Lessons Learned. In proceedings of American Society of Heating, Refrigerating, and Air-Conditioning Engineers (*ASHRAE)* Annual Winter Meeting, Atlanta, GA, USA, 27–31 January 2001; Volume 107-1, pp. 191–197.
26. Murakami, Y.; Masaaki, T.; Kana, M.; Masayuki, H.; Satoru, K. Field experiments on energy consumption and thermal comfort in the office environment controlled by occupants' requirements from PC terminal. *Build. Environ.* **2007**, *42*, 4022–4027.
27. Tuohy, R.P.; Humphreys, M.A.; Nicol, J.F.; Samuel, A.; Clarke, J. Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. *Energy Build.* **2007**, *39*, 823–836.
28. Redmann, N.; Mingsheng, L. Improving Building Control and System Operation Through the Continuous Commissioning® Process: A Case Study. In *Proceedings of the Third International Conference for Enhanced Building Operations*, Berkeley, CA, USA, 13–15 October 2003; Architectural Engineering—Faculty Publications; ESL-IC-03-10-13. Available online http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1036&context=archengfacpub (accessed on 9 July 2012).
29. Gou, Z.H.; Lau, S.; Chen, F. Subjective and objective evaluation of the thermal environment in a three-star green office building in China. *Indoor Built Environ.* **2012**, *21*, 412–422.
30. Dall'O', G.; Sarto, L.; Sanna, N.; Martucci, A. Comparison between predicted and actual energy performance for summer cooling in high-performance residential buildings in the Lombardy region (Italy). *Energy Build.* **2012**, *54*, 234–242.
31. Pisello, A.L.; Xu, X.; Taylor, J.E.; Cotana, F. Network of buildings' impact on indoor thermal performance. *Smart Sustain. Built Environ.* **2012**, *1*, 73–86.
32. Pisello, A.L.; Taylor, J.E.; Xu, X.; Cotana, F. Inter-building effect: Simulating the impact of a network of buildings on the accuracy of building energy performance predictions. *Build. Environ.* **2012**, *58*, 37–45.
33. Crawley, B.D.; Pedersen, C.O.; Lawrie, L.K.; Winkelmann, F.C. EnergyPlus: Energy simulation program. *ASHRAE J.* **2000**, *42*, 49–56.
34. Weather Data. EnergyPlus. Available online: http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data2.cfm/region=4_north_and_central_america_wmo_region_4 (accessed on 9 July 2012).

35. Dall'O', G.; Speccher, A.; Bruni, E. The green energy audit, a new procedure for the sustainable auditing of existing buildings integrated with the LEED protocols. *Sustain. Cities Soc.* **2012**, *3*, 54–65.
36. ASHRAE. *ASHRAE Guideline 14–2002 for Measurement of Energy and Demand Savings*; ASHRAE: Atlanta, GA, USA, 2002.
37. Efficiency Valuation Organization. *International Performance Measurement and Verification Protocol*; Efficiency Valuation Organization: Washington, DC, USA, 2007.
38. Nexant, Inc. M&V Guidelines: Measurement and Verification for Federal Energy Projects, Version 3.0; US Department of Energy: Washington, DC, USA, 2008.
39. Fink, A. *How to Conduct Surveys. A Step-by-Step Guide*, 4th ed.; SAGE Publications, Inc.: Thousand Oaks, CA, USA, 2009, pp. 1–136.
40. Howard, B.; Parshall, L.; Thompson, J.; Hammer, S.; Dickinson, J.; Modi, V. Spatial distribution of urban building energy consumption by end use. *Energy Build.* **2012**, *45*, 141–151.
41. Pisello, A.L.; Goretti, M.; Cotana, F. A method for assessing buildings' energy efficiency by dynamic simulation and experimental activity. *Appl. Energy* **2012**, *97*, 419–429.
42. Newsham, G.R.; Mancini, S.; Birt, B.J. Do LEED-certified buildings save energy? Yes, but... *Energy Build.* **2009**, *41*, 897–905.
43. Raftery, P.; Keane, M.M.; O'Donnell, J. Calibrating whole building energy models: An evidence-based methodology. *Energy Build.* **2011**, *43*, 2356–2364.
44. Raftery, P.; Keane, M.M.; Costa, A. Calibrating whole building energy models: Detailed case study using hourly measured data. *Energy Build.* **2011**, *43*, 3666–3679.
45. ASHRAE. *ASHRAE Handbook of Fundamentals*; ASHRAE: Atlanta, GA, USA, 2005; ISBN 13-978-1931862738.