BUILD SIMUL (2016) 9: 513–527
DOI 10.1007/s12273-016-0293-4

A BIM-GIS integrated pre-retrofit model for building data mapping

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Abstract

In response to rising energy costs and the impetus to reduce environmental impacts, upgrading the large building stock that is responsible for 40% of the total energy consumption to maximum energy efficiency is becoming an important task. Despite the many benefits associated with retrofit projects, they are still only slowly being implemented because of the many challenges that exist. One of these challenges is optimizing the decision between renovation scenarios based on economic and environmental goals, which can be made possible with an accurate pre-retrofit model. The intention of this paper is to introduce a pre-retrofit model that efficiently obtains and integrates multiple forms of building data as a critical step to develop a comprehensive understanding of a building to be renovated. Opportunities for utilizing building information modeling (BIM) and geographical information systems (GIS) for retrofitting projects were explored through the study of a historical campus building. With the use of as-is geometric data and as-is data, building data maps were obtained. The next step of this study is to use the model to conduct scenarios comparison and optimize renovation decision based on economic and environmental goals.

Keywords

pre-retrofitting,
as-is built modeling,
post-occupancy evaluation,
building information modeling (BIM),
geographical information systems (GIS),
data mapping

Article History

Received: 4 September 2015
Revised: 23 March 2016
Accepted: 6 April 2016

1 Introduction

It is projected that worldwide energy consumption will grow by 56% between 2010 and 2040 (EIA 2013). According to the Human Development Report of the United Nations (United Nations 2007), climate change, the human development challenge of the 21st century, is not simply a future scenario. From the view point of building science, one of the potential solutions to climate change is to ensure that buildings, which are responsible for approximately 40% of all annual energy consumption and related green house gas emissions, should be environmentally sustainable throughout their lifecycle (Miller and Buys 2008). Rising energy costs and the impetus to reduce environmental impacts have made reusing an existing building and upgrading it to achieve the maximum energy efficiency the best option, regardless of building type and climactic conditions (National Trust for Historic Preservation 2011; Verbruggen 2008; Verbeeck and Hens 2005). The recently released European Parliament Report on the Energy Roadmap 2050 (EU 2012) stated that building renovations are essential to bringing economical and environmental benefits to public and private sectors. Moreover, there is a need to scale up the current rate of building renovations to mitigate climate change and achieve adaptation goals. This strategy sets the foundation for a transformation of existing building stocks and would drive significant improvements in developing minimum energy efficiency standards. Related to these considerations, there is a growing interest in the market for an "energy efficient retrofit" of existing buildings, which offers significant benefits towards improved energy conservation, operation cost reduction (Wang and Xia 2015), increased indoor environmental quality, user satisfaction, and work productivity (Ma et al. 2012).

There is a large global building stock that needs to be retrofitted in order to reduce energy consumption and environmental impact. The practice of energy efficient retrofitting in terms of replacing chillers and boilers with

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more efficient ones and renovating building windows has been well known for years (Henriques et al. 2015; Berardi 2015). However, considering the long-term benefits of retrofits within a holistic approach is still an issue worth exploring (Olgyay and Seruto 2010). Retrofitting an existing building poses many challenges in addition to the benefits mentioned above. Due to the multifaceted goals of retrofit projects, including expansion of facility capacity, incorporation of new green technologies, improvement of indoor environmental quality, and safety, these projects are becoming increasingly complex and usually involve many stakeholders and a substantial amount of professional expertise. Retrofit projects are still only slowly being implemented for several reasons such as (i) the complexity resulting from aging systems and changes that have occurred, (ii) user involvement, (iii) the involvement of multiple stakeholders at different stages of the building lifecycle, (iv) additional challenges in financing retrofit projects, and (v) a lack of a comprehensive understanding of the financial benefits of retrofitting buildings (Yu et al. 2011; Miller and Buys 2008; Ma et al. 2012). There are still tools and methodologies that must be discovered in order to scale up the current retrofitting practice to transform the large existing building stock. These tools must be capable of factoring in multiple variables for identifying retrofit opportunities. From the perspective of investors and homeowners, financial returns and risks are unclear. This uncertainty results in a lack of a central database of aggregated retrofit savings potential that could lead and motivate future strategies. Financial barriers, limitations, and payback periods were introduced to retrofit analysis in addition to energy analysis of retrofitting buildings by several researchers (Rysanek and Choudhary 2013; Heo et al. 2012; Kumbaroglu and Madlener 2012).

Despite the increasing demand, there is limited literature on building retrofit methodology and outcomes (Balaras et al. 2000; Caputo et al. 2013; Amstalden et al. 2007; Cellura et al. 2013). With regard to the short-term benefits and the limited framework, studies focusing on "energy efficient retrofitting" have become prominent (Tommerup and Svendsen 2006; Fracastoro and Serraino 2011; Ben and Steemers 2014; Goldstein et al. 2014). Some of these relevant studies reveal a number of methods that can be classified into the following groups: (i) those based on a statistical approach (Polly et al. 2011; de Wilde et al. 2011; Heo and Zavala 2012), (ii) those based on artificial neural networks (Kwok et al. 2011; Yalcintas 2008; Swan et al. 2011; Mavromatidis et al. 2013) and (iii) those based on computational models (Asadi et al. 2012; Poel et al. 2007). In addition, some applied simulation-based studies with the use of building simulation programs such as EDSL Tas software, EnergyPlus, DOE-2, TRNSYS, ESP-r, and BLAST (Ascione 2011; Güçyeter and Günaydın 2012; Stazi et al. 2013). Many of these methods produce 2D graphical elements and cannot satisfy users' needs of complex information sharing (Che et al. 2010). There is an obvious lack of a well-defined methodology that can be used to develop pre-retrofit models to meet the requirements of collaborative design teams in retrofit projects. This study emphasizes the need for pre-retrofit model generation in order to understand and manage building information for further retrofitting studies. Based on these findings, the proposed building information modeling (BIM) and geographical information systems (GIS) integrated with a pre-retrofit model can improve the performance assessment and provide a multidisciplinary source to address all the geometric and functional information concerning an entire building. Based on a thorough review of 3D as-is geometric modeling tools, we propose a novel method to create a pre-retrofit model that efficiently obtains and integrates multiple forms of building data (Fig. 1).

2 The crucial need for pre-retrofit models

The task of converting a substantial inventory of large, dated, energy-intensive buildings into sustainable and energy efficient buildings can be overwhelming. A cost-effective way to analyze building performance, and optimize renovation scenarios based on economic and environmental goals, can be found using an accurate pre-retrofit model. Gathering this data, which is segmented and has seldom been analyzed, is one of the major challenges of retrofitting. Appropriate information capture, management, and visualization techniques may solve, mitigate, or circumvent problems caused by inefficient communication and thus decrease project costs, shorten schedules, and enhance performance outcomes. In addition, clients can be better protected from major sources of delays and cost overturns. An integrated design and engineering process can be front-loaded and proceed more efficiently. There is an obvious need for data-embedded tools which could be used to support and optimize retrofit decisions. With an accurate pre-retrofit model of an existing building, it is possible to visualize, analyze and ensure that proposed retrofit solutions meet the owner's requirements and provide the best value (Woo et al. 2010).

The need to gather data in various formats and consider input from multiple stakeholders makes retrofitting of an existing building more difficult than construction of a new green building. During the retrofitting process, there are critical disconnections and gaps that commonly exist as obstacles in the process. Outdated or nonexistent building 2D or 3D drawings and energy consumption histories can limit the prediction of the proposed renovation project's future performance. Considering that 74% of the building stock in the United States was built before 1990 (EIA 2013), it is well understood that as-is building documentation may

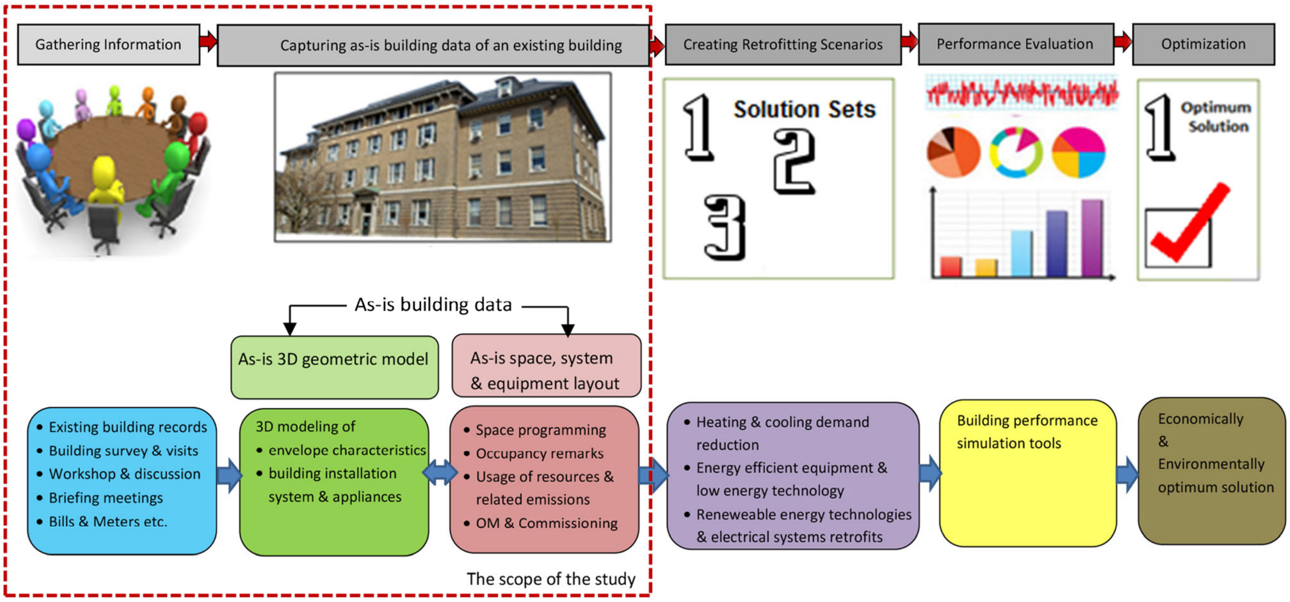


Fig. 1 Retrofitting process

not have been modified to reflect changes made during subsequent renovations or these records may simply not exist. Under these circumstances, there are a number of drivers for retrofitting in existing building projects, and by extension, the use of BIM for these purposes. The concept of BIM and BIM tools has shown great potential for the future of the Architecture, Engineering and Construction (AEC) industry. There is a rapid increase in the current use of BIM for new construction to create and maintain an integral digital representation of all building information for different phases of a project (Gu and London 2010). In contrast, only a few examples of the adoption of BIM or BIM-related concepts in retrofits exist (Woo et al. 2010; Tang et al. 2010) showing that the general rate of BIM adoption in retrofit projects is slow. Hence, the use of BIM while retrofitting buildings is an emerging research field that has been the subject of limited research.

3 The structure of "pre-retrofit model"

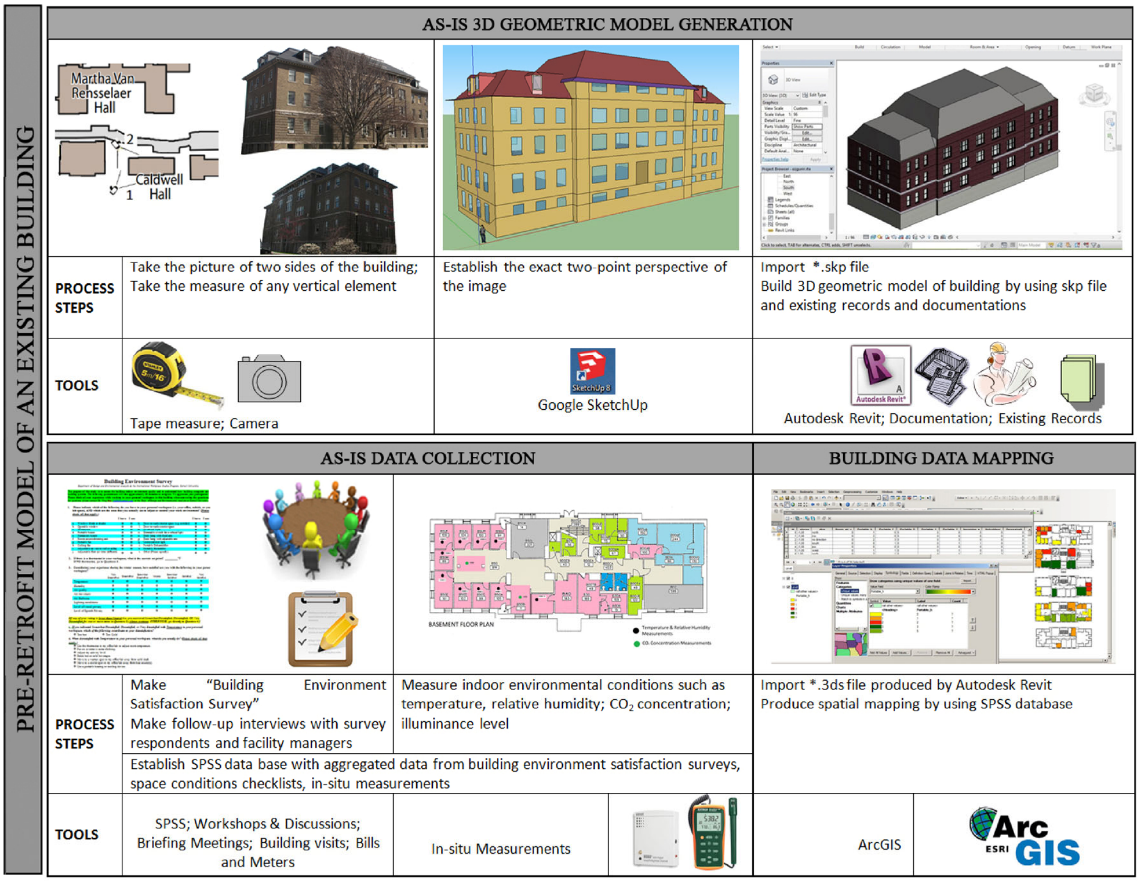
This paper presents a pre-retrofit model that efficiently obtains and integrates multiple forms of building data as a critical step in developing a comprehensive understanding of a building to be renovated. Addressing the gap that building data is fragmented and user data is lacking and not integrated, we have proposed a novel BIM-GIS integrated model to combine different types of data on the same platform by creating a database structured on the geometric model. To generate the as-is 3D geometric model, photogrammetry and BIM tools are used, and to analyze and visualize as-is collected data on generated 3D model, GIS is used. With the integration of BIM and GIS, building data maps have been obtained as seen in Fig. 2.

3.1 As-is 3D geometric model generation

The availability of many powerful graphic workstations and technological advancements in digital and computer multimedia (Styliadis 2007) has made it possible to generate 3D models to assess as-is building conditions. The creation of as-is geometric models using existing technologies can capture detailed depictions of the state of a building as it exists currently and allows for visualizing and analyzing proposed retrofit scenarios more accurately. Existing as-built survey technologies were reviewed and compared according to the settings of the study (laboratory work vs. fieldwork) for the data collection stage, format of the produced data, and accuracy (Table 1).

In traditional manual methods, simple devices are used and little training is needed; however, qualified workers are required in order to integrate produced data in 2D paperwork into digital 3D format. This stage is time-consuming and the accuracy verification of the as-built documentation is required.

Recent advances in technology made laser scanning for digital documentation of buildings very popular due to how it measures the angles and distances automatically and rapidly (1000 points/second) (Arias et al. 2006). While the laser scanning method is preferred for capturing complex shape geometry and detecting small details (Fröhlich and Mettenleiter 2004), its high cost of the equipment can be a disadvantage.



Take the picture of two sides of the building; Take the measure of any vertical element

Establish the exact two-point perspective of the image

Import *.skp file
Build 3D geometric model of building by using skp file and existing records and documentations

Make "Building Environment Satisfaction Survey"
Make follow-up interviews with survey respondents and facility managers

Measure indoor environmental conditions such as temperature, relative humidity; CO_2 concentration; illuminance level

Establish SPSS data base with aggregated data from building environment satisfaction surveys, space conditions checklists, in-situ measurements

Import *.3ds file produced by Autodesk Revit
Produce spatial mapping by using SPSS database

Fig. 2 The structure of the pre-retrofit model

The large amount of spatial information aggregated with the 3D point clouds method is required to be converted into a 3D geometric model. For this purpose, commercial softwares are available such as Meshlab, Leica cloudWORX, and 3Dipsos. The available processes for the transformation of laser scanning point cloud data, which include millions of points, still have significant limitations (Laefer et al. 2011). Gao et al. (2012) proposed a method to perform multiple laser scans of a facility and fuse the laser scan data captured at different times to overcome the challenge due to the occlusions caused by furniture, machinery, and building components. On the other hand, Bhatla et al. (2012) reported that the laser scanning approach has limitations due to expensive and fragile equipment, lack of portability, and a need for trained operators.

The other remote sensing method, "photogrammetry", uses extracted input data from two-dimensional photo images to map them onto a three-dimensional space (Dai and Lu 2010) This results in a low-cost, quick, simple, and safe method (Rodríguez et al. 2008). However, this method requires calibration (self-calibration and object-based calibration), which cannot work in uncontrolled environments (Peng and Li 2010). In order to overcome the problems of resolution, accuracy, speed, and operational requirements in as-is BM, there are a number of publications on the combination of photogrammetric and laser scanner systems, which complement one another (Lerma et al. 2010; Rönnholm et al. 2007; Jean-Angelo 2004; Kern 2001).

In conclusion, existing as-built survey technologies (from traditional manual methods to advanced techniques such as photogrammetry, laser scanner systems, and a combination of these) need expensive and fragile equipment, trained operators, and can be time consuming.

Today, it is possible to use Autodesk Photofly, 123D Catch, and Photo Scene Editor to generate 3D models of image-captured facilities in 3D point clouds or discrete point formats. These software programs are mainly based on the principle of semi-automatically selecting and matching visual feature points, calculating camera positions, distortions, and orientations, and generating 3D point clouds (Klein et al. 2012). Klein et al. (2012), used Autodesk 123D Catch in capturing a 3D model of a test bed building along with an interior field test.

Another very simple and easy way to create as-is geometric models is the photo-matching technique found in Google SketchUp, which allows a model to be built

Table 1 Existing as-built survey technologies in capturing as-is geometric model

Method	Tools	Laboratory work	Fieldwork data collection stage	Accuracy	Produced data
Traditional manual methods (*X*, *Y* & *Z*, Triangulation)	Tape measure, plumbs, manual laser distance measurement, flexometers, plumb lines, poles, squares, manual laser distanciometers (Arias et al. 2006), caliper (Addison and Gaiani 2000)	Simple, requires, at least 2 persons	Time consuming	5.30–2.46 cm [http://nickerson.icomos.org/steve/papers/ mea-c.htm]	2D plans
Topographic methods	Tachometers (total stations) & Theodolite (optical and electronic)	Simple, easy	Time consuming & complex	30" up to 1/1'-6" [http://totalstation.org/]	3D point clouds
Laser scanning	(Gao et al. 2012; Tang et al. 2010)	Complex	Quick measurement, only few minutes	5 mm and 5 m (Arias 2006)	3D point clouds
Time of flight (Fröhlich and Mettenleiter 2004)	Callidus, Leica, Mensi, Optech, Riegl			< 10 mm	
	Optech, Riegl			< 20 mm	
Phase measurement (Fröhlich and Mettenleiter 2004)	IQSun, Leica, VisImage			< 10 mm	
Optical (Fröhlich and Mettenleiter 2004)	Mensi, Minolta			< 1 mm	
Close-range Photogrammetry	Camera	Simple, easy	Short period of time spent measuring requires camera calibration techniques (Peng and Li 2010), reference points approach (Achour and Benkhelif 2001)	from 1 mm (highly accurate methods) to 5 cm (simple photogrammetric methods) (Arias 2006)	
Laser scanning & Photogrammetry	(Kern 2001; Jean-Angelo 2004)	Complex			3D point clouds
Videogrammetry	Kodak DCS420-DCS460 (Ganci and Handley 1998)	Complex			3D in digital format
Converting from 2D drawings	Upgrading to BIM from a 2D drafting system	Requires skilled workers	Time consuming	Not accurate (Woo et al. 2010)	3D

based on a photograph or by matching the model view to a photograph (www.sketchup.com). By using two sides of a building, the exact two-point perspective of the image can be established. The obtained 3D as-is geometric model can be exported in different formats as 3ds, dwg, dxf, etc.

In this study, the appropriateness of the tools such as Autodesk 123D Catch, Google SketchUp, and Autodesk Revit to generate geometric models was explored. The possibility of generating more precise models to support retrofitting projects has been investigated. An as-is 3D geometric model of a case building has been obtained by integrating Autodesk Revit and Google SketchUp. The model created by using the photo-matching technique in Google SketchUp was imported to Autodesk Revit and transformed into a BIM smart object. Using this simple and easy method to get as-is 3D geometric models, testing was implemented on a historical campus building. However, generating 3D models of image-captured facilities with the use of the photo-matching technique in Google SketchUp still needs to be improved since the difference between real and simulated dimensions exceeds 2%.

3.2 As-is data collection

Retrofitting projects are becoming increasingly complex and usually involve many stakeholders and professional expertise. There is also an increase in the amount of building data that needs to be communicated among multiple stakeholders with diverse backgrounds. It is difficult to establish a common understanding of working procedures among the stakeholders, including the client and the users. The lack of efficient communication and data sharing often leads to misinterpretation and missed opportunities for better performance outcomes and returns on investment.

Table 2 shows the contribution of stakeholders with various types of unstructured data sources in retrofitting projects. Traditional ways of communication create "a barrier for integrated design teams to make decisions efficiently as information is frequently conveyed through documents in tabular (pdf, xls, doc etc.) formats, and perceived outside of the context of the 3D representation" (Yang et al. 2013).

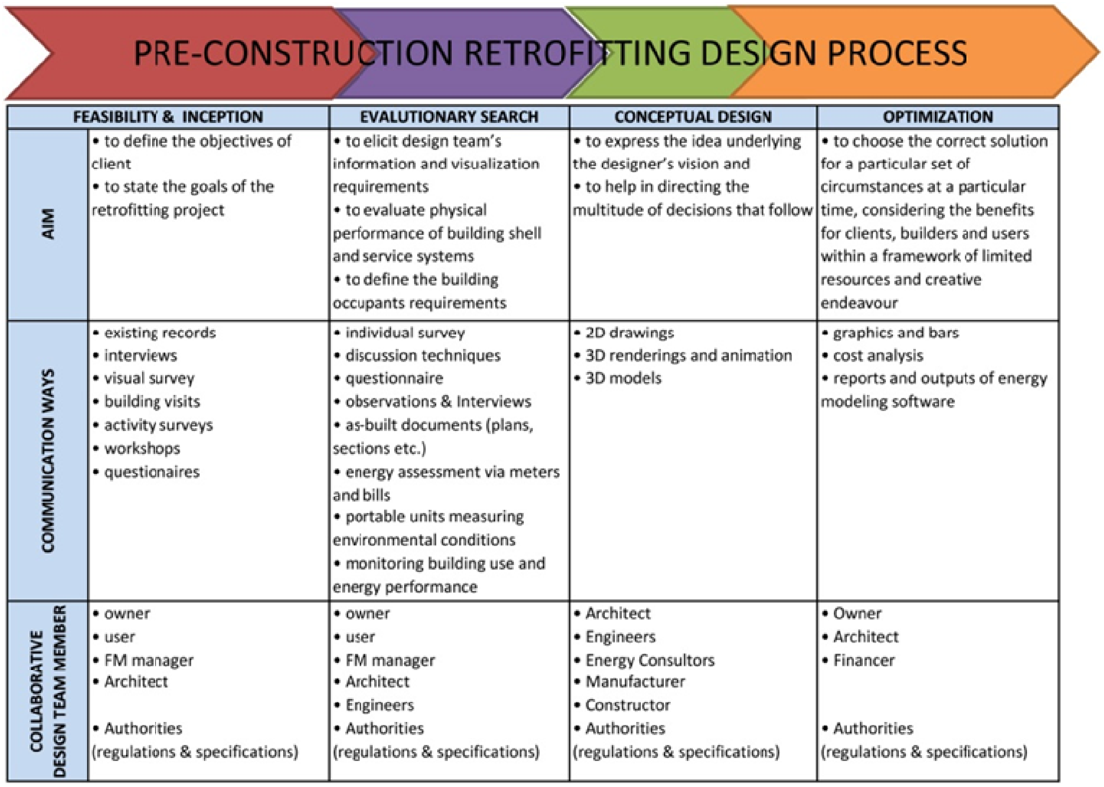
In order to have a comprehensive assessment of existing building performance, the data creates a pre-retrofit model (Fig. 1) in various formats with characteristics inputed by multiple stakeholders. To find the optimum solution through different retrofitting scenarios, the following building data needs to be gathered on the same platform;

- 3D drawings of building in dwg, dxf, 3ds etc. (site plan, floor plans, sections, elevations etc.)
- Energy performance data in kWh and related emissions in kg CO_2 /kWh (energy consumption, peak loads, CO_2)
- Water consumption and production of sewer and waste in m^3 (potable water, sewer, waste etc.)
- Indoor environmental conditions in g/m^3, °C/°F, dB, lx etc. (concerning hygro-thermal, acoustic and visual comfort)
- Indoor air quality in g/m^3, air m^3/hour etc. (indoor air pollution, existence of mold and moisture, air ventilation)
- Occupancy evaluation (behavior and attitude of occupants, their satisfaction)
- Commissioning (initial, retro-, and continuous)
- Maintenance (corrective, preventive, predictive, & deferred)

3.3 Building data mapping: Integrating BIM and other collected data into GIS

BIM technologies can be used to capture as-is geometric data, which is needed for various aspects of the energy performance analysis. However, the pre-retrofit model, including only as-is geometric data, is not sufficient to perform the activities mentioned above. The use of BIM during construction has focused, for the most part, on the visualization and manipulation of geometric model elements (East et al. 2010). Some exchange programs have been developed for information capture and management needs (Eastman et al. 2011). Retrofit projects not only focus on upgrading building envelope, but also on upgrading building systems, such as installing efficient lighting, mechanical and electrical systems, and water-efficient plumbing that results in financial savings (Bernstein 2010). Due to the fact that old buildings do not have information technology tools for facility management, substantial effort should be given to reveal as-is functional data from files filled with the technical descriptions of the

Table 2 Steps of retrofit design process and multiple channels of communication among multi-stakeholders



PRE-CONSTRUCTION RETROFITTING DESIGN PROCESS

	FEASIBILITY & INCEPTION	EVALUTIONARY SEARCH	CONCEPTUAL DESIGN	OPTIMIZATION
AIM	• to define the objectives of client • to state the goals of the retrofitting project	• to elicit design team's information and visualization requirements • to evaluate physical performance of building shell and service systems • to define the building occupants requirements	• to express the idea underlying the designer's vision and • to help in directing the multitude of decisions that follow	• to choose the correct solution for a particular set of circumstances at a particular time, considering the benefits for clients, builders and users within a framework of limited resources and creative endeavour
COMMUNICATION WAYS	• existing records • interviews • visual survey • building visits • activity surveys • workshops • questionaires	• individual survey • discussion techniques • questionnaire • observations & Interviews • as-built documents (plans, sections etc.) • energy assessment via meters and bills • portable units measuring environmental conditions • monitoring building use and energy performance	• 2D drawings • 3D renderings and animation • 3D models	• graphics and bars • cost analysis • reports and outputs of energy modeling software
COLLABORATIVE DESIGN TEAM MEMBER	• owner • user • FM manager • Architect • Authorities (regulations & specifications)	• owner • user • FM manager • Architect • Engineers • Authorities (regulations & specifications)	• Architect • Engineers • Energy Consultors • Manufacturer • Constructor • Authorities (regulations & specifications)	• Owner • Architect • Financer • Authorities (regulations & specifications)

materials, products, equipment, and systems used in the building.

Retrofit design requires a pre-retrofit model which has accurate as-is geometric data as well as information about the existing space, system and equipment layouts, and relevant user data for a proper analysis. The proposed pre-retrofit modeling suggests the integration of data such as program requirements as well as the priorities and complaints of clients and users which are captured in the end-of-briefing process through building surveys, questionnaires, discussions, etc. First Hua et al. (2014) suggested using ArcGIS which enables processing post-occupancy evaluation (POE) data as an input data from different information and systems. "The GIS-based spatial mapping method" builds a link with BIM tools and combines data-collecting and data-presenting methods with the use of geographic information system (GIS) technology. The GIS-based spatial mapping method has been adapted and expanded by exploring capturing as-is 3D geometric data and forming a "pre-retrofit model" which would be used later to achieve better energy performance and user satisfaction.

The ArcGIS-based digital floor plans are connected to a BIM model and can be queried directly from the BIM model. More specifically, a BIM geometric file is used as an input file in ArcGIS to locate data from a POE study. A POE study was carried out by gathering quantitative and qualitative data collected through surveys and physical measurements. The statistical program SPSS was used to store aggregated data. Qualitative data was converted into quantitative data with an ID number for each workplace. With the use of crosstab descriptive techniques in SPSS, it is possible to assign the same ID for both environmental data and users sharing the same space. Each space was defined as a polygon in ArcGIS. Doing so allowed each polygon, which refers a space, to become a database that we can upload every kind of data to. This method (Göçer et al. 2015) has been adapted and expanded by exploring capturing as-is geometric data in forming a pre-retrofit model that can be used later to achieve better energy performance and user satisfaction. The spaces having their own ID involve environmental data and user data to visualize design outcomes easily. Each space and data collected from this is given a unique ID number. Then, each space is redefined as a polygon in ArcGIS. A polygon is the basic unit of analysis in ArcGIS and each polygon is essentially a database. Thus, when a given space is redefined as a polygon, it acquires the ability to hold any data. Transforming a space into a database allows it to become a flexible toolthat can be adapted to various needs. The procedure of creating a database using different types of building data and outputting their maps can be seen in Fig. 3.

4 Implementation of the proposed "pre-retrofit model"

The model was applied on a campus building constructed in 1913, which had a major renovation in 1935. After that, numerous piecemeal renovation projects were performed

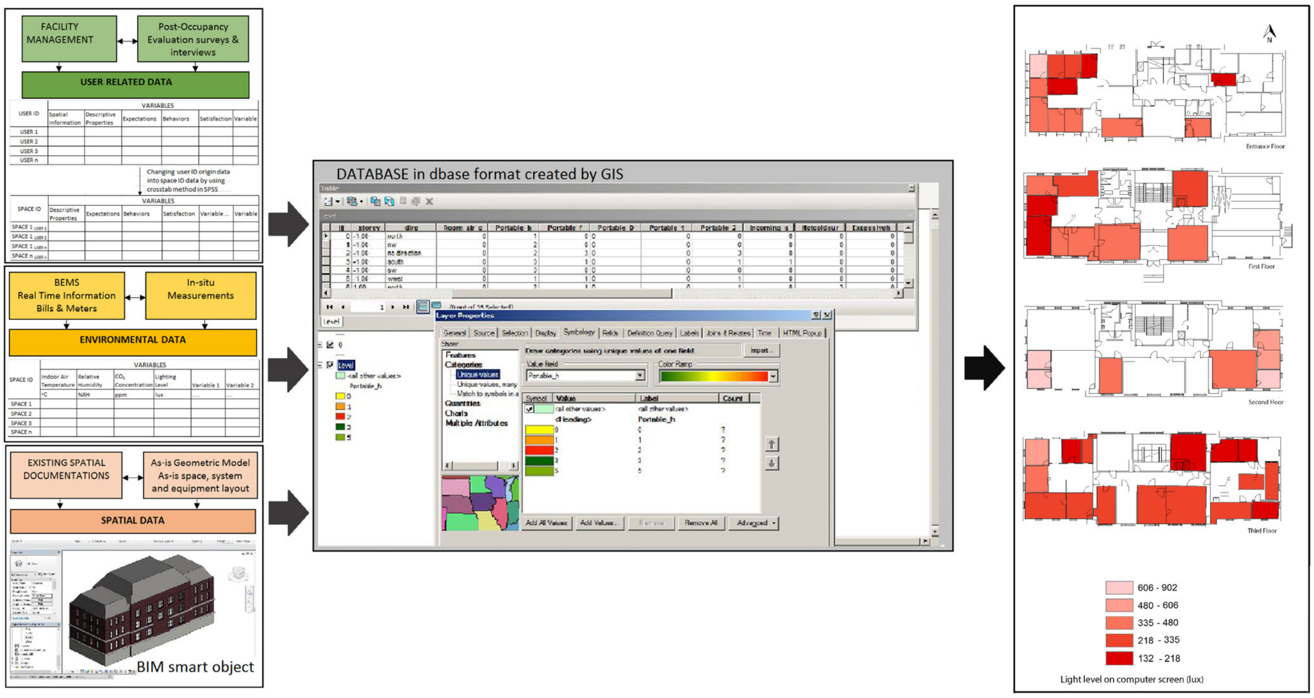


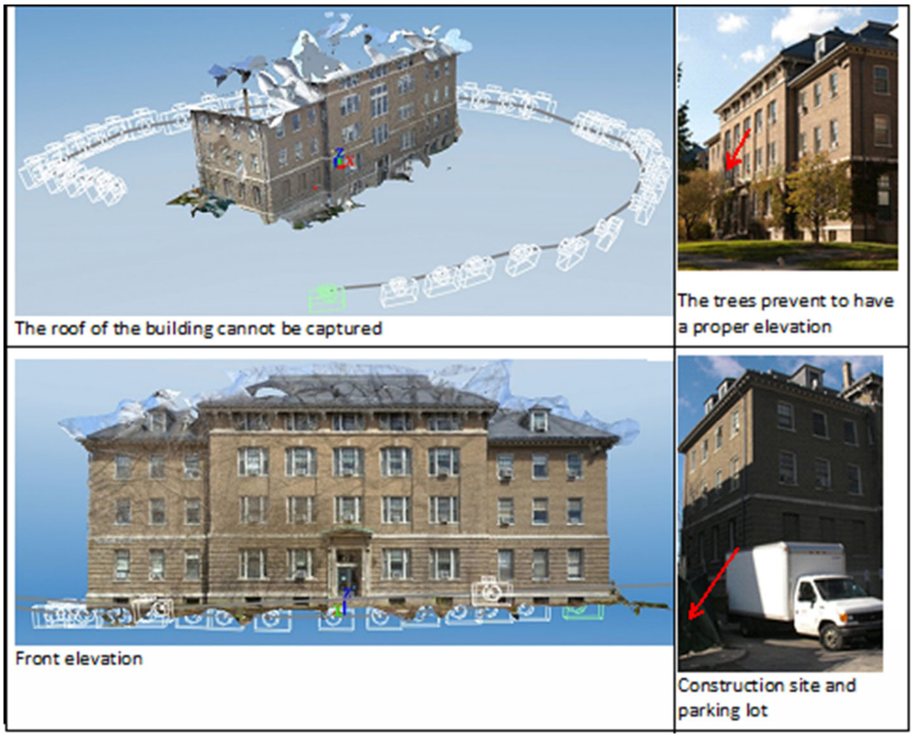
Fig. 3 Integration of BIM and collected data into GIS to generate building data maps

to address functional requirements and to replace building materials.

4.1 As-is 3D geometric model generation of the case building

Due to the obstacles caused by vegetation and the adjacent buildings (as seen in Fig. 4), an accurate model could not be captured by Autodesk 123D Catch. Capturing only a partial view of a building limits the construction of an as-is geometric model of any building.

The building was modeled using a photo-matching technique in Google SketchUp. The generated model was imported directly into the Autodesk Revit BIM tool as a Revit Building mass for further geometric data installation (Fig. 5). Existing building records, interior space photo shooting, and 2D drawings were used for the data installation. The Autodesk Revit model, which represents the building as an integrated database of coordinated information, gives architects immediate feedback in order to evaluate design alternatives early in the design process (Autodesk 2005). With the use of Autodesk Revit, it is possible to generate more precise insight to better support energy performance simulation of a retrofitting project and work more efficiently with extended project teams (www.autodesk.com). However, manually measured dimensions were used to verify the

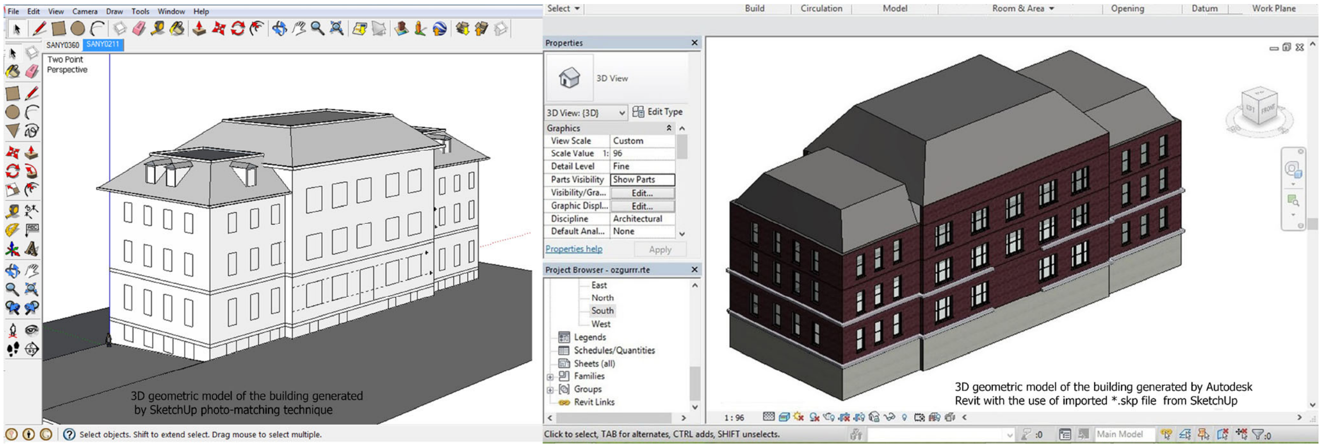

The roof of the building cannot be captured

The trees prevent to have a proper elevation

Front elevation

Construction site and parking lot

Fig. 4 Capturing as-is 3D geometric model of campus building with the use of Autodesk 123D Catch



3D geometric model of the building generated by SketchUp photo-matching technique

Select objects. Shift to extend select. Drag mouse to select multiple.

Graphics
View Scale: Custom
Scale Value 1: 96
Detail Level: Fine
Parts Visibility: Show Parts
Visibility/Gra...: Edit...
Graphic Displ...: Edit...
Discipline: Architectural
Default Anal...: None

Project Browser - ozgurrr.rte
East
North
South
West
Legends
Schedules/Quantities
Sheets (all)
Families
Groups
Revit Links

Click to select, TAB for alternates, CTRL adds, SHIFT unselects.

3D geometric model of the building generated by Autodesk Revit with the use of imported *.skp file from SketchUp

Fig. 5 Capturing as-is 3D geometric model of the building with the use of SketchUp and Autodesk Revit corresponding dimensions extracted from the as-built BIM model. The percent errors for exterior surfaces range from −0.56% to 4.33% or −0.56 to 9.59 cm. Since a notable level of disagreement was found between the manual measurements and simulated survey assessment outcomes, it can be concluded that generating 3D models of image-captured facilities is out of the current capabilities of Google SketchUp.

4.2 As-is data collection of the case building

Detailed information about the inspected buildings was gathered from the appropriate sources such as facilities inventory, energy and sustainability division of facilities services, facilities and operation service, walk through observations, building visits, and a pre-retrofit survey. Through a building audit, information on the building's physical properties in terms of structure, material and size, building installation systems and appliances, operation, maintenance and commissioning, usage of resources and related emissions, programming and spatial arrangement, occupancy remarks, and exterior environmental factors could be aggregated and organized.

A total of 53 occupants participated in the pre-retrofit survey. The occupancy profile is seen in Table 3. The average number of hours that the participants spent in the building per week was 40. Overall, the occupants were statisfied with the workspace, which can be seen on a seven-point Likert scale as shown in Fig. 6. However, during the winter, thermal comfort was comparatively low. The indoor environmental quality for work performance was generally high.

From the view point of visual privacy, the results (Table 4) show that occupants in individual offices were more satisfied than those in shared offices. The occupants' control over their work environment was surveyed. In controlling temperature, the occupants' "coping" methods and abilities were very limited.

The satisfaction levels of the participants in different zones and interior workplaces were examined regarding indoor air quality (Fig. 7). The satisfaction level of indoor environmental quality in workspaces with varying orientation was investigated. Temperature satisfaction levels were very low, especially for the Northwest, West, and interior zones. There is a significant decline in the satisfaction level of air quality and air movement for the East zone and in air freshness for the Northwest zone in the winter and summer months. However, the Southwest zone exhibited the highest ratings in terms of indoor environmental conditions of the workspace.

Table 3 Summary of occupant profiles

Age	40 years old and up		Up to 40 years	
	64.7%		35.3%	
Job category	Administrative support staff	Management personnel	Faculty staff & graduate students	Others
	50%	34%	8%	8%
Working experience in that building	> 12 months		6–12 months	<1 month
	81.1%		5.6%	1.9%

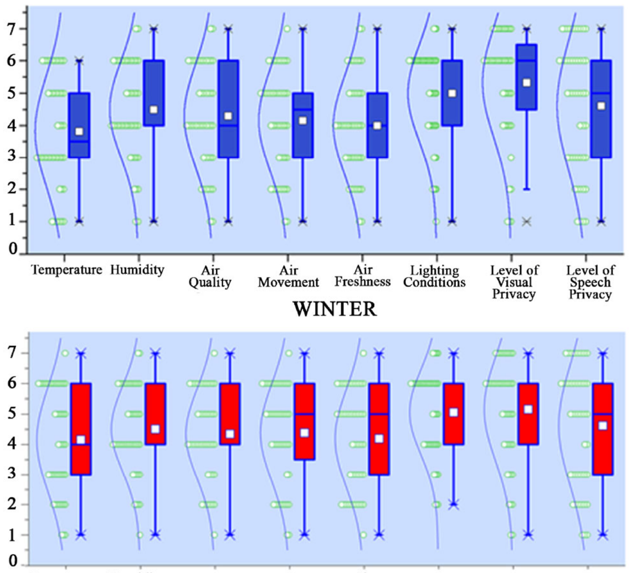


Fig. 6 Overall satisfaction with indoor environment quality during winter and summer (7-point Likert scale)

Table 4 The visual and speech privacy and controlling behaviour results of the survey

	Shared offices (lower dissatisfaction)	Individual offices (lower dissatisfaction)	
Visual privacy	44.4%	5.1%	
Speech privacy	80%	23.1 %	
Controlling behavior over work environment	Adding or removing clothing (58%)	Drinking hot or cold beverages (50%)	use thermostat (38%)
	Calling the facility and maintenance services when needed (4%)	Using portable heaters (54%) Using portable fans (34%)	

4.3 Building data mapping of the case building

Pre-retrofitting data maps were created with aggregated information and these maps were given under the following sub-headings.

4.3.1 *Indoor Environment*

The measurements were carried out during two weeks in the

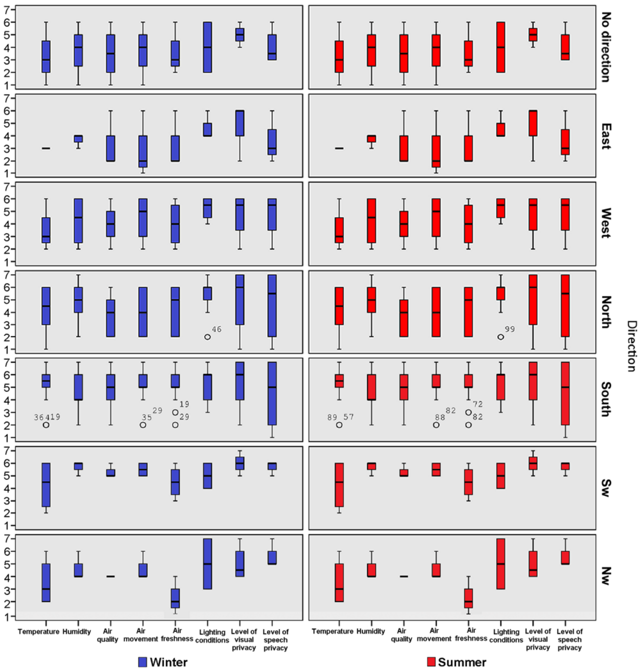


Fig. 7 Overall satisfaction level in accordance with orientation (7-point Likert scale)

summer. Building data maps of temperature and humidity distributions were prepared using GIS (Fig. 8) to explain hygro-thermal and air quality dissatisfaction reports in workspaces.

1. Hygro-thermal Conditions

The hourly temperature and humidity distributions during a workday for each zone on the 1st and 2nd floors were prepared using GIS (Fig. 8). The highest indoor air temperatures were recorded in the South zone on the basement floor and in the West zone on the 1st floor. These temperatures exceed 26 °C most of the time. As expected, the lowest temperatures were recorded in the Northwest zones on the 1st and 2nd floors. The minimum and maximum indoor air temperature difference was 8.52 °C on the 1st and 2nd floors.

The 2nd floor air temperature was higher than the other floors. The highest temperatures were recorded above 24.6 °C in the West, East, and interior zones on the 2nd floor. All of the participants in the West zone cited their reason for dissatisfaction as the space being "too hot". The lowest temperature was recorded below 21.2 °C in the South zone on the 1st floor, which is used as a design studio.

The recorded relative humidity was within the comfort level (45%–60%) in all zones, except the North zone on the 1st and 2nd floors (Fig. 8). The lowest relative humidity was recorded as 43.3% in the North zone. The participants (33.3% in the winter and 20% in the summer, respectively) in the North zone reported their reason for dissatisfaction as "too low relative humidity".

2. Indoor Air Quality

Throughout this study, CO_2 levels of the shared offices in the 1st and 2nd floor workspaces were measured, and it was concluded that the level of CO_2 was not always within the range recommended by the ASHRAE Standard 62.1-2010

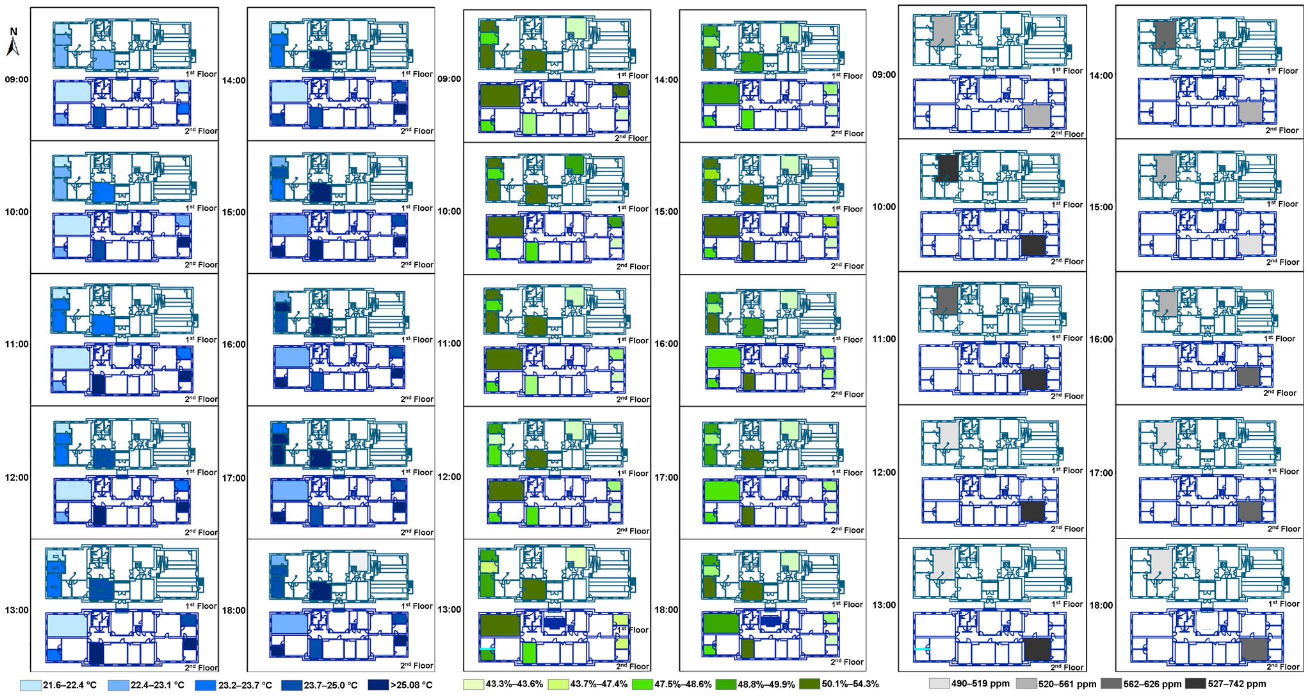


Fig. 8 Spatial mapping of temperature (°C), relative humidity (%) and CO_2 (ppm) distributions for each zone on each floor

(ASHRAE 2010). The recorded data was reorganized according to working hours: from 9 am to 6 pm. It is clear that the CO_2 concentration was above the required comfort level both in the interior and in the perimeter offices (Fig. 8). During the measurements on the 2nd floor, the air conditioning unit was running. Because the windows remained closed while the air conditioning units were on, there was no natural ventilation. With regard to this, it was observed that especially during the hours between 10 am to 2 pm, the CO_2 concentration was above the acceptable level. There is an air exchange unit that exchanges the air four to six times per hour on the 1st level. Because of this, the recorded CO_2 concentration level on the 1st level was lower than that of the 2nd level.

Survey results revealed that an unpleasant odor is a common problem, especially for basement floor occupants, due to unventilated restrooms on this floor.

3. Lighting conditions

The lighting system only consists of old incandescent bulbs and fluorescent lamps without any control mechanisms, such as motion or light-sensitive sensors that can help to save energy.

The illuminance measurement revealed very high levels (above 500 lx, 56%) on the occupants' primary work surfaces and on computer monitors in many areas of the building. Participants were asked if the "as-is conditions" were typical, and 80.4% of the participants indicated that the configurations of the lights and blinds were in their normal state at the time of survey. It was noted that,45.1% and 78.4% of the participants did not have under-bin lights and task lights, respectively, and 60.7% and 45.5% of the participants who had under-bin lights and task lights did not need to use their desk lamp or under-bin lights, respectively.

The spot measurement lighting levels of the work table and monitors indicated that the workspaces were illuminated above a comfortable level. Only 10% of the participants turn the overhead lights off when not needed. Further discussion is needed to understand occupants' attitude in controlling the lighting system.

4.3.2 System equipment and layout

The building is heated using a hot water pipe system. Steam comes from a central plant at the university. The heat emitters have control valves for regulating zone air temperature by increasing or decreasing the flow rate of steam. The heating system is set to maintain the zone at a constant temperature of 20 °C. There is no differentiation among different types of zones such as offices, corridors, entrance halls, and staircases. It is observed that occupants are not satisfied with the zone temperature based on the fact that many of them have their own space heaters. Only the basement floor of the building is cooled by chilled water because of the existence of a server room on that story. The other stories are naturally ventilated. There are some cooling units attached on the windows and these units are used by the occupants to meet their cooling needs. The cooling units that were replaced during the renovation in 2001 are not energy efficient. Because they are attached to the windows, air leakage and energy loss problems occur during hot and cold seasons (Fig. 9).

4.3.3 Detected problematic points

To understand the problematic aspects of the building, the participants are asked report if certain conditions existed in their personal workspaces. The statements reported by the participants are seen in Fig. 10. The most commonly reported

Fig. 9 Spatial mapping of the portable devices for each zone on each floor

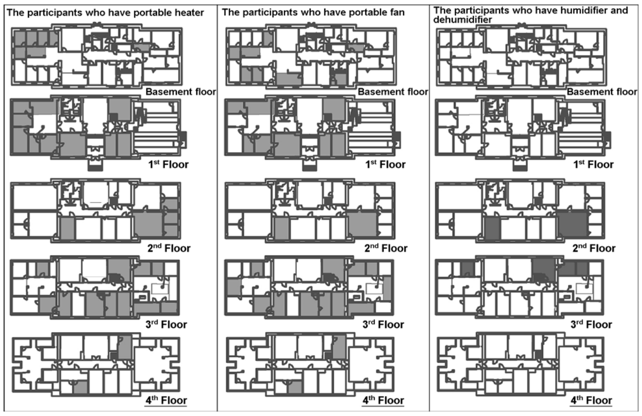


Fig. 10 Spatial mapping of the detected problematic points for each zone on each floor

complaint was a "draft from windows" due to the single glazed windows in use. Other complaints about thermostats and the heating/cooling system point to a necessary heating and cooling system renovation. Noise problems caused by mechanical systems were reported only in the basement and on the 1st level because the other floors do not have any mechanical heating systems. Solar radiation penetration is also another recorded problem, especially in the South, East and West zones.

5 Discussion of case study findings

This pre-retrofit study of an historical campus building revealed several key findings which are listed below.

Study finding: Overall, the occupants were satisfied with the indoor environment in their workspaces in the building of study; however, thermal comfort was comparatively low during the winter. The complaints were focused on the arguments that occupants felt "too cold" and "too hot" during the winter and summer, respectively.

What to do: This problem points to the urgent need for an energy efficient retrofitting. Energy-efficient retrofitting measures on the window area and building envelope can solve thermal discomfort in users. Beside this, the building heating and cooling system should be renewed with efficient HVAC systems. Also, "mixed mode" natural ventilation through operable windows should be allowed. "Mixed mode" refers to a hybrid approach to space conditioning that uses a combination of natural ventilation from operable windows (either manually or automatically controlled), and mechanical systems that provide air distribution and some form of cooling.

Study finding: The air movement dissatisfaction was reported as "too high" during the winter in the North zones. Users commonly reported problems with "drafts from windows".

What to do: Replace old windows with efficient ones.

Study finding: There were predominantly higher CO_2 levels in interior offices on the basement floor (exceed the limit of ASHRAE Standard 62.1-2010).

What to do: Air change per hour should be increased in these zones.

Study finding: The lighting levels in the building studied were determined to be higher than needed. According to this, 45.1% and 78.4% of the participants did not have under-bin lights and task lights, respectively, and 60.7% and 45.5% of the participants who had under-bin lights and task lights did not need to use their task lights and under-bin lights, respectively. The lighting system needs to be replaced with efficient and dimmable lamps to minimize energy consumption.

What to do: Integrate an electric lighting system with daylighting features. Reduce the lighting density and make task lights more usable (e.g. desk lights with articulated arm, underbin lights) and prevalent in all workspaces.

Study finding: From the view point of visual and speech privacy, occupants in individual offices were more satisfied than those in shared offices, which was expected.

What to do: Make a new spatial arrangement and evaluate unfunctional zones. Proper space planning is needed to improve productivity and satisfaction. Avoid sharing workspaces and provide occupants individual control over their work environment.

Study finding: Personal control over the indoor environment through "adjust thermostat", "light switch", and "window blinds" was found unsatisfactory in the building. Some of the participants were sharing thermostats with an adjacent office. Because of this, occupants mostly have their own portable equipment, such as heaters, fans, and humidifiers, to regulate the indoor environment in response to their needs. This also causes excessive and unpredictable electricity consumption. Moreover, it conflicts with the heating and cooling strategy of the university's campus buildings.

What to do: Improve personal control over indoor environment via thermostat and dimming control of the light fixtures.

Study finding: Despite being faced with uncomfortable working conditions, the participants generally expressed that "they prefer to work in a historical building instead of the new and modern ones", and one of them pointed out that "I can control my own workspace with my portable equipment and I can even open my window whenever I want". These remarks show the power of participants' sense of belonging.

What to do: Take into consideration the identity of the building and try to keep it during renovation. Be aware of the users' sense of belonging.

6 Conclusions

With regard to the rising energy costs and the impetus to reduce environmental impacts, energy efficient retrofitting is gaining importance. Although there are several benefits associated with retrofit projects, implementation of them are limited. Retrofitting existing buildings is challenging due to the requirements for gathering data in various formats and input from multiple stakeholders. The understanding of a building requires complete cooperation and participation from a wide range of stakeholders (i.e., owners, managers, occupants and contractors), who often reside in the building during the potentially disruptive retrofitting process. During the retrofitting process, there are critical disconnections and gaps that commonly exist as obstacles. Outdated or nonexistent building plans and incomplete energy consumption histories make it difficult to predict the future performance of a proposed renovation project. Gathering this type of data, which is segmented and have rarely been analyzed, is a major challenge for the building industry.

One of the most significant challenges during the process of retrofitting design is capturing an accurate as-is building model. Existing as-built technologies (from traditional manual methods to advanced techniques such as photogrammetry, laser scanner systems and combination of these) have limitations in capturing 3D as-is building models due to the need of expensive and fragile equipment, trained operators, and time consuming practices. To obtain geometric models, different tools were explored and their appropriateness for retrofitting was tested. Although an accurate model could not be captured with the use of Autodesk 123D Catch, the integration of Google Sketchup and Autodesk Revit 3D allowed for a geometric model to be created. Using this method, the possibility of generating more precise models to better support the energy performance evaluation stage of a retrofitting project and to work more efficiently with extended project teams has been proved. Although a very simple and economical method to get an as-is geometric models has been introduced, a notable level of disagreement was found between the manual and simulated survey assessment. Generating 3D models of image-captured facilities with the use of BIM still needs to be improved. This study not only makes the use of 3D modeling and building envelope characteristics information available in a BIM model, but also leverages the spatial programming and data input by various parties involved in the project. The integration of GIS with BIM is proposed for visualization and organization of building data mapping.

The study is about generating a pre-retrofit model that efficiently obtains and integrates multiple forms of building data as a critical step to developing a comprehensive understanding of a building to be renovated, addressing the gap that building data is fragmented and user data is lacking and not integrated. As a follow-up to this study, a model can be used to conduct different scenario comparisons and to optimize renovation decisions based on economic and environmental goals. The concluding remarks and recommendations for future work are as follows:

- Building scientists and professionals should raise social consciousness for reusing an existing building and upgrading it to achieve the maximum energy efficiency. However, retrofitting projects are still only slowly being implemented.
- Replacing chillers and boiler with more efficient ones and renovating building windows have been well known for years, but considering the long-term benefits of the whole-of-building retrofit is still an issue worth exploring.
- The use of BIM for building retrofit projects is an emerging research field that has been the subject of limited research.
- There is a crucial need for a well-defined methodology that can be used to develop 3D pre-retrofit models to meet the requirements of collaborative design teams in retrofit projects.
- The proposed BIM- and GIS-based pre-retrofit method allows researchers: (i) better social, geometric and physical data organization, (ii) more effective building diagnosis analysis to improve performance, and (iii) through the use of data visualization, a contribution to more effective communication among stakeholders for optimizing retrofit scenarios.
- The paper points out the lack of support for BIM systems used for the retrofitting of buildings and how to embed pre-retrofit information in real BIM tools. The further step for the project team will be to implement the information in the retrofit process itself.

Acknowledgements

The authors would like to acknowledge the financial support provided by the Joan & Irwin Jacobs Technion-Cornell Innovation Institute (JTCII) and the Scientific and Technological Research Council of Turkey (TUBITAK) for this research.

References

Achour K, Benkhelif (2001). A new approach to 3D reconstruction without camera calibration. *Pattern Recognition*, 34: 2467–2476.

Addison AC, Gaiani M (2000). Virtualized architectural heritage: New tools and techniques tools for building virtual heritage. *IEEE MultiMedia*, 7(2): 26–31.

Amstalden RW, Kost M, Nathani C, Imboden DM (2007). Economic potential of energy-efficient retrofitting in the Swiss residential building sector: The effects of policy instruments and energy price expectations. *Energy Policy*, 35: 1819–1829.

Arias P, Ordóñez C, Lorenzo H, Herraez J (2006). Methods for documenting historical agro-industrial buildings: A comparative study and a simple photogrammetric method. *Journal of Cultural Heritage*, 7: 350–354.

Asadi E, Gameiro da Silva GM, Antunes CH, Dias L (2012). Multi-objective optimization for building retrofit strategies: A model and an application. *Energy and Buildings*, 44: 81–87.

Ascione F, de Rossi F, Vanoli GP (2011). Energy retrofit of historical buildings: theoretical and experimental investigations for the modelling of reliable performance scenarios. *Energy and Buildings*, 43: 1925–1936.

ASHRAE (2010). ASHRAE ANSI/ASHRAE Standard 62.1-2010, Ventilation for Acceptable Indoor Air Quality. Atlanta: ASHRAE.

Autodesk (2005). Autodesk Revit White Paper. Available at http://www.tpm.com/wp-content/uploads/2013/02/AGC_Guide_to_BIM.pdf. Accessed 24 Jul 2015.

Balaras CA, Droutsa K, Argiriou AA, Asimakopoulos DN (2000). Potential for energy conservation in apartment buildings. *Energy and Buildings*, 31: 143–154.

Ben H, Steemers K (2014). Energy retrofit and occupant behaviour in protected housing: A case study of the Brunswick Centre in London. *Energy and Buildings*, 80: 120–130.

Berardi U (2015). The development of a monolithic aerogel glazed window for an energy retrofitting project. *Applied Energy*, 154: 603–615.

Bernstein HM (2010). The Green Outlook 2011: Green Trends Driving Growth through 2015. New York: McGraw-Hill Construction.

Bhatla A, Choe SY, Fierro O, Leite F (2012). Evaluation of accuracy of as-built 3D modeling from photos taken by handheld digital cameras. *Automation in Construction*, 28: 116–127.

Caputo P, Costa G, Ferrari S (2013). A supporting method for defining energy strategies in the building sector at urban scale. *Energy Policy*, 55: 261–270.

Cellura M, Di Gangi A, Longo S,Orioli A (2013). An Italian input–output model for the assessment of energy and environmental benefits arising from retrofit actions of buildings. *Energy and Buildings*, 62: 97–106.

Che L, Gao Z, Chen D, Nyugen T-H (2010). Using building information modeling for measuring the efficiency of building energy performance. In: Proceedings of the International Conference on Computing in Civil and Building Engineering, Nottingham, UK.

Dai F, Lu M (2010). Assessing the accuracy of applying photogrammetry to take geometric measurements on building products. *Journal of Construction Engineering and Management*, 136: 242–250.

de Wilde P, Tian W, Augenbroe G (2011). Longitudinal prediction of the operational energy use of buildings. *Building and Environment*, 46: 1670–1680.

East WE, Nisbet N, Wix J (2010). Lightweight capture of as-built construction information. In: Dikbas A, Ergen E, Girtili H (eds), Managing IT in Construction. Istanbul: CRC Press, pp. 53–62.

Eastman C, Teicholz P, Sacks R, Liston K (2011). BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, 2nd edn. Hoboken, NJ, USA: John Wiley & Sons.

EIA (2013). International Energy Outlook 2013. US Energy Information Administration. Available at http://www.eia.gov/forecasts/ieo/pdf/0484 (2013).pdf. Accessed 3 Jun 2014.

EU (2012). European Parliament Report on the Energy Roadmap 2050. https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf . Accessed 24 Feb 2016.

Fracastoro GV, Serraino M (2011). A methodology for assessing the energy performance of large scale building stocks and possible applications. *Energy and Buildings*, 43: 844–852.

Fröhlich C, Mettenleiter M (2004). Terrestrial laser scanning-new perspectives in 3D surveying. In: Proceedings of ISPRS Workshop of Laser-Scanners for Forest and Landscape Assessment, Freiburg, Germany, pp. 7–13.

Ganci G, Handley H (1998). Automation in videogrammetry. Available at http://www.geodetic.com/f.ashx/papers/Automation-in-Videogrammetry.pdf.

Gao T, Akinci B, Ergan S, Garrett JH (2012). Constructing as-is BIMs from progressive scan data. *Gerontechnology*, 11: 75.

Göçer Ö, Hua Y, Göçer K (2015). Completing the missing link in building design process: Enhancing post-occupancy evaluation method for effective feedback for building performance. *Building and Environment*, 89: 14–27.

Goldstein K, Blasnik M, Heaney M, Polly B, Christensen C, Norford L (2014). Developing a pre-retrofit energy consumption metric to model post-retrofit energy savings: Phase one of a three-phase research initiative. *Energy and Buildings*, 80: 556–561.

Gu N, London K (2010). Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction*, 19: 988–999.

Güçyeter B, Günaydın HM (2012). Optimization of an envelope retrofit strategy for an existing office building. *Energy and Buildings*, 55: 647–659.

Henriques CO, Coelho DH, Antunes CH (2015). A multi-objective input-output model to assess E4 impacts of building retrofitting measures to improve energy efficiency. *Technological and Economic Development of Economy*, 21: 483–494.

Heo Y, Choudhary R, Augenbroe GA (2012). Calibration of building energy models for retrofit analysis under uncertainty. *Energy and Buildings*, 47: 550–560.

Heo Y, Zavala VM (2012). Gaussian process modeling for measurement and verification of building energy savings. *Energy and Buildings*, 53: 7–18.

Hua Y, Göçer Ö, Göçer K (2014). Spatial mapping of occupant satisfaction and indoor environment quality in a LEED certified campus building. *Building and Environment*, 79: 124–137.

Jean-Angelo B (2004). Integration of laser scanning and close-range photogrammetry—The last decade and beyond. In: Proceedings of XXth International Society for Photogrammetry and Remote Sensing (ISPRS) Congress. Commission VII, Istanbul, Turkey, pp. 972–983.

Kern F (2001). Supplementing laser scanner geometric data with photogrammetric images for modeling. In: Proceedings of XVIIIth International CIPA Symposium on Surveying and Documentation of Historic Buildings, Monuments Sites: Traditional and Modern Methods, Potsdam, Germany.

Klein L, Li N, Becerik-Gerber B (2012). Imaged-based verification of as-built documentation of operational buildings. *Automation in Construction*, 21: 161–171.

Kumbaroglu G, Madlener R (2012). Evaluation of economically optimal retrofit investment options for energy savings in buildings. *Energy and Buildings*, 49: 327–334.

Kwok SSK, Yuen RKK, Lee EWM (2011). An intelligent approach to assessing the effect of building occupancy on building cooling load prediction. *Building and Environment*, 46: 1681–1690.

Laefer DF, Truong-Hong L, Fitzgerald M (2011). Processing of terrestrial laser scanning point cloud data for computational modelling of building facades. *Recent Patents on Computer Science*, 4: 16–29.

Lerma JL, Navarro S, Cabrelles M, Villaverde V (2010). Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: The Upper Palaeolithic Cave of Parpalló as a case study. *Journal of Archaeological Science*, 37: 499–507.

Ma Z, Cooper P, Daly D, Ledo L (2012). Existing building retrofits: Methodology and state-of-the-art. *Energy and Buildings*, 55: 889–902.

Mavromatidis G, Acha S, Shah N (2013). Diagnostic tools of energy performance for supermarkets using Artificial Neural Network algorithms. *Energy and Buildings*, 62: 304–314.

Miller E, Buys L (2008). Retrofitting commercial office buildings for sustainability: Tenants' perspectives. *Journal of Property Investment & Finance*, 26: 552–561.

National Trust for Historic Preservation (2011). The greenest building: Qualifying the environmental value of building reuse. Preservation Green Lab, National Trust for Historic Preservatio, USA.

Olgyay V, Seruto C (2010). Whole-building retrofits: A gateway to climate stabilization. *ASHRAE Transactions*, 116(2): 244–251.

Peng E, Li L (2010). Camera calibration using one-dimensional information and its applications in both controlled and uncontrolled environments. *Pattern Recognition*, 43: 1188–1198.

Poel B, van Cruchten G, Balaras CA (2007). Energy performance assessment of existing dwellings. *Energy and Buildings*, 39: 393–403.

Polly B, Gestwick M, Bianchi M, Anderson R, Horowitz S, Christensen C, Judkoff R (2011). A Method for Determining Optimal Residential Energy Efficiency Retrofit Packages. National Renewable Energy Laboratory, Available at http://www.osti.gov/bridge. Accessed 3 Dec 2013.

Rodríguez J, Marín MT, Arias P, Ordóñez C, Herráez J (2008). Flat elements on buildings using close-range photogrammetry and laser distance measurement. *Optics and Lasers in Engineering*, 46: 541–545.

Rönnholm P, Honkavaara E, Litkey P, Hyyppä H, Hyyppä J (2007). Integration of laser scanning and photogrammetry. In: Proceedings of ISPRS Workshop on Laser Scanning 2007 and SilviLaser 2007, Espoo, Finland, pp. 355–362.

Rysanek AM, Choudhary R (2013). Optimum building energy retrofits under technical and economic uncertainty. *Energy and Buildings*, 57: 324–337.

Stazi F, Vegliò A, Di Perna C, Munafò P (2013). Experimental comparison between 3 different traditional wall constructions and dynamic simulations to identify optimal thermal insulation strategies. *Energy and Buildings*, 60: 429–441.

Styliadis AD (2007). Digital documentation of historical buildings with 3-d modeling functionality. *Automation in Construction*, 16: 498–510.

Swan LG, Ugursal VI, Beausoleil-Morrison I (2011). Occupant related household energy consumption in Canada: Estimation using a bottom-up neural-network technique. *Energy and Buildings*, 43: 326–337.

Tang P, Huber D, Akinci B, Lipman R, Lytle A (2010). Review Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques. *Automation in Construction*, 19: 829–843.

Tommerup H, Svendsen S (2006). Energy savings in Danish residential building stock. *Energy and Buildings*, 38: 618–626.

United Nations (2007). Human Development Report of United Nations 2007/2008, United Nations Development Programme, USA, available at http://hdr.undp.org/sites/default/files/reports/268/hdr_20072008_en_complete.pdf. Accessed 3 Jun 2014.

Verbeeck G, Hens H (2005). Energy savings in retrofitted dwellings: Economically viable? *Energy and Buildings*, 37: 747–754.

Verbruggen A (2008). Retrofit of a century old land-house to a low-energy house. *International Journal of Environmental Technology and Management*, 9: 402–412.

Wang B, Xia X (2015). Optimal maintenance planning for building energy efficiency retrofitting from optimization and control system perspectives. *Energy and Buildings*, 96: 299–308.

Woo J, Wilsmann J, Kang D (2010). Use of as-built building information modeling. In: Proceedings of Construction Research Congress 2010: Innovation for Reshaping Construction Practice, Banff, Canada, pp. 538–547.

Yalcintas M (2008). Energy-savings predictions for building-equipment retrofits. *Energy and Buildings*, 40: 2111–2120.

Yang X, Liu Y, Ergan S, Akinci B, Leicht R, Messner JI (2013). Lessons learned from developing immersive virtual mock-ups to support energy-efficient retrofit decision making. In: Proceedings of ASCE International Workshop on Computing in Civil Engineering, Los Angeles, California, pp. 210–217.

Yu S-M, Tu Y, Luo C (2011). Green retrofitting costs and benefits: A new research agenda. Working Paper Series, Institute of Real Estate Studies, National University of Singapore.