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BEPAT: A platform for building energy assessment in energy smart homes and design optimization

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Abstract. Energy simulation tools can provide information on the amount of heat transfer through building envelope components, which are considered the main sources of heat loss in buildings. Therefore, it is important to improve the quality of outputs from energy simulation tools and also the process of obtaining them. In this paper, a new Building Energy Performance Assessment Tool (BEPAT) is introduced, which provides users with granular data related to heat transfer through every single wall, window, door, roof, and floor in a building and automatically saves all the related data in text files. This information can be used to identify the envelope components for thermal improvement through energy retrofit or during the design phase. The generated data can also be adopted in the design of energy smart homes, building design tools, and energy retrofit tools as a supplementary dataset. BEPAT is developed by modifying EnergyPlus source code as the energy simulation engine using C++, which only requires Input Data File (IDF) and weather file to perform the energy simulation and automatically provide detailed output. To validate the BEPAT results, a computer model is developed in Revit for use in BEPAT. Validating BEPAT's output with EnergyPlus "advanced output" shows a difference of less than 2% and thus establishing the capability of this tool to facilitate the provision of detailed output on the quantity of heat transfer through walls, fenestrations, roofs, and floors.

Keywords: building energy simulation; energy retrofit; energy smart home; energy monitoring; EnergyPlus

1. Introduction

Building energy simulation can play an important role in reducing buildings energy consumption. Despite advancements in energy simulation tools, there are still areas that can be further improved concerning energy modeling including data input process, energy simulation accuracy, and quality or presentation of outputs.

The major objective of the research discussed in this paper was to develop a tool, which can facilitate and improve quality of energy simulation outputs and also facilitate the process of acquiring such data from an energy simulation tool. The two aspects of energy simulation output considered in this paper include the type of output and the process required for obtaining such

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data. For example, an energy simulation tool such as EnergyPlus provides two types of output, standard and advanced. Standard output includes the common and accumulative energy-related output such as annual energy consumption, heating and cooling loads, energy loss through air infiltration, and accumulative energy loss through windows. Advanced output includes average heat loss/gain through different building envelope components such as walls, roof, floors, and doors. There are also efforts by other researchers to improve the quality of output in energy simulation tools such as enhancing the current simulation tools with 1D heat transfer assumptions to 3D heat transfer models in order to improve the energy simulation output (Kośny and Kossecka 2002).

These output types can be obtained and presented to users in different ways. More common output types such as annual energy consumption or heating and cooling loads are available in energy simulation graphical user interfaces (GUIs) such as OpenStudio, DesignBuilder, and BEopt, which use EnergyPlus as their energy simulation engine. They can present such output graphically and directly provide users with such data. On the other hand, more advanced output types such as average heat loss/gain through different building envelope components are not available in these commercial GUIs. Therefore, to access such data, users should be familiar with the definition of these advanced output types and acquire them through a process, which is not straightforward and automated. Moreover, using such data in emerging technologies that require semi-real-time data monitoring such as energy smart homes requires more ease of access and faster calculation process. Therefore, it is important to facilitate and automate obtaining detailed data related to the energy consumption of a building.

The first contribution of BEPAT is focused on improving types of output. This tool provides detailed data on heat transfer through building envelope components as opposed to accumulated energy consumption data. The current energy analysis tools present the accumulative energy-related data such as whole-house energy consumption, heating or cooling total energy consumption, and energy consumption due to lighting systems (Crawley *et al.* 2008), while the concept presented in this paper is focused on detailed energy consumption data. Detailed or granular output such as the amount of heat transfer through a single window in a specific thermal zone could also be acquired by existing energy simulation tools such as EnergyPlus; however, the process needs software-related skills, is time-consuming, and is error-prone, which is related to human error during data input. With the goal of making some improvement in this regard, BEPAT provides granular energy consumption data related to heat loss/gain through each wall, roof, floor, and fenestrations, i.e., windows and doors. As examples of other studies focused on detailed heat transfer through building envelope components, one can mention Sanguinetti *et al.* (Sanguinetti *et al.* 2014) who developed a tool to calculate the accumulative heat transfer through each façade of buildings. Building Information Modeling (BIM) file and Input Data File (IDF) file are used in their tool to perform energy simulation using EnergyPlus. However, the output is not granular and does not provide the heat transfer through every single envelope component such as windows and walls, separately. On the other hand, Carlini *et al.* (Carlini *et al.* 2014) is an example of other efforts that are limited to modeling a building envelope component separately as opposed to whole-house energy modeling, using COMSOL Multiphysics tool in order to assess the impact of a single envelope component on energy performance.

The second contribution of BEPAT is focused on improving the process of obtaining such detailed output. The output from BEPAT is obtained automatically from EnergyPlus simulation output and saved in separate text files for ease of access and automation purposes, which could be further enhanced by using these data in other GUIs or tools dedicated to building design, energy retrofit, and energy monitoring systems. Modifying the source code of EnergyPlus, which is the basis of developing BEPAT, has eliminated the need for user interaction. BEPAT can run using the input file and weather file to perform energy simulation and generate detailed output in separate text files. Visualizing and presenting energy simulation output is also another important area, which can be improved. For example, a tool developed by Sanguinetti et al. (Sanguinetti *et al.* 2014) is capable of visualizing the energy consumption data, which shows the related numerical data in text format accompanied by a graphical model of the building. One of the effective tools used in data visualization is BIM, which is adopted by other researchers to visualize the energy related output from eQuest (Tu and Vernatha 2016). Data visualization features also need to be added in future versions of BEPAT using similar BIM tools.

Potential applications of BEPAT's output can be categorized under three major groups based on three emerging technologies, These include 1) energy smart homes that are developed for building energy management, 2) tools that are being adopted during design, and 3) energy retrofit decision-making process that requires proper input in order to provide accurate and useful output more efficiently for reduction in energy consumption. These three areas are shown in Fig. 1. Detailed heat transfer data through building envelope components such as walls, windows, and roof can contribute to these three major areas including monitoring systems in energy smart homes, decision-making process for energy retrofit of buildings, and evaluation process in pre-construction or design phase of buildings.

The first system that can benefit from BEPAT is energy smart home. Alam *et al.* (Alam *et al.* 24-26 August 2016) defined smart homes as "…an application of ubiquitous computing in which the home environment is monitored by ambient intelligence to provide context-aware services and facilitate remote home control." Different services exist for smart homes and improving energy efficiency of a building is one of the most important services identified by researchers. Adopting sensors, actuators, and monitoring energy related data could contribute to energy smart homes (LaMonica 2013, Aman *et al.* 2013). Energy monitoring systems are mainly limited to either whole house or appliances energy meters (Lobacco *et al.* 2016). Energy smart homes can also be equipped with energy data processing capabilities such as energy simulation tools to perform more in-depth energy analysis based on the acquired data. The concept studied in this paper is based on equipping the building with an energy simulation tool, which can provide detailed information on the amount of heat transfer through building envelope components for monitoring purposes. Similar concepts are adopted by other researchers focused on other components such as appliances and mechanical systems. Energy Aware Smart Home (Jahn *et al.* 2010) is an example of such energy smart homes equipped with an energy monitoring and control system that provides users with detailed energy consumption profile for different appliances to identify the appliances with highest energy consumption. The same concept can be used for building envelope components, which is studied in this paper. There are also other examples of GUIs designed for energy smart homes using energy simulation tools, which show the applicability of such GUIs in improving the energy performance of buildings (Omole *et al.* 2016, Helal *et al.* 2005, Kim *et al.* 2011).

Energy retrofit is the second approach in reducing building energy consumption. The detailed output concerning heat transfer through each wall or window can also contribute to evaluation and decision-making process of energy retrofit of a building to make more cost-effective decisions by identifying the components that contribute more to energy loss as opposed to whole-house energy retrofit. There are many research and case studies only focused on building envelope energy retrofit in contrast with retrofit of HVAC (heating, ventilation, and air conditioning) system or lighting systems (AlFaris *et al.* 2016, New Building Institutes 2012, Bianco and Wiehagen

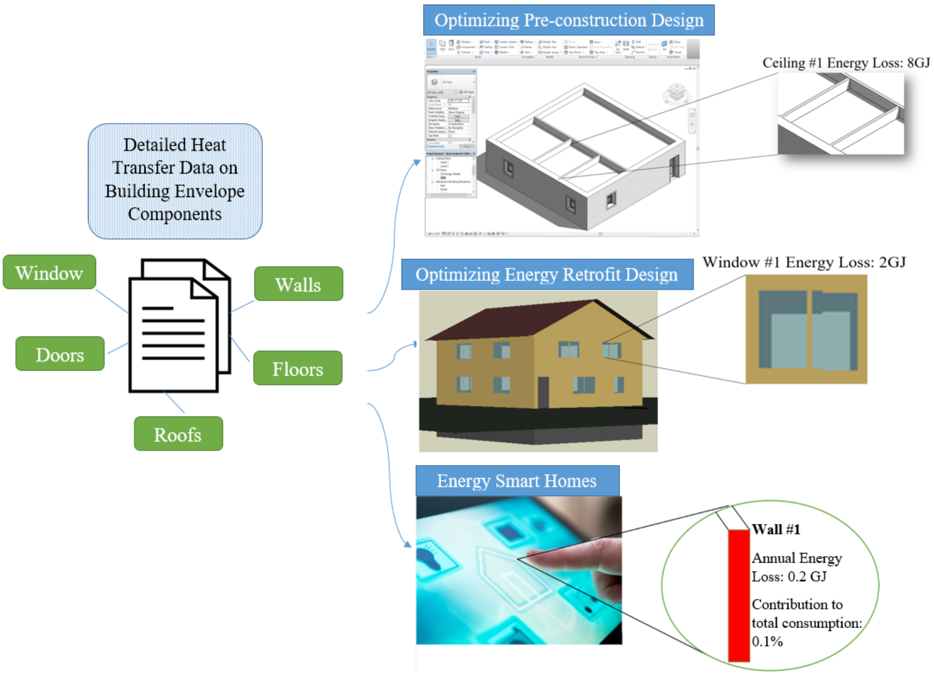

Fig. 1 Schematic illustration of potential applications and contributions of BEPAT

2016, Rocky Mountain Institute 2012, Chang *et al.* 2014). The research intensity highlights the importance of this area and contribution of this tool in improving the process of building energy retrofit. Other researchers working to improve energy retrofit of buildings agree on the need to understand detailed energy loss through each component such as a wall or a window (Denis 2014, Salem *et al.* 2018) and in certain climate zones, optimizing the energy retrofit of building envelope can be even more important and effective than retrofitting other components such as mechanical and electrical systems (AlFaris *et al.*, 2016). Moreover, these studies show how different building façades can perform differently in terms of temperature and heat transfer. For example, instrumenting houses under energy retrofit using sensors shows that different façades of the same building can vary about 10 degrees of Celsius (Bianco and Wiehagen 2016).

Optimizing thermal properties of building components during the design phase is the third approach in reducing building energy consumption. Decisions made at the design-phase and early stages of building design could be more effective in terms of energy efficiency compared to measures adopted later during the use phase (Tian *et al.* 2015, Pacheco-Torres *et al.* 2015, Granadeiro *et al.* 2013). Similar studies have also emphasized the importance of design phase for implementing energy efficiency measures (Pacheco-Torres *et al.* 2015) with different areas of focus such as building envelope shape (Granadeiro *et al.* 2013) or suggesting indicators that correlate between design variations and energy consumptions (Granadeiro *et al.* 2013). These research studies show how a single component in a building can affect the energy performance. For example, different window system on the north façade and south façade of a building can lead to a better energy performance due to the difference in the solar radiation angle and duration through a year. Moreover, different wall systems might perform differently in different floors and faces of a building due to the shadings and solar radiations. Designers can optimize the building by changing the dimensions of each window for example or modifying the materials in a wall system on only one face of the building. Designers can use detailed information about each component and design or modify each component, separately. For example, Lin *et al.* (2016) studied the effect of multiple envelope components on energy performance by optimizing the retrofit scenarios and noticed about 41% energy saving, however, the evaluation was based on total energy consumption, while detailed heat transfer through each component could be an important asset in such studies. High energy saving potentials show how important detailed heat transfer data for each building components can be and how they can contribute to optimize building design during the decision-making process.

Fig. 1 shows the summary of these three major potential application and contributions of BEPAT and demonstrates how such output types can be used in other GUIs in three different areas. For example, it allows the user to select a specific building envelope component or thermal zone and it provides the user with detailed energy loss/consumption through/within that component/zone and within a certain period. Hence, for example, it can help decision making on possible energy retrofit scenarios and the effect of partial energy retrofit of buildings on total energy consumption (Häkkinen *et al.* 2016).

The adopted methodology for developing the tool is explained in the next section. Development of a computer model for validation purposes is also covered subsequently, followed by results of the computer model and comparison between the BEPAT's output and two other methods to obtain either detailed or accumulative energy-related output types. Finally, the results are discussed in more details and the summary and conclusion is provided.

2. Methodology for Developing and Validating BEPAT

The adopted approach for developing BEPAT is to modify the EnergyPlus source code, an existing open-source energy simulation software developed by National Renewable Energy Laboratory (NREL) (EnergyPlus 2017). EnergyPlus and DOE2 are the most prevalent energy simulation engines running behind various energy analysis software such as DesignBuilder and eQuest, which can provide granular energy consumption data in buildings. Such granular data can be used for predicting energy consumption and production in different locations, especially for designing net-zero energy homes (Kim 2014, Ataei and Dehghani 2016). EnergyPlus also works as the simulation engine in other interfaces and is capable of performing a comprehensive building energy analysis (Pertosa *et al.* 2014, NREL 2011a, b, 2013a, b, Santos, Schleicher, Caldas 2017). Input is fed to the software as text file known as IDF. Multiple variables can be defined in IDF files, which makes it easy for researchers to study the effect of these variables on energy performance, separately. Important factors and components such as different climate zones (NREL 2011b), electricity cost (NREL 2013a), necessary electric lighting to achieve certain foot candles of illumination (NREL 2013b), and non-planar surfaces (Santos *et al.* 2017) are calculated or modeled in EnergyPlus by different researchers. The basic IDF editor available for EnergyPlus is EPlaunch illustrated in Fig. 2. To either work with such an editor or directly modify the IDF file, the user would need an in-depth understanding of the IDF structure and different attributes related to envelope, HVAC, electrical, or schedules within the IDF file. In addition, many Graphical User Interfaces (GUI) exist, which are developed for energy simulation and analysis that use EnergyPlus as their core simulation engine and facilitate the energy modeling by providing graphical interfaces such as OpenStudio, BEopt, and DesignBuilder (Maile *et al.*

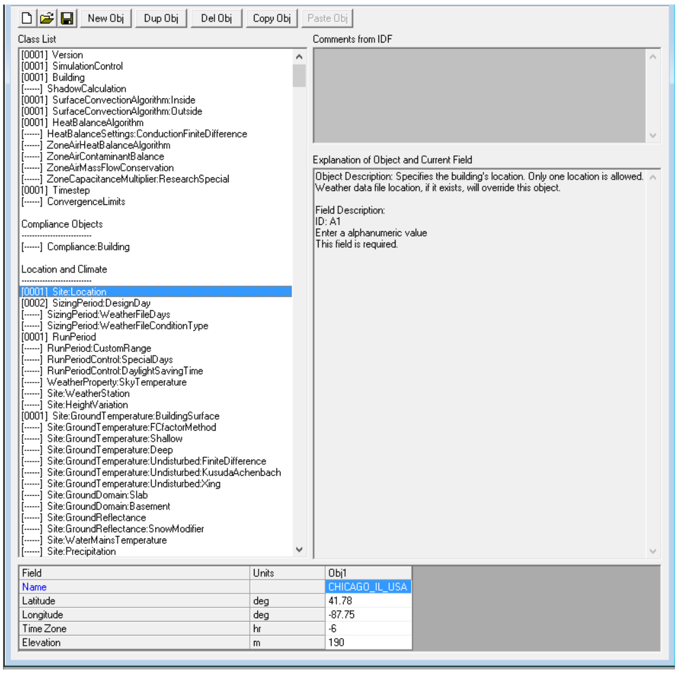

Fig. 2 IDF editor used for modifying EnergyPlus files in EPlaunch

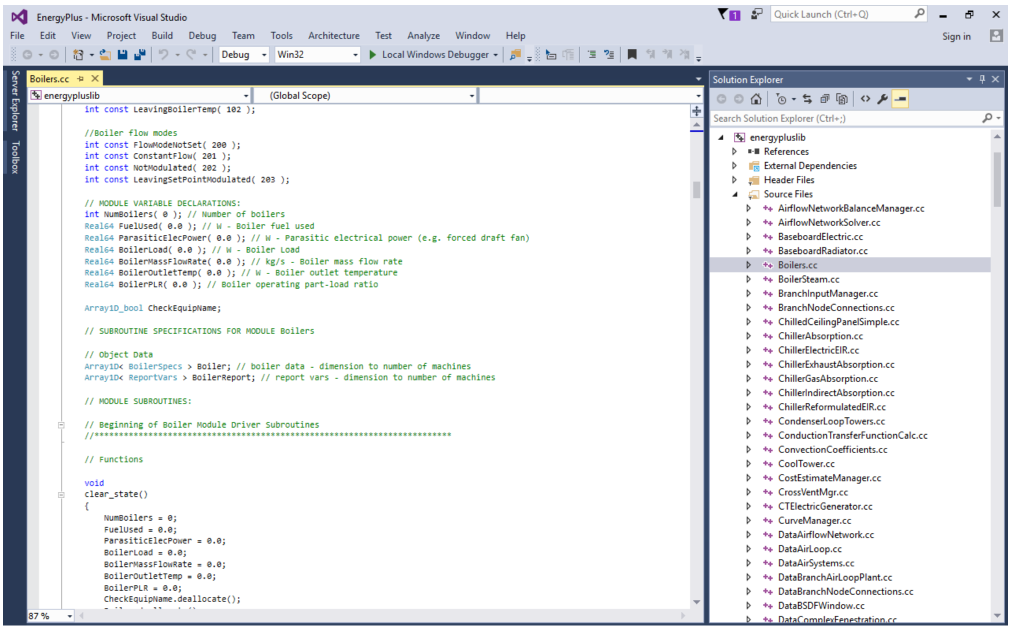

Fig. 3 Modules in EnergyPlus source code opened in VisualStudio

2007, Pinheiro *et al.* 2016). Although application of these tools is more straightforward, the whole process for modeling and obtaining outputs is not automated and still needs manual process, which could be time taking, costly, and error prone. Moreover, all of the aforementioned tools only provide accumulated heat transfer for windows, walls, roofs, and floors in each thermal zone as opposed to detailed information for each envelope component.

The availability of EnergyPlus source code as an open-access tool helps users to modify this simulation engine in order to integrate it with other tools or obtaining customized outputs. The latter function has been quite beneficial to this study, part of which involves developing a tool based on modification of EnergyPlus source code to develop BEPAT. The freely available EnergyPlus 8.6.0 on GitHub is the source code version used for this research. The set of instructions for building the executable file for EnergyPlus is also available on GitHub website (GitHub, 2017). The source code can be viewed and modified by any Integrated Development Environment (IDE) such as VisualStudio, which is the IDE used in this study (version 14.0 Update 3, 2015). The old version of EnergyPlus is developed in FORTRAN; however, the recent versions use C++ as the main programming language, and the previous modules in FORTRAN are converted to corresponding codes in C++.

Open-source software tools consist of multiple modules, each including hundreds of lines of a certain programing language, which could be boiled down to several subroutines and functions responsible for a certain task or output. For example, EnergyPlus consists of about 275 modules. Fig. 3 illustrates some of the modules such as Boilers, CoolTower, and BaseboardElectric modules, which could be viewed and modified in VisualStudio. Each module is focused on different parts of the whole-house energy consumption calculations such as the amount of heat transfer through conduction, convection, radiation, different components of the HVAC system, lighting, shadings, and appliances. These modules are interconnected and data are transferred back and forth between them until the final outputs are obtained. To develop BEPAT, the modules and variables related to heat transfer through different surfaces are identified and modified using C++.

Different modules in EnergyPlus source code calculate different factors that contribute to building's energy consumption. The current version of BEPAT is only focused on building envelope components and is intended to obtain detailed data on heat gain or loss through certain components within a certain period. The components considered in this study to develop BEPAT include both opaque and transparent components such as walls, roof, floors, windows, and doors. Therefore, the first step is to identify the source code modules in which the related calculations and output are provided. In this case, two main modules are modified that contribute to the heat balance and data related to surfaces in buildings. The code developed in C++ is added in these two modules and the corresponding required changes are applied in the header files (*.hh* files).

The new C++ commands added to the existing source code modules perform the following tasks:

-Define a new variable to collect the detailed heat transfer through each component as opposed to accumulated heat transfer.

-Add up the heat transfer for each time step of the analysis in order to obtain the total heat gain/loss.

-Generate a text file that contains the total heat transfer through every single building envelope component, separately.

-Group the total heat gain/loss for each opaque and transparent component based on their respective thermal zone.

-Assign a number to each thermal zone and a proper name to each component in order to facilitate identifying these components and their corresponding thermal zone to be used in other tools.

Annual Building Sensible Heat Gain Components

Zone Number		Window Heat Addition [GJ]	Interzone Air Transfer Heat Addition [GJ]	Infiltration Heat Addition [GJ]	Opaque Surface Conduction and Other Heat Addition [GJ]	Equipment Sensible Heat Removal [GJ]	Window Heat Removal [GJ]	Interzone Air Transfer Heat Removal [GJ]	Infiltration Heat Removal [GJ]	Opaque Surface Conduction and Other Heat Removal [GJ]
SPACE1-1	. . .	0.206	0.000	0.000	0.002	0.000	-0.087	0.000	-0.011	-0.262
SPACE2-1		0.091	0.000	0.000	0.001	0.000	-0.032	0.000	-0.005	-0.110
SPACE3-1		0.107	0.000	0.000	0.000	0.000	-0.095	0.000	-0.011	-0.173
SPACE4-1		0.114	0.000	0.000	0.000	0.000	-0.032	0.000	-0.005	-0.132
SPACE5-1		0.000	0.000	0.000	0.001	0.000	0.000	0.000	-0.022	-0.339
PLENUM-1		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.089
Total Facility		0.517	0.000	0.000	0.004	0.000	-0.246	0.000	-0.054	-1.104

Fig. 4 Example of the sensible heat gain summary table generated by standard EnergyPlus

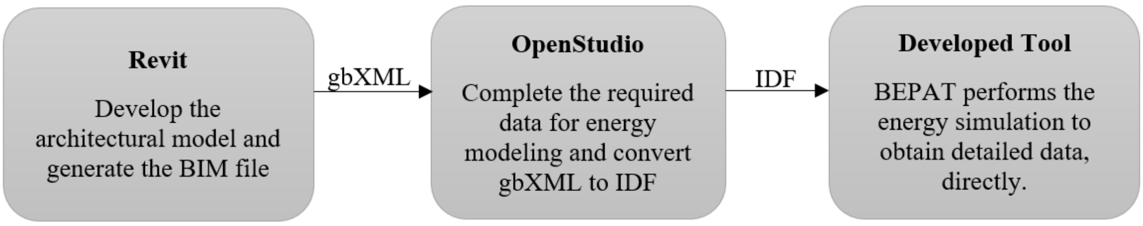

Fig. 5 Overview of the energy analysis process used in this study for BEPAT's data validation

To obtain the heat transfer data through building envelope components, it should be noted that EnergyPlus source code considers the three major heat transfer modes of radiation, convection, and conduction. The same concept is used in other energy simulation tools; however, the codes used in different tools might define different functions and modules to model heat transfer and perform the process. The subroutine used in one of the EnergyPlus's modules adopts the first law of thermodynamic to obtain the heat flow rate using Eq. (1). Depending on the HVAC system, the fluid considered in Eq. (1) could be different. In this study, the HVAC uses air, where the heat capacity c_p constant would be $c_{p,air}$. The air flow rate ($\dot{m}_{sys}$) represents the air flow rate. T_{in} and T_z are the air temperature blown in the zone and zone mean air temperature obtained based on well-stirred model, respectively. Q_{sys} gives the required energy to heat up/cool down the zone (i.e., the demand). To obtain T_z it is required to calculate the temperature on all the surfaces within a thermal zone, which is obtained based on the amount of heat transfer through these surfaces. To calculate the heat transfer through conduction (Q), it requires the thermal properties of building envelope components such as U-value (u), exterior temperature (to calculate the ΔT), and the surface area of the component (A), all shown in Eq. (2). In this study, it is assumed that the heat loss through convection or air infiltration is zero to simplify the process. Using Eqs. (1)-(2), the required thermal energy to keep the temperature of thermal zone within a certain range is calculated and reported in EnergyPlus.

$$\dot{m}sys = Qsys/(Cp, air \cdot (Tin - Tz)) \tag{1}$$

$$Q = u.A.\Delta T \tag{2}$$

An example of standard output of EnergyPlus is shown in Fig. 4. As it can be observed, all the data are accumulated for each zone. For example, the *window heat addition* and *opaque surface conduction* provide the heat gain through all the windows together and all the opaque components together (such as walls, roof, and floor) within a certain thermal zone, respectively. All the available energy simulation interfaces that use EnergyPlus or even other simulation engines such as DOE2 only provide these standard outputs as the accumulated results. This figure helps to better understand the contribution of BEPAT, which provides granular heat transfer through each building envelope component.

Other than using BEPAT the only other method to obtain the granular heat transfer information through building envelope components in EnergyPlus is to use the *advanced output* option in the IDF editor, i.e., EPlaunch directly by user, which is explained in the next section as one of the methods used to validate BEPAT's output, referred to as Method #1 in this study. The issue with this method is that it is not convenient for users to obtain such data, and it complicates the process, which could be labor intensive, time-taking, and error prone; therefore, allowing direct access to these data through BEPAT can reduce the risk of human errors and save time.

In order to make sure the changes in the source code of EnergyPlus are working properly and BEPAT's outputs are valid, a data validation, which is explained in more detail in the next section, needs to be performed.

3. Computer model and validation method

The workflow of validation of BEPAT's output is shown in Fig. 5. Revit is used in this study to prepare the architectural model, which is later exported to a gbXML BIM file format. OpenStudio is used as a middleware to add the required data for energy modeling such as data related to the HVAC system and schedules, and to convert the BIM file to IDF, which is the input file for EnergyPlus. Other researchers have also adopted similar approach in their studies using BIM in energy modeling and adding information either manually or by using middleware tools (O'Donnell *et al.* 2011, Bazjanac 2008, Dimitriou *et al.* 2016, Guzmán Garcia and Zhu 2015, Kamel and Memari 2018).

In order to validate the output generated by BEPAT, a simplified one-story house with four thermal zone is modeled in Revit. Two methods based on EnergyPlus used in the study for output validation are illustrated in Fig. 6. The validation study using a house modeled in Revit is meant to show the capability of BEPAT in providing detailed output through an easy and automated method; it was not modeled to evaluate any energy performance. The whole process also depicted in Fig. 7 shows how these methods relate to each other and illustrates the process within EnergyPlus (E+). The detailed output from BEPAT (Method #2) is compared to that obtained from *advanced output* in EnergyPlus (Method #1). Based on the overview shown in Fig. 7, it can be observed that the major difference between Methods #1 and #2 is ease of access. BEPAT fetches such outputs and saves them in series of text files, which enables the user or software developers to monitor the data or integrate them with other software tools in easier, faster, more reliable, and automated way compared to regular energy simulation and output acquisition methods. BEPAT

Table 1 Number of different components in each thermal zone

Zone #	Number of windows	Number of doors	Number of exterior walls	Number of interior walls
1	2	1	3	3
2	1	1	2	2
3	0	1	1	3
4	2	1	2	2

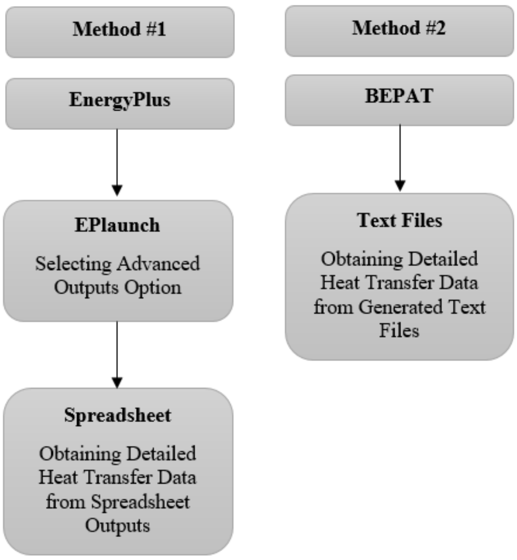

Fig. 6 Method #1 used in this study to validate BEPAT's outputs

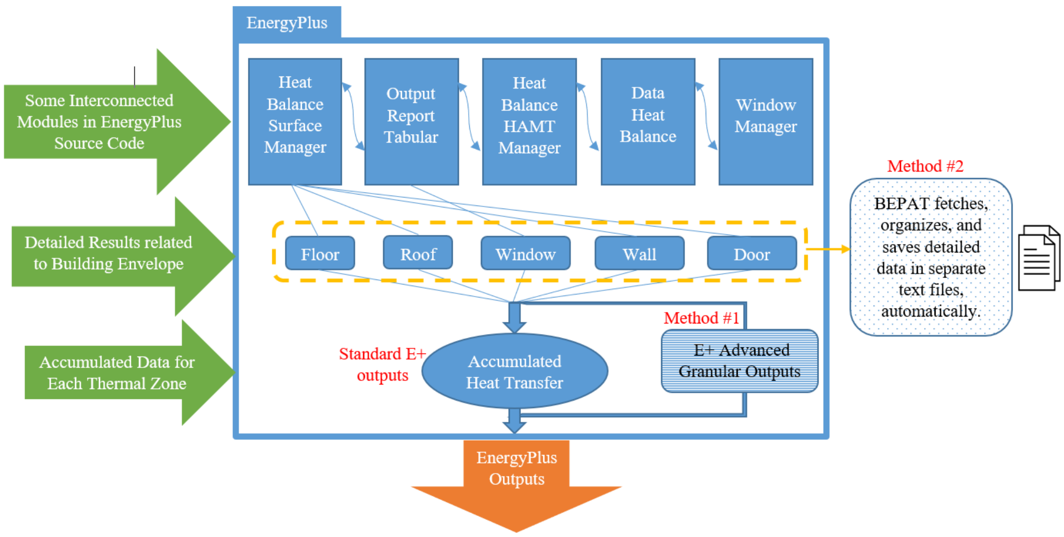

Fig. 7 Overview of BEPAT's workflow (Method #2) and E+ advanced outputs (Method #1) used for data validation

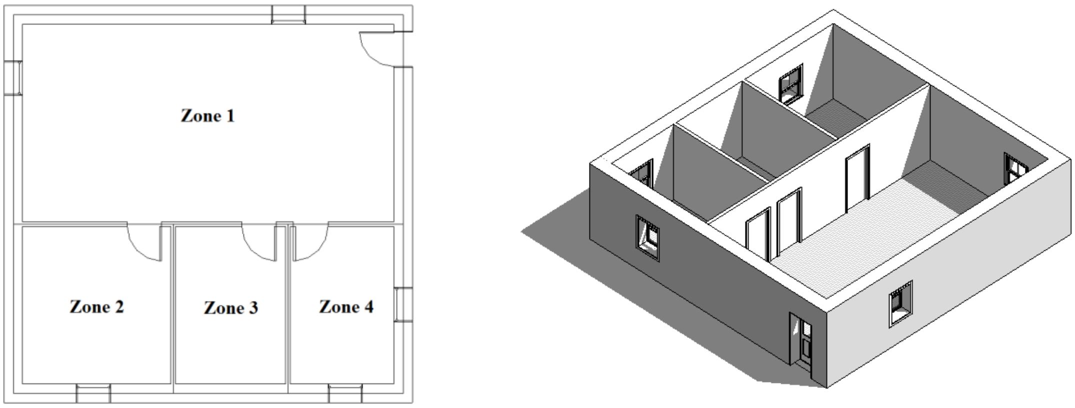

Fig. 8 Plan view (Left) and 3D view (Right) of building modeled in Revit to investigate the performance of BEPAT

Table 2 Properties of the building modeled in this study to investigate the performance of BEPAT

Building component and energy settings	Properties
Bedrooms	3
Living room	1
Square footage	1098 SF
Exterior wall	Brick/Air/Rigid Insulation/Vapor barrier/CMU/Metal Furring/Gypsum board (R-32)
Interior wall	Gypsum board/Metal Stud/Gypsum board (R-21)
Roof	Asphalt shingle/Plywood/Wood joist (R-58)
Ceiling	Acoustic Ceiling Tile (R-1.6)
Windows	Double Hung with Trim (36”×48”)(SHGC=0.78)(R-1.5)
Spaces	4 Spaces
Zones	4 Thermal Zones
Location	Boston, MA
Building type	Single Family
Building operating schedule	Default
HVAC system	Residential 17 SEER/9.6 HSPF Split HP <5.5 ton
Outdoor air per person	15 CFM
Export category	Spaces
Project phase	New Construction
Building service	VAV-Single Duct
Building infiltration class	Medium
Export Default Values	Yes

only fetches, organizes, and saves the data as opposed to performing any calculation and it does not interfere with the energy simulation process; therefore, its output could be easily validated as long as similar outputs is obtained by EnergyPlus (E+), since the source of such output is the same, only obtained through a different path. Fig. 7 also shows the main modules in EnergyPlus source code, which are modified to develop the BEPAT such as “heat balance surface manager” and “window manager”. These modules include the C++ codes to calculate the heat transfer through opaque and transparent components such as walls and windows, respectively. They report the output for building envelope components and then standard EnergyPlus shows the accumulated heat transfer in a tabular format.

The properties of the building modeled in this study are presented in Tables 1 and 2. Fig. 8 also shows the plan and 3D view of the building modeled in Revit. Table 1 summarizes the number of interior and exterior walls and openings for each zone. The output types discussed in this paper will be based on these components, and detailed amount of heat transfer through these components is the focus of BEPAT. The output types are based on a one-year simulation and Boston weather file as it is presented in Table 2. A rooftop air conditioning system is defined as the HVAC system using OpenStudio GUI and connected to all four thermal zones. Schedules, loads, and thermostat setpoints are also assigned to each thermal zone using OpenStudio interface. Finally, OpenStudio is used to generate the IDF file needed for both methods illustrated in Fig. 6. Both IDF file and a weather file required for energy simulation should be provided for BEPAT, as it generates the text files containing the detailed output. BEPAT works by running an executable file, which is generated based on the modified source code of EnergyPlus.

4. Results and discussion

As it is shown in Fig. 6, E+ advanced output is used to validate the BEPAT’s output. The data obtained from each method are presented in Figs. 11-13. The details of each method and their corresponding output are discussed in this section.

Method #1 output is the advanced EnergyPlus output including the detailed energy consumption of each component in each thermal zone, separately. These data are stored in a spreadsheet within output folders after running EnergyPlus. The spreadsheet file should be opened manually and data need to be extracted, assuming the user is familiar with the process.

Method #2 output is the BEPAT’s granular output, which includes similar data to the first methods except that data acquisition is automated and the intended data will be stored in a series of text files for each building envelope component by an easier, faster, and more accurate method. Fig. 9 shows the automatically generated text files named after each category of building envelope component, which contain the heat transfer data for each component and its corresponding thermal zones. The text file containing the data related to walls heat gain/loss is also illustrated in Fig. 9 as an example. However, authors are working on better visualization of BEPAT outputs. At this stage, providing textual output is adopted as the basis of future works. Comparison of these values with data adopted from EnergyPlus presented in Figs. 11-13, which shows BEPAT also obtain similar data and proves the functionality of this tool.

For a better understanding of BEPAT is different from the alternative methods for obtaining granular heat transfer through every single building envelope component, the procedure to obtain the output in each method could be reviewed. The following steps explain the complicated process to get the granular values in a conventional method shown as “advanced output of E+” in Figs. 11-13 from EnergyPlus using IDF file, which is method #1:

1) Open the IDF file in EPlaunch, which is an IDF editor tool.

2) Pick the advanced output option to enable accessing detailed output by defining a new object

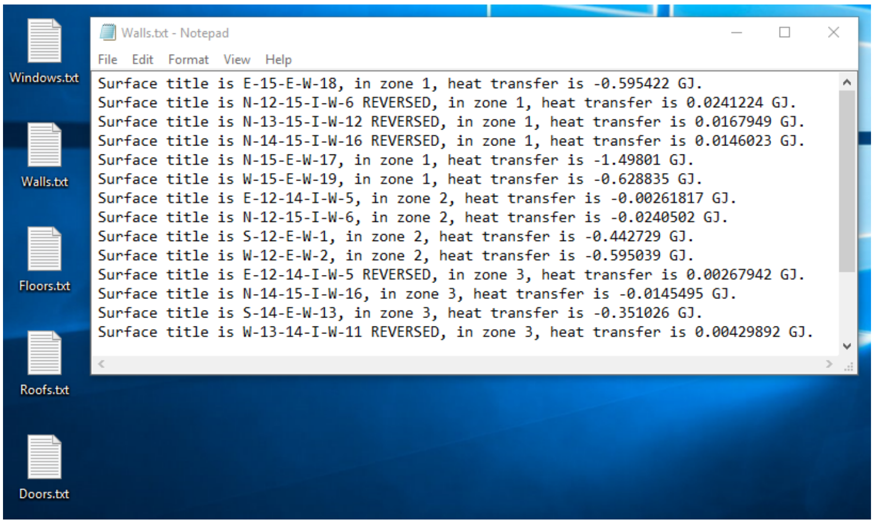

Fig. 9 Automatically generated text files containing heat gain/loss data for each component and their thermal zones

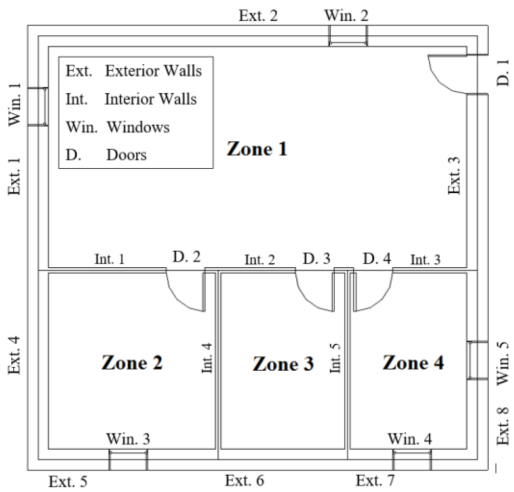

Fig. 10 Building components tags

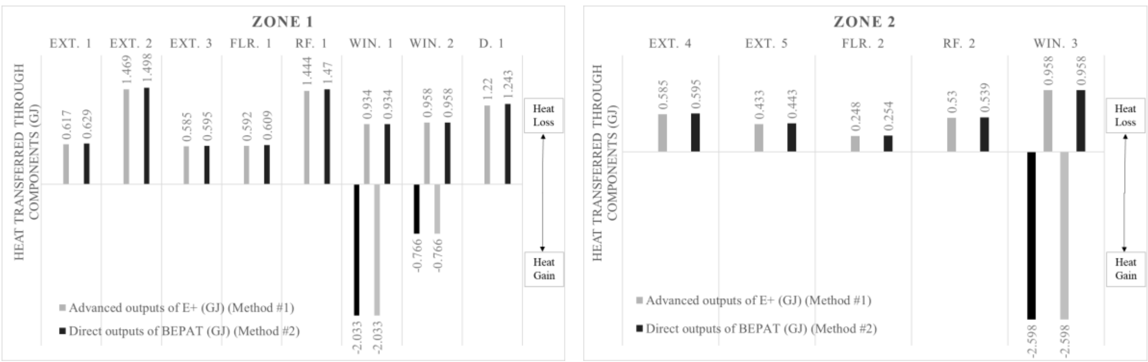

Fig. 11 Predicted heat transfer through exterior building envelope components in thermal zones 1 and 2

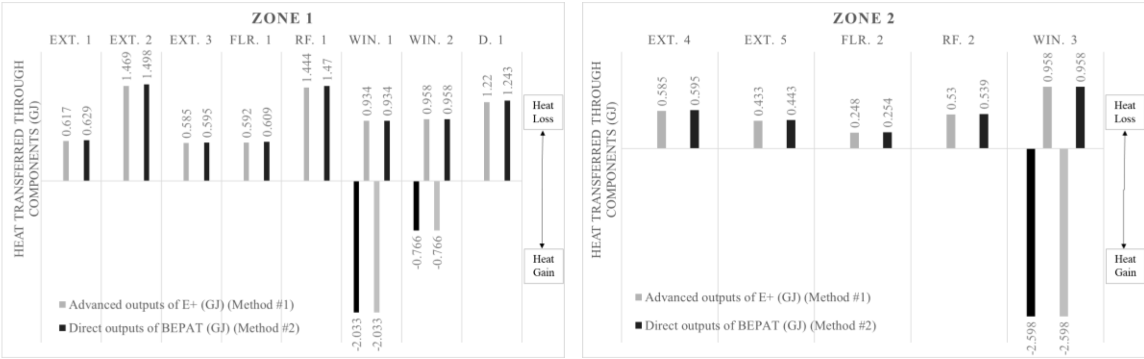

Fig. 12 Predicted heat transfer through exterior building envelope components in thermal zones 3 and 4

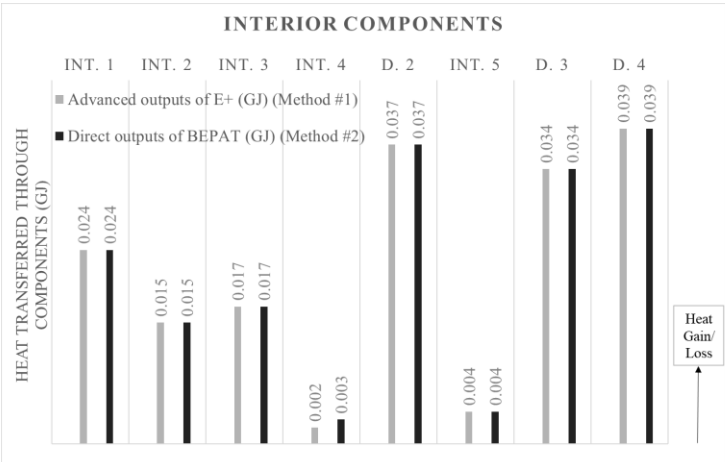

Fig. 13 Predicted heat transfer through interior components in thermal zones 1 through 4

in *Output: Variable*.

3) Pick the related output types such as Surface Window Heat Loss Energy, Surface Window Heat Gain Energy, and Surface Average Face Conduction Heat Transfer Energy among about 140 advanced outputs that need deep understanding of each item.

4) Run EnergyPlus and open the related spreadsheet output file.

5) Check the name of each component in the IDF file and determine the corresponding wall number in order to find other properties such as thermal zone.

On the other hand, as method #1, BEPAT is used to obtain the values shown Figs. 11-13. BEPAT obtains the detailed values automatically and indicates the thermal zone of each component in separate text files. The process is faster and reduces the risk of human errors. The breakdown of the process adopted in using BEPAT could be as follows:

1) Prepare the IDF and weather file.

2) Run BEPAT.

3) Open the generated text files related to each category of building envelope component such as walls or windows to check out the amount of heat transfer through each of them.

It turns out that the alternative process used in Method #1 could be complex, excessively time consuming, and error-prone. In addition, it requires certain software related skills and understanding of components in energy modeling. Advanced output needs to be selected manually and preferred over the detailed output because the tags used for each component do not necessarily represent the thermal zones. BEPAT, on the other hand, identifies the thermal zone of each building envelope component and also the detailed heat transfer.

Comparison of EnergyPlus advanced output related to average heat conduction and energy loss/gain through opaque and transparent building envelope with BEPAT's output helps validating BEPAT's output. Fig. 10 shows the abbreviations used in Figs. 11-13 and the location of each building envelope component. For example, exterior walls for zone 2, which includes Ext.4 and Ext.5 walls, allow 0.585 and 0.433 GJ of heat transfer, respectively. As it is presented in Figs. 11-13, BEPAT's output shows 0.595 and 0.443 GJ of heat loss through these walls, respectively. It can be observed that BEPAT has identified all the components and their corresponding heat gain or loss and the difference between BEPAT's direct output and EnergyPlus advanced output is less than 2%; while the latter is obtained through a complicated and error-prone process. For example, in zone 4, the EnergyPlus output calculated -2.574 heat gain through Win.4, which is equal to what is obtained through BEPAT. All the other interior components such as Int.1 through Int.5 and interior doors, are illustrated in a separate graph, which shows much smaller heat transfer through these components.

Obtaining granular output using BEPAT, which can be accessed through a straightforward and accurate process, eliminates the need for sophisticated conventional process of obtaining detailed energy simulation output and the accuracy in results shows such tools can lead to promising improvements in energy simulation tools, the quality of output, and facilitating obtaining such output.

5. Conclusions

This paper has discussed development of software capability Building Energy Performance Assessment Tool (BEPAT), a tool for evaluating the amount of heat transfer through every single building envelope component in an automated, more reliable, and faster process compared to conventional energy modeling and simulation process using energy simulation tools such as EnergyPlus. It can contribute to 1) energy smart homes, which target improving the energy performance of a building and automation of data acquisition and monitoring; 2) design phase of buildings by providing detailed information on the amount of heat transfer through each component for optimization methods; and 3) decision-making process of building energy retrofit. The approach used in developing BEPAT is editing the source code of EnergyPlus to generate an executable file. This tool can provide detailed energy-related information as opposed to accumulated heat transfer. It is important to be able to monitor and assess each component (e.g., an exterior wall) separately compared to total energy loss through the exterior walls all together. The detailed data on heat gain/loss of building envelope components can help improving and facilitating the decision-making process for energy retrofit of a building. It would be more cost effective to be able to recognize specific envelope components of the building, which contribute to energy loss more than other components.

The BEPAT tool requires an IDF and weather file to generate five separate text files containing detailed data on heat gain/loss through building envelope components, including windows, doors, walls, roofs, and floors. Moreover, the label of the thermal zone of each component is also assigned to it in order to make it easier to interpret and use the outputs in other GUIs for monitoring, optimization, and evaluation purposes. These data could be used directly from text files or could be linked to another GUI specifically designed for smart homes or building energy retrofit in order to visualize the output, which will be implemented in future versions of BEPAT. Users can monitor zone energy consumption and the amount of heat transfer through each component in building envelope and check out the energy gain/loss. Moreover, the generated detailed data could be used for further statistical analysis and provide useful information such as the percent contribution of each component in total energy consumption. Such information could be beneficial for decision-making process during the design phase of the building or energy retrofit of existing homes.

In order to validate BEPAT's output, a building with four thermal zones is modeled in Revit. A BIM authoring tool (Revit) and OpenStudio were used to generate the buildings geometry, required data for energy simulation, and the IDF file. The IDF file was fed to BEPAT and EnergyPlus. Standard output of EnergyPlus only provides accumulated data, while advanced output could provide granular data about the amount of heat transfer through each building envelope component. However, the process for obtaining these data through EnergyPlus is complex, time consuming, and error prone. Therefore, the advanced output is used only for validating BEPAT's output. On the other hand, BEPAT provides detailed information automatically and saves them in text files with additional information about their thermal zone, which makes it easy to interpret.

Based on the results of the study, the following concluding remarks are offered:

- Based on the provided literature review, automation in building energy modeling and providing detailed data related to energy consumption for monitoring purposes can contribute to efforts toward optimizing the building design, energy retrofit decision-making process, and development of energy smart homes. For example, it can contribute to identifying the thermal zones or building envelope components, which has higher contribution in building energy consumption and could be retrofitted.
- According to research studies reviewed in this paper, current energy simulation tools cannot provide detailed energy consumption data in an easy and straightforward process. Facilitating the data acquisition and making the process faster and more accurate could contribute to both energy simulation tools, energy smart homes, improving the decision-making process of building energy retrofit, and optimizing the design during the design-phase.
- It was noticed that application of BIM in energy simulation can facilitate the process; however, there are still deficiencies, as it is not fully automated for functions such as transferring data related to mechanical systems between different drawing and energy simulation tools. Moreover, more complex buildings need to be modeled and simulated using BEPAT in order to further investigate its performance.
- It was observed that multiple energy-related information is calculated within EnergyPlus such as detailed information on different types of heat transfer contributed by radiation, conduction, and convention; however, not all of them are presented and available in energy simulation tools and GUIs. It is recommended that similar studies be performed and similar tools be developed focused on such information, which could make acquiring such data easier and more accurate.
- It was shown that BEPAT can provide detailed data about the amount of heat transfer through every single building envelope component, separately. The provided granular data are accurate and easy to interpret, which can be used in GUIs designed for energy smart homes, building energy retrofit, or design process of buildings.

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