A CRITICAL REVIEW ON BUILDING PERFORMANCE SIMULATION TOOLS

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ABSTRACT

Building Performance Simulation (BPS) is an effective tool for informed decision making and providing feedback in all stages of building lifetime due to their ability to evaluate the effects of multiple parameters per multiple evaluation criteria. The energy, exergy, economy, environment, and occupant comfort (thermal and visual) are evaluation criteria in high performance building design. The decision variables or multiple parameters include architectural parameters, building materials traits, indoor and outdoor conditions, economic and ecological indicators, the characteristics of building services. Yet state-of-the-art BPS tools still need to overcome challenges to become more user friendly, improve simulation capabilities and tool interoperability. This paper surveys BPS tools by investigating their key features and limitations to help guide experts from all domains with energy efficient building design. Tool categorization based on multiple criteria is done and key findings are summarized in tables. Future development opportunities are elaborated.

Keywords: *: Building energy efficiency, building energy modeling, building performance simulation, decision-support systems.*

1. INTRODUCTION

Today, a big part of the total energy consumption worldwide stems from buildings. According to the energy consumption statistics for different sectors in International Energy Agency report, buildings are responsible for nearly 30-35% of the world's total energy consumption (during construction and operation processes), and 40% of total CO2 emissions (IEA, 2018). Reducing energy consumption and green house gas emissions in buildings through energy efficiency solutions is a key goal for achieving energy and environmental goals. Towards this goal, important initiatives have been started for improving energy performance of new and existing buildings. For example, Energy Performance of Buildings Directive (EPBD) (EU, 2002) published by EU European Parliament and Council in 2002 was aimed to build standards and a common methodology for evaluation of the building energy performance, and it was later revised in an attempt to start the applications for "zero-energy building" concept (EU, 2010). Similarly, U.S. Department of Energy's (DOE) Building Technologies Office instituted some goals to decrease the energy use intensity (EUI) of buildings almost 30% until 2030, and 50% over the long term (Hong et. al., 2018).

Identification of energy efficiency improvements for buildings is a difficult process. Buildings are complex systems with their architectural, mechanical, environmental and social aspects. There is no single parameter affecting building energy performance, on the contrary, the building performance is determined as a result of simultaneous interactions of multiple parameters. Furthermore, the design team generally have to optimize a large number of conflicting criteria such as energy demand, thermal comfort, indoor environmental quality, life cycle cost and more concurrently. As a result, there is a need for decision support systems like building performance simulation (BPS) tools that support decision-making and guide the design and operation of high performance buildings.

Hence the main aim of this paper is to survey the state-of-art in BPS tools, the validation concept, key developments, applications, and also to identify the current limitations and challenges for future development of BPS tools. This paper introduces the categorization of BPS tools based on their simulation principles and interoperability issue. A group of current validated BPS tools are analyzed and compared to each other according to several uniform criteria to illustrate what simulation tools are available in building design process to help architects, engineers and other design team members for informed decision making, and also what their strengths and limitations are within the specified framework. The promising and trending issues such as enabling cloud computing, uncertainty and sensitivity analysis, parametric design and single/multi objective optimization or user customization feature of these tools are investigated to provide a base plate for the future simulation frameworks.

2. BUILDING PERFORMANCE SIMULATION (BPS)

Today, the most widely used methodology to performance evaluation and analysis of building in both design and retrofit phases is simulations. Simulation is an imitation of the physical behaviors of a system. Identifying a system with certain number of internal variables, boundaries and external variables ensures the idealization, measurement and simplification of system's behavior in real world and the outcome is called a physical model (De Wilde, 2004). The definition of a set of relationships among the variables of the physical model results in a mathematical model, which is usually analytical in nature but sometimes involves making numerical approximations. Building performance simulation tools were developed to reduce the complexity of the basic algorithms, the computational load, and the expected inputs from the users. Detailed simulation tools labors the development of complex mathematical models and the representation of the each possible energy flow in the building (Doyle, 2008).

Building performance simulation tools are classified according to various criteria such as calculation methods, modeling levels and usage area. Clarke (2001) separated them into two groups according to calculation methods: 1) Simplified (static), 2) Detailed (dynamic). Most of the simulation tools widely used today utilize dynamic numerical methods. The dynamic tools that have a high accuracy results use either one of the finite difference, finite elements, boundary elements methods in order to calculate building energy loads, and thermal system interactions. Dynamic tools generally calculate on an hourly basis and for each zone individually in order to take into consideration of dynamic interactions between all thermal based building elements (i.e. building envelope, HVAC system, lighting and control systems) associated with comfort and energy consumption.

Alternatively, tools can be grouped in two types: the first one is design tools such Revit, Rhino, SketchUp, and the second one is detailed simulation tools such as EnergyPlus, DOE2, and TRNSYS (Hong et. al., 2000). Additionally, there exists other software (OpenStudio, DesignBuilder, Green Building Studio) that uses the other tools' simulation engines (Han et. al., 2018). Design tools are generally static programs and are used in the early design phase of the project. These are simpler and require less input than complex programs. On the other hand, detailed performance simulation tools are usually dynamic, integrated with calculation techniques for building loads and energy calculations, and can analyze the building performance completely. Besides, detailed tools also check the design to compliance with performance-based building energy standards.

Today, there are many BPS tools available in the market (IBPSA, 2019). Some are mainly used in academia, while others are provided as commercial tools, but each one has its imperfections in terms of accuracy and ease-of-use (Zhou et. al., 2014). The wide ranges of tools are used for specific simulation purposes and are able to analyze building performance in several performance categories such as whole building energy simulation, thermal load calculations, HVAC system selection and sizing, energy conservation measures, thermal comfort analysis, indoor air quality, weather data and climate analysis, building energy auditing and monitoring, lighting and daylighting simulation, air flow simulation, solar and photovoltaic analysis, rating and certificates, acoustic analysis, and life cycle analysis. Additionally, these tools can analyze building performance for a complex combination of geometry, building components and systems.

The selection of BPS tool is also a significant issue, since each stakeholder is interested in particular aspect of the project. Some of the selection criteria are summarized below (Hong, et. al., 2000; Attia et. al., 2012; Crawley, 2015):

- The level of accuracy and detail
- Usability and information management
- Data exchange capacity
- Database support
- Interoperability with building modeling
- Integration of building design process
- Speed and cost
- Ease of use

Although BPS tools have seen significant development, there are still several challenges for using them in design process. For instance, Ostergard et.al. (2016) has identified a number of challenges preventing deployment of these tools in design process: a) interoperability pointing out data exchange between BIM/CAD models and simulation programs, b) time-consuming modeling referring to the process of modeling building geometry, zones, HVAC systems, schedules, c) stricter and contradicting requirements to meet many performance objectives such as demanding for energy, building code, sustainability with the existence of trade-offs, d) lack of simulation guidance ability indicating tool's ability to guide the designer for proper solutions, e) limited reuse of knowledge referring not reusing and sharing experience between modelers.

Most recently, Hong. et. al. (2018) has surveyed the several studies pointing out the challenging issues in BPS tools, and by summarizing and making in-depth analysis, they demonstrated key challenges for future BPS development. The main challenges that cover several existing and emerging areas of BPS are presented in ten categories: (1) finding out the performance gap between predicted building performance during design stage and actual energy performance of the building during life cycle in order to achieve performance goals, (2) Modeling and accurately simulating human-building interactions, which affect significantly both building energy use and thermal comfort level, in order to represent expected occupants behavioral interaction with buildings and their effects on simulated building energy flows in design stage, and also to ensure control schemes for building operations to optimize building energy use and occupant thermal comfort simultaneously in building operation stage, (3) Improving the modeling capabilities of the performance simulation tools to accurately represent the actual performance of the model, and decreasing the discrepancies between simulated energy using thermal model data and the actual measured data, (4) Improving the applicability of building energy simulation during building operation, control and retrofit phases to identify and evaluate the most effective energy saving solutions for the building, (5) Ensuring modeling of operational faults such as control faults, sensor offset, equipment performance degradation (Cheung et. al., 2015), to estimate of the severity common faults and hence to provide decision making in a timely manner, (6) Supporting the design of Net-zero-energy-buildings (NZEB), modeling passive and advanced control strategies, and quantitative evaluation and optimization of design alternatives. Moreover, enabling the simulation of renewable energy generation and on-site energy generation of buildings that are able to adjust electricity demand based on grid needs, (7) Supporting the simulation of city/urban scale building energy performance to aid urban planning, and to achieve energy and environmental goals, (8) Supporting a quantitative evaluation of energy use and CO2 emissions at national and regional scales, and making future projections, (9) Modeling the adoption of building energy efficiency technologies, and ensuring decision-making for research and technology development, and identifying the impact of adoption of new building technologies, (10) Supporting decision-making process across the building life cycle by ensuring the integration of four dimensions: data, domain, simulation tool and workflow.

The defined challenges derived from literature and their mitigations with respect to building life cycle process are summarized in Table 1.

Table 1: The summary of challenges and mitigation of BPS tools

Building Life Cycle Phase	**Challenges**	**Mitigation**
Design	CAD-BPS Tool Interoperability (interoperability, time consuming modeling, rapid change of design)	Integration of models, run-time coupling, and shared schema to ensure fast and consistent modeling.
Design	Data Integration	Data from all available sources should be integrated under the Building Information Modeling (BIM)
Design	Domain integration	Multiple technical domains must be integrated
Design	Workflow Integration / limited reuse of knowledge	BPS tools should be integrated existing project workflows through some platforms such as web based tools or other web services
Design	Stricter and contradicting performance requirements	Stricter (e.g. energy, comfort, building code) and contradicting requirements (increasing cooling consumption or worsen thermal comfort) should be handled by BPS tools

Design	Lack of simulation guidance	BPS tools ability to guide the project team to favorable solutions
Design & Operation	Finding out the performance gap between predicted building performance and actual performance	BPS supports verification of the building performance goals
Design & Operation	Modeling and simulation of human-building interactions	BPS encapsulates models of occupants' behavioral interaction with buildings, which affect significantly building energy use and thermal comfort
Design & Operation	Supporting the design of Net-zero-energy-buildings (NZEB), and grid responsive buildings	BPS should support the design and optimization of NZEB buildings, and simulation of building energy loads dynamics to adjust energy demand per grid needs
Operation	Energy model calibration	Improving the modeling capabilities of the BPS tools to accurately represent the actual performance of the model
Operation & Retrofit	Improving the applicability of simulations for building operation, control and retrofit phases	BPS tools' applicability during building operation, control and retrofit phases to identify and evaluate the most effective building energy saving solutions
Operation & Retrofit	Modeling of operational faults in buildings	BPS should support the modeling of operational faults to estimate of the severity common faults for providing a timely manner decision making
Operation & Retrofit	City/urban scale modeling and simulation of building energy performance	BPS should support the modeling and simulation of city/urban scale building energy performance
Operation & Retrofit	Evaluation the energy saving potential of building technologies at national and regional scales	BPS should support decision-making for research and technology development of building energy efficiency
Operation & Retrofit	Modeling the adoption of building energy efficiency technologies	BPS should support the modeling the adoption of energy efficiency technologies, and identifying the impact of new technologies

3.VALIDATION OF BPS TOOLS AND MODEL CALIBRATION

In building performance simulation, validation is the process of determining if a simulation model is a good representation of real world scenario (Oberkampf and Roy, 2010). The biggest problem with validating simulation programs is the complexity of actual operational conditions such as schedules, HVAC settings (Ryan and Sanquist, 2012). In general, there are three approaches for validation: 1) Empirical, 2) Analytical and 3) Comparative (Judkoff, 1988). Empirical validation is based on comparing real-world measurement data with simulations results. Analytical verification stems from comparing simulation results with known analytical or numerical solutions. Lastly, in comparative testing, the simulation results from different programs are compared against each other. Analytical validation approaches are inexpensive and offer robust algorithmic solutions to certain thermal problems. However, it doesn't cover all sources of error and it can only validate the numerical portion of solution. On the other hand, empirical validation is expensive and time consuming due to the detailed measurements, and it can approximate the ground truth within certain accuracy, and deal with high level of complexity. The comparative analysis is a useful technique because it does not require data from a real building, however the great disadvantage of the comparative technique is the absence of a truth model (Judkoff, 2008).

Several organizations that specialize in building energy simulations have launched standards and guidelines for the validation process of whole building energy simulation programs, such as International Energy Agency Building Energy Simulation Test and Diagnostic Method (IEA BESTEST) and ASHRAE Standard 140. BESTEST was originally developed in collaboration with The National Renewable Research Laboratory (NREL) and the main aim is to compare building energy simulation outputs of a case building and to determine the error margins. BESTEST includes several case buildings and their related test results. The results of a model generated with any simulation program are compared with the test case and if the error margin is between the limits, the program passes the test and its accuracy and reliability are ensured by this way.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) adopted the BESTEST method with some refinements in accordance with American National Standard Institute (ANSI) procedures and formed ANSI/ASHRAE Standard 140, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs (ASHRAE, 2004; Neymark and Judkoff, 2008). ANSI/ASHRAE Standard 140 was first published in 2001, and updated last time in 2017. It sets a standard method to evaluate the applicability of software for thermal and HVAC simulations, and identifies the differences between whole-building simulation software.

Example of works that focused the validation of simulation tools and energy models are given. As an example for the empirical validation approach, the calibration process of building energy models in DOE-2 simulation program for both hypothetic and actual office buildings was demonstrated (Reddy et. al., 2007). Similarly, an existing high-rise building in Shanghai was created and validated by using DOE-2 (Pan et. al., 2007). Calibration of a building energy model with double skin façade created in EnergyPlus simulation tool was done by using extensive empirical data from a dedicated experimental set-up (Kim and Park, 2011). A university building energy model created and simulated in DesignBuilder/EnergyPlus was calibrated by comparing collected measured data with simulation outcomes (Mustafaraj et. al., 2014). The calibration of an EnergyPlus simulation model of a school building with displacement ventilation and radiant thermal slab was presented (Kandil and Love, 2014). Six buildings located in a university campus in US were created and validated through comparing measured data with probabilistic simulation results (Sun, 2014). A calibrated EnergyPlus simulation model of an office was performed by using long-term monitored data from an office area (Tahmasebi and Mahdavi, 2016). The simulated building model on TRNSYS building performance simulation tool was validated with the National Institute of Standards and Technology (NIST) residential test facility in Gaithersburg, USA by integrating the NIST test facility design conditions into the TRNSYS model to simulate the heating and cooling loads (Harkouss et. al., 2018). According to comparison data between measured and simulated results, the root mean square error (RMSE) and the percentage root mean square error (PRMSE) were 1.56 kWh/ym2 and 4% for cooling load, and 1.26 kWh/ym2 and 6% for heating load. Hence the NIST experimental measures are good fit with TRNSYS simulation results and the validated building energy model was used for passive design optimization process. Similarly, an existing school building energy model was created with EnergyPlus simulation tool, and then by using the actual monthly utility data, the validation of the building energy model was done according to two indicators from ASHRAE Guideline 14: CV_RMSE and NMBE were determined as 12.81% and 3.26%, respectively, and the base case energy model developed was considered acceptable (Senel Solmaz et. al., 2018).

As for the analytical validation, a mathematical model was developed to simulate the effect of the contraction of the HVAC system air duct insulation on the zone heat gain, supply air temperature (Kumar et. al., 2018). The model was validated by comparing the amount of total heat gain between simulation and measured data (5 kW vs. 5.21 kW). Similarly, an analytical optimization methodology based on degree-days and life cycle cost analysis was used for optimization of building wall insulation material thermal properties (Kumar et. al., 2019), and the optimum insulation thickness were calculated based on energy savings, payback periods and CO2 emission rates of buildings (Kucuktopcu and Cemek, 2018). As for the comparative validation, a thermal model of building was generated with EneryPlus, and the model was validated according to ANSI/ASHRAE Standard 140- Case 600 (Rad et. al., 2019). According to results, the difference between ANSI/ASHRAE Standard 140 for modeling of case 600 by EnergyPlus and created thermal model are 3.24% for annual heating, and 0.67% for annual cooling.

As mentioned before in the main challenges of BPS, the significant discrepancies between simulated energy consumption data and actual data plays a key role for relying on model predictions, hence limiting the adoption of building performance simulation tools during building life cycle. So, building energy models should be improved to represent the building performance as closely as the actual performance of modeled buildings. This can be achieved through model calibration: the tuning of various simulation inputs to match predicted and observed energy usage (Reddy, 2006). While the simulation accuracy of building energy models is determined by thousands of parameters, there are usually limited measured data available as calibration inputs. Although, the simulation accuracy of the building energy models is determined based on a huge number of parameters, there are generally limited numbers of measured data available as calibration inputs. Therefore calibration becomes an over-parameterized problem with no unique solution where matching can be obtained in many different ways (Coakley et. al., 2014). Presently, according to ASHRAE Guideline 14 (ASHRAE, 2014), the standard for model calibration is defined, although it does not consider the uncertainty of simulation inputs or the accuracy of BPS tool. The main approaches to model calibration are categorized as manual and automated. Manual calibration approaches rely on iterative trial and error process driven by users, a very time-consuming process due to the nature of trial-error process, and having no form of automation. On the other hand, automated calibration approaches based on mathematical/statistical techniques, and a number of automated calibration methods ranging from optimization techniques such as Bayesian calibration, object penalty function to other modeling techniques like artificial neural networks (ANN), meta-modeling have been developed in this area (Coakley et. al., 2014).

4.COMPARISON OF BPS TOOLS

So far, the general overview of BPSs and various requirements and challenges has been presented. In this section, features and limitations of current validated and dynamic BPS tools are assessed. A reduced set of simulation tools has been selected for further investigation and comparison per several criteria (e.g. validation/accuracy).

The 9 selected tools are: DesignBuilder, EDSL-TAS, EnergyPlus, ESP-r, eQUEST, Green Building Studio (GBS), IES-Virtual Environment (IES-VE), OpenStudio and TRNSYS. The reviews and comparisons of the tools are made according to:

- The general properties of tools (i.e. major capabilities, expertise required, users, programming language/platform, license, developer/company)
- Tool integrated design stage, geometric modeling unit (design tool, GUI), simulation engine, interoperability/data exchange, user customization, performance criteria, applications/functions
- Main strengths and limitations, input and output file formats, weather data and validation

4.1.Comparison of BPS tools per general properties

The comparison of the tools in terms of general properties including major capabilities (indicating the tool's main performance analysis), expertise required, users (tool primarily intended for), programming language/platform, tool's license (open source or not), developer/company information is presented in Table 2. More specifically, the tools are mainly capable of making different performance analysis not for only energy criterion. For instance, some tools can perform an airflow analysis, parametric analysis and even single/multi-criteria optimization. The primary users of tools could be from multiple domains with or without deep understanding of building systems and technology. From an "expertise required" perspective, almost all the tools have similar requirements such as having information or good understanding about building physics and environmental systems, or having an experience with 3D geometry modeling with CAD/BIM systems, in order to use them and understand the simulation process and results adequately.

4.2.Comparison of BPS tools per integrated design stage, GUI, simulation engine, interoperability, customization, performance criteria and applications

Since the categorization made in Table 2 is general, and there is a need for further investigation about the details of tool interoperability indicating how BPS tools integrate/connect to CAD/BIM environment. The detailed information for fulfilling this need is given in Table 3. The detailed descriptions of the categorization are as follows:

Table 2: Comparison of selected building performance simulation (BPS) tools with respect to general properties

BPS Tools	Major Capabilities	Expertise Required	Users	Language/ Platform	License	Company/ Country	Ref
DesignBuilder	▪ Whole building energy simulations ▪ Load calculations ▪ HVAC system selection and sizing ▪ Parametric and optimization ▪ Air flow simulation ▪ Ratings and certificates ▪ Code compliance checking	▪ No steep learning curve	▪ Architects ▪ Engineers ▪ Building designers ▪ Building scientist ▪ Academic research and teaching	▪ Linux ▪ Windows	License is required, free to try	DesignBuilder software Ltd./UK	(DesignBuilder, 2019)
EDSL-TAS	▪ Whole building energy simulations ▪ HVAC system selection and sizing ▪ Parametrics and optimization ▪ Lighting simulation ▪ Airflow simulation ▪ Code compliance checking ▪ Detailed cost analysis	▪ Qualified engineer and architect ▪ Training courses are not necessary ▪ Includes comprehensive tutorials	▪ Architects ▪ Building services engineers ▪ Consulting engineers	▪ Windows	Free for non-commercial & academic use, free to try	Environmental Design Solutions Limited (EDSL)/UK	(EDSL, 2019)
EnergyPlus	▪ Whole building energy simulations ▪ Load calculations ▪ HVAC system selection and sizing ▪ Lighting simulation ▪ Air flow simulation ▪ Code compliance checking	▪ Background in building physics and mechanical engineering is helpful	▪ Architects ▪ Engineers (mechanical, energy, control) ▪ Building auditors and operators ▪ Energy-efficiency policy analysts ▪ Researchers	▪ Linux ▪ Windows ▪ Mac OS X	Free/Open source license	US Department of Energy (DOE)& National Renewable Energy Laboratory (NREL)/US	(DOE and NREL, 2019)
ESP-r	▪ Whole building energy simulations ▪ Complex buildings and systems	▪ Researchers and building designers having good understanding of building physics, environmental systems and controls is necessary	▪ Building designers ▪ Engineers ▪ Energy consultants ▪ Researchers ▪ Multi-disciplinary design firms	▪ Linux ▪ Windows ▪ Mac OS X	Free/Open source license	University of Strathclyde Energy Systems Research Unit (ESRU)/UK	(ESRU, 2019)
eQUEST	▪ Whole building energy simulations	▪ Experience with energy analysis is necessary ▪ Knowledge of building technologies is required	▪ Building designers ▪ Operators ▪ Owners ▪ Energy/LEED consultants	▪ Windows	Free/Open source license	James J. Hirsch & Associates/US	(James J. Hirsch & Associates, 2019)
Green Building Studio (GBS)	▪ Whole building energy simulations ▪ Parametrics and optimization ▪ Energy conservation measures	▪ No expertise is required to use Green Building Studio ▪ 3D-CAD/BIM experience is required for geometry ▪ modeling	▪ Architects ▪ Engineers ▪ Construction managers	▪ Web/SaaS	Free for non-commercial & academic use, free to try	Autodesk Inc./US	(Autodesk Inc, 2019)
IES-Virtual Environment (IES VE)	▪ Whole building energy simulations ▪ Load calculations ▪ HVAC system selection and sizing ▪ Lighting simulation ▪ Code compliance checking	▪ Software knowledge is required but includes documentation for learning	▪ Architects ▪ Engineers ▪ Sustainability and Energy Consultants ▪ Building Owners ▪ Facilities Managers ▪ Contractors	▪ Windows ▪ Mac OS X	License is required, free to try	Integrated Environmental Solutions (IES)/UK	(IES, 2019)
OpenStudio	▪ Whole building energy simulations ▪ Energy conservation measures ▪ Lighting simulation	▪ Building physics and mechanical engineering background is helpful	▪ Architects ▪ Engineers (mechanical, energy) ▪ Energy-efficiency policy analysts ▪ Researchers ▪ Students, educators ▪ Software developers	▪ Linux ▪ Windows ▪ Mac OS X ▪ Web/Saas	Free/Open source license	National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy	(NREL, 2019)
TRNSYS	▪ Whole building energy simulations ▪ Parametrics and optimization ▪ Detailed component simulation	▪ No need an expertise for standard package use ▪ Fortran knowledge is helpful for generating new components	▪ Architects ▪ Engineers ▪ Researchers ▪ Consulting firms	▪ Windows	Reduced for non-commercial & academic use	Thermal Energy System Specialists, LLC/US	(Thermal Energy System Specialists, 2019)

Plugins for design tools to use external simulation engines: These are plugins for different design tools (i.e. SketchUp, Revit) in order to couple with external simulation engines to perform specific simulations. Among the selected tools, OpenStudio and Green Building Studio (GBS) are in this group (Table 3). OpenStudio (NREL, 2019) is an open-source software development kit (SDK) that accompanies Sketch-up and takes care of constructions, schedules, HVAC systems of the energy model while Sketch-up is used for 3D geometry. It is originally developed for EnergyPlus simulation engine and now also supports ESP-r, Radiance for advanced lighting analysis, CONTAM airflow engine, CEN/ISO 13790, and the code compliance engine CBECC-Com. OpenStudio SDK can also be customized using Ruby and Python programming languages. A cloud-based service GBS (Autodesk Inc, 2019) is Autodesk's core whole building energy simulation tool that enables energy analysis for Autodesk Revit, Autodesk Insight 360 and Autodesk Formlt 360. It uses DOE-2.2 simulation engine for energy analysis, and creates accurate input files for EnergyPlus for interoperability at the same time. It provides decision making for design team by performing an entire building energy analysis, energy consumption optimization and the other sustainability criteria such as carbon data, water use, renewable energy, natural ventilation especially in the early design stage. GBS creates the energy model by automatically reading building information and geometry from Revit and 3D-CAD program.

Graphical User Interface (GUI) without an external simulation engine: This category includes the tools with a GUI and are being developed based on existing simulation engines such as EnergyPlus, DOE 2. Among selected tools, DesignBuilder and eQUEST are in this group (Table 3). DesignBuilder (DesignBuilder, 2019) is a comprehensive interface and visual modeling tool based on the EnergyPlus dynamic simulation engine for building performance evaluation. The program has its own modeling window, and includes a total of 11 modules: 3D-modeler, simulation, visualization, certification, daylighting, HVAC, cost, LEED, scripting, optimization, and CFD. It has several types of building templates, which have large amount of building information data regarding construction materials, schedules, occupancy, lighting, HVAC and more. When the specific building template is chosen, the corresponding building information data is brought automatically from the database and the users can modify these default settings according to their input data, and develop their own building energy model. DesignBuilder allows both inner creation of building geometry and import from other files such as dxf, gbxml file formats (IBPSA, 2019). eQUEST (James J. Hirsch & Associates, 2019) is a whole building energy performance design tool based on the DOE 2.2 dynamic simulation engine. It provides the design team assessment and detailed analysis of building energy performance throughout the entire design process from the conceptual stages to final stage with its detailed interface and two design wizards (schematic design wizard and design development wizard). It provides users to import building geometry from CAD tool with (.dwg) and gbxml file formats.

Tools with own GUI and simulation engine: Among selected tools, IES-VE, EDSL-Tas, ESP-r, TRNSYS are in this group (Table 3). IES-Virtual Environment (IES-VE) (IES, 2019) building simulation tool was developed by Integrated Environmental Solutions (IES). IES-VE has its own simulation engine for energy simulation and RadianceIES for daylighting analysis, and encapsulates two packages: VE for architects and VE for engineers. It has its own visual 3D modeling block, providing users to create a building energy model directly in the tool, and also IES developed plug-ins for Revit and Sketch-up that ensures tool interoperability and interconnection between BIM and CAD tools in order to simplify modeling process. Therefore, IES-VE can also be categorized under the first group. EDSL-Tas (EDSL, 2019) is a dynamic whole BPS tool, and has its own simulation engine and user interface. It has a modular characteristic, with committed programs serving a specific application such as Tas 3D modeler for creation of building geometry; Tas building simulator and viewer for building information modeling, simulation, and viewing and exporting simulation results both 2D and 3D formats; Tas system for HVAC modeling and simulation; Tas ambiens 2D is for a modeling airflow in buildings and CFD analysis. Tas 3D modeller allows users to import data files such as dwg, gbxml, EnergyPlus input file (.idf), DOE2/eQUEST input file (.inp). ESP-r (ESRU, 2019) is a whole building energy simulation program with its own simulation engine and GUI for integrated modeling of building energy performance, and definition of building systems and equipment. Particularly, it allows users to define detailed HVAC and renewable energy systems. It is capable of simulating innovative technologies such as combined heat and electrical power generation, PV facades, 3D transient CFD, multi-gridding, and control systems. Transient System Simulation Program (TRNSYS) (Thermal Energy System Specialists, 2019) is a whole building simulation tool having modular system characteristics including its own graphical interface (Simulation Studio), a dynamic simulation engine and detailed component library ranging from variety of building models and standard HVAC systems to renewable energy systems. It enables users to create their new components. It is capable of simulating building energy and thermal comfort performance, sizing HVAC systems and their analysis, multi-zone airflow analysis, solar design and electric power simulation and more. TRNSYS is capable of interfacing with other simulation packages/software such as Excel, FLUENT, GenOpt and Matlab.

Simulation Engine without having own GUI for geometry design: This is the last group of tools, which were developed originally as a simulation engine

Table 3: Comparison of selected BPS tools in terms of integrated design stage, GUI, simulation engine, interoperability, customization, performance criteria and applications

BPS Tools	Integrated Design Stages					Design Tool/GUI	Simulation Engine	Interoperability/ Data Exchange	User Customization	Performance Criteria									Applications			
	Pre-design	Conceptual design	Design development	Detailed design	Operation & Management & Retrofit					Energy	Thermal	Daylighting	Environmental Emission	Life Cycle Analysis (LCA)	Energy Cost/Life Cycle Cost (LCC)	CFD Analysis	Code/Certification Compliance	Renewable System Analysis	Cloud Computing	Uncertainty/ Sensitivity Analysis	Parametric analysis	Optimization
Design Builder	✓			✓		Self	EnergyPlus/ Radiance	File exchange	EMS, FMU, C#, Python scripting tool	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓
EDSL-Tas			✓	✓		Self	Self	Standalone	TasGenOpt	✓	✓	✓	✓		✓	✓		✓			✓	✓
Energy Plus				✓		DesignBuilder/ OpenStudio	Self	Standalone (IFC, gbxml)	EMS, FMI, External Interface	✓	✓		✓									
ESP-r				✓		Self	Self	Standalone	N/A	✓	✓		✓		✓							
eQuest	✓	✓		✓		Self	DOE 2.2	Standalone	N/A	✓					✓		✓					
Green Building Studio (GBS)	✓	✓				Revit	DOE 2.2 & Energy Plus	File exchange	N/A	✓		✓	✓				✓		✓			
IES-VE	✓		✓	✓	✓	Self/Revit/ SketchUp	Self & Radiance IES	File exchange	"Hone", "Parametric tool" Python scripting	✓	✓	✓	✓	✓	✓	✓					✓	✓
Open Studio	✓		✓	✓	✓	SketchUp	EnergyPlus/ Radiance	File exchange	API modification by Ruby, Python, C#, JavaScript	✓	✓	✓	✓		✓				✓	✓	✓	
TRNSYS			✓	✓		Self/TRNSYS3D for SkectchUp/ TRNLizard	Self	Standalone	N/A	✓	✓				✓			✓				

without no 3D geometry design GUI. Among the selected tools, EnergyPlus simulation engine is the only one in this group (Table 3). EnergyPlus (DOE and NREL, 2019) dynamic simulation tool was designed with its own calculation algorithms, implements ASHRAE Heat Balance method for zone thermal modeling, and has the capability to build with a wide variety of system configurations and conditions. EnergyPlus is an advanced simulation engine that combines best features of DOE-2 and BLAST. Input file (IDF) is text based and created in IDF Editor, and its advanced simulation engine is used by multiple tools with GUI such as DesignBuilder, OpenStudio, Sefaira. The other comparison criterion in Table 3 is "integrated design stage", indicating the design stage(s) the tool is specifically/typically used in. Generally, the building design process is separated into five stages: pre-design, conceptual design, design development, detailed design, and operation-management- retrofit. Most of the simulation tools are widely used in the later design stages such as detailed design, and their use in both early design and retrofit stages is limited. However, the design decisions being made in the early phases have a significant impact on final performance of building and project costs and the integration of the building simulations in early design stages should be increased. Similarly, the use of BPS tools in the operation, management and retrofit of existing buildings should be improved.

"Interoperability/Data exchange" criterion in Table 3 indicates the different ways that ensure the connection between CAD/BIM design tools/models and BPS tools. In the literature, there are four different methods of linking CAD and BPS models: integrated method referring to the situation that numerical calculations are integrated into CAD environment; run-time interoperability method indicating the links between CAD tools and analytical models constituted by plugins or application programming interface (API); file exchange method based on common file exchange format that is readable and also sometimes writable from CAD and BPS tools (i.e. Industry Foundation Classes (IFC), XML, gbXML, dwg); standalone method defining that the data is interpreted by users (Ostergard et al. 2016). So, most of the tool interoperability is based on the file exchange or standalone.

"User customization" in Table 3 points out if the simulation program allows users to customize via scripting, programming, or any advanced system. For example, EnergyPlus provides users to customize with Energy Management System (EMS), and enables co-simulation with other engines through Functional Mockup Interface (FMI). In addition, OpenStudio API can be scripted via programming languages such as Ruby, Python, C#, JavaScript in order to extend, customize and automate the design applications.

"Performance criteria" in Table 3 presents the significant independent performance criteria/objectives/categories for high performance buildings. Each of these tools can be used for specific simulation purposes, and while some of them are able to analyze building performance for several performance criteria ranging from energy to CFD analysis, others are capable of making assessment only in limited categories, or specialize in very specific performance objectives. Therefore, application of interest determines the selection of simulation program. Among the selected tools, IES-VE dynamic performance simulation software has high capacity to assess building performance according to many criteria (e.g. energy, thermal comfort, daylighting, CFD).

"Applications" criteria in Table 3, encapsulates significant applications/ functions that BPS tools have to support design team through an iterative process, giving feedback for making rapid design changes during the design process and ensuring informed decision-making. These applications are: ability of tools to make a parametric analysis, to perform uncertainty analysis (UA)/ sensitivity analysis (SA), to perform a single/multi objective optimization, and to enable to cloud computing. DesignBuilder has a parametric analysis block inside the tool that can analyze the influence of design parameters on building performance, and identify trade-off relationships between parameters (DesignBuilder, 2019). IES-VE has a standalone Parametric Tool that enables users to create and automatically run the simulation of multiple design scenarios without the need to manual interference (IES, 2019). The Parametric Tool is completely customizable and during parametric analysis, the VE can still be used. Similarly, OpenStudio plugin has an independent package named Parametric Analysis Tool (PAT) for parametric analysis and UA/SA applications, which can be realized by coupling these two units. This feature extends the tool's capabilities by enabling to simulate and compare multiple design options (Macumber et al., 2014). As for the optimization function, Design Builder has an optimization module that can optimize multiple variables and find the optimum set of solution per objective functions. IES-VE has a standalone "Hone" optimization tool that enables users to discover the optimal building design parameters that achieve the defined objective criteria. The "Hone" is capable of optimizing multiple design variables such as thermal comfort, total energy, and carbon emission simultaneously. Similarly, TasGenOpt is a utility, and a result of combining EDSL-Tas engineering simulation program and GenOpt optimization package developed by LBNL, for performing parametric simulation and optimization. TasGenOpt allows users to change aspect of energy models dynamically using C# programming language (EDSL, 2019). Beside built-in optimization modules, there are many independent optimization software such as GenOpt, BEOpt, jEPlus, MOBO, which can be coupled with several BPS such as EnergyPlus, TRNSYS, DOE2 to solve single/multi-objective optimization problems. However, they are not easy to use because they require users to understand optimization theory and have computer programming skills. Therefore, building performance optimization unit like DesignBuilder and IES-VE may be more suitable especially for architects due to the user-friendly interface and easy-to learn operation process. Lastly, finding an optimal design solution within a huge design space requires exploring thousands of detailed simulations. Cloud computing can help with such time consuming process to increase the usability of building performance simulation/optimization tools in design process. There is a growing interest for it in building simulation field. For example, DesignBuilder, Green Building Studio and OpenStudio all enable cloud computing to ensure considerable time saving on simulation runs, and quickly measure and analyze key building performance data.

4.3.Comparison of BPS tools per strengths/limitations, input/output files, and validation

Lastly, the comparison of selected BPS tools in terms of main strengths and limitations, input and output file formats, weather data and validation are presented in Table 4. The input file formats indicate original input file formats and other file formats that ensure data exchange and interoperability with the other programs. Similarly, while there is some variation on the weather files that the tools use, most of the tools utilize the common weather files such as International Weather for Energy Calculations (IWEC), Typical Meteorological Year (TMY) and TMY-2. As for the validation, most tools are validated based on the ANSI/ASHRAE Standard 140 and ASHRAE 90.1-2007 for several years. Other tools have other validation test results, e.g. EDSL-Tas has a several validations according to EN ISO13791: 2012/ EN ISO13792: 2012/ EN ISO15255: 2007/ EN ISO15265: 2007, CIE 171:2006 (for daylighting calculations), and CFD validation based several criteria. In Table 4, the general and specific limitations for each tool are determined as a result of detailed literature survey. Examples to common limitations are if the tool offers modelling capabilities of human-building interaction, supports city/ urban scale building energy modelling and analysis, support an evaluation of the building stock' energy use and CO2 emissions, or support building codes/ certification compliance checking.

5.CONCLUSION

This study provided a critical overview of the recent developments in BPS tools, evaluated their effectiveness in design process. A group of validated and accurate BPS tools were investigated, categorized and compared based on general properties, validation, interoperability, user customization, application/ functions, strengths and limitations. As a result, the most significant research issues/limitations were considered and development challenges lying ahead in both academia and software industry were summarized in order to propose a simulation framework that covers and addresses all of these important issues in BPS tools.

The main limitations to be addressed and future directions of BPS tools are: In terms of integration of the tools during process, most tools are used during the detailed design stage. Therefore, the applicability of these tools during not only early design stages, but also building operation, management and retrofit phases should be improved to make the most effective decisions for building energy and environmental performance.

Most tools are capable of evaluating the building performance in common domains such as energy, thermal comfort, and environmental emissions. They should add support for assessment of other crucial analyses like CFD, code compliance and renewable energy systems, and the simulation of renewable energy generation and on-site energy generation of buildings in order to adjust electricity demand of buildings. Supporting users for modeling and simulating human-building interactions in order to develop advanced interactive control strategies and improve building energy efficiency and thermal comfort could be a valuable addition. Moreover, it is crucial to expand the modeling capabilities to include design and modeling of building stocks and simulation of urban scale building energy performance and environmental emissions to ensure decision making for urban planning strategies and achieve energy and environmental goals in regional/national scale. Lastly, the tools should support the development of new building technologies in terms of research and technology development, and identification the impact of these brand new technologies on building energy efficiency.

The interoperability issue addressing the data exchange between BIM/ CAD programs/models, and simulation tools by different ways is significant development area, and yet it is still not fully solved. Besides continuity and interdisciplinary collaboration issues, the interoperability is mostly addressing the time-consuming modelling problem during geometry design and simulation phases due to the missing or defective data transfer among the tools. Users are sometimes forced to create the building geometry from scratch while transferring the building model among the tools. A wide range of plugins have been developed to ensure run-time coupling between CAD software and analytical models for fast feedback and parametric analysis such as OpenStudio, TRNSYS3D for SketchUp design tool, and DesignBuilder and OpenStudio for EnergyPlus.

Expansion of the BPS tool functionality to support the design team by giving immediate feedback for rapid design changes, and enable exploration of the

Table 4: Strengths, limitations, file formats and validation of building performance simulation (BPS) tools

BPS Tools	Strengths	Input File	Output File	Weather Data	Validation	Limitations
eQUEST	• Detailed (DOE-2) interface that supports detailed analysis from construction documents to post-occupancy phases. • Ability to evaluate whole-building energy performance throughout the entire design process • Ability to provide schematic design wizard, design development wizard and detailed interface that enable design team to explore the energy performance of design concepts from early design stage • Ability to perform many evaluations of large models and hold interactions between building systems by its execution speed • Having rule-based processor that ensure automated quality control checks of simulation inputs and results	• Provides the inputs at three levels: schematic design wizard, design development wizard and detailed (DOE-2) interface • Input default settings are based on the California Title 24 building energy code	• Graphical summary reports including single-run and comparative run summaries and tabular reports • Input/output summary reports • Hourly and non-hourly simulation results • California Title 24 compliance analysis reports	Typical Meteorological Year (TMY), TMY-2, Weather Year for Energy Calculations (WYEC), DOE-2 file format (BIN)	• ANSI/ASHRAE Standard 140-2014 • ASHRAE 90.1-2007	Requires extensive knowledge on building technology • Program's defaults and automated compliance analysis have been done only with California Title 24, no support for ASHRAE 90.1 yet. • Only supports IP units (not SI units). • Daylighting analysis can only be applied in a convex space configuration. • Limitation for custom code development in eQUEST. • Does not offer modelling capabilities of human-building interaction • Does not support city/urban scale building energy modelling and analysis • Does not support an evaluation of the building stock's energy use and CO_2 emissions
Green Building Studio (GBS)	• Ability to provide energy analysis for Autodesk Insight 360, Autodesk Revit and Autodesk Formlt 360 • Ability to provide cloud-based service feature to quickly find the effective energy efficiency measures • Ability to run building performance simulations to optimize energy-efficiency, carbon emissions in the early design stage • Ability to provide default settings based on the ASHRAE 90.1, ASHRAE 90.2, ASHRAE 62.1 and CBECS data • Ability to synchronize historical weather data and utility billing data for existing building retrofit • Ability to provide optimization based on parametrization • Ability to create geometrically accurate input files for EnergPlus (.IDF) • Ability to calculate the building model's credits based on EnergyStar and LEED daylighting	• All building geometry data from gbXML file format generated by BIM or 3D-CAD	• gbXML for Trane TRACE 700 and other tools • DOE 2.2 file for eQuest • Energy Plus IDF file • VRML file • Design Review file • US EPA ENERGY STAR • Water preliminary analysis for LEED • Customizable charts • Weather file (Binary (BIN) and CSV) • Weather data summary	• The Autodesk Climate Server provides to access a large weather database and file formats like TMY, TMY2, DOE-2 Binary file,	• ANSI/ASHRAE Standard 140-2007, 2004, 2011 • ASHRAE 90.1-2001 • Regression testing (for internal analytical results) Note: GBS uses DOE-2.2 simulation engine for energy analysis. DOE-2.2 is validated by Lawrence Berkeley National Laboratory and the Los Alamos National Laboratory.	• Requires good knowledge of Revit including gbXML export feature • Limited for architectural design, and able to generate complex building models. Contrarily, it is not suited for control purposes. • Only supports Imperial (IP) units (not SI units) (EMIN MISIN) • Requires internet connection due to being a web-base tool • Does not ensure model viewing during performance analysis, so the project settings can not be checked after sending model for analysis • Does not offer modeling capabilities of human-building interaction • Does not support city/urban scale building energy modeling and analysis • Does not support an evaluation of the building stock's energy use and CO_2 emissions
IES-Virtual Environ ment (IES VE)	• Ability to analyze different design alternatives for best energy efficiency solutions, low carbon and renewable energy technologies, energy use, CO_2 emissions, occupant comfort. • Ability to provide comprehensive building performance analysis with wide range of performance metrics • Ability to provide integrated central data model that makes the design changes immediately updated for other modules such as HVAC system modeling, natural ventilation modeling, CFD analysis, daylight control, solar shading analysis, cost analysis • Interoperability with other CAD/BIM tools • Ability to increase productivity and simulation time using cloud-based services, and parallel execution.	• Geometrical building data from CAD/BIM systems • Can import gbXML, IFC, and DXF files	Analysis results in wide range of formats (e.g. tabular, graphical, video, 3D geometric visualization, LEED/BREEAM matching reports)	• IES VE can read the weather file formats like (.fwt) (VE proprietary format), EnergyPlus Weather file (.epw), and others (IWEC, TMY, TMY-2) • Generate hourly data from monthly averages • Estimate diffuse radiation from global radiation	• ANSI/ASHRAE Standard 140-2014 • ASHRAE 90.1-2004, 2007, 2010, 2013 - Performance Rating Method (Appendix G) • ASHRAE 90.1-2010, 2013 – Energy Cost Budget Method (Chapter 11) • ASHRAE 90.1-2016 (Fixed Baseline) / ASHRAE 90.1-2013 • NECB in Canada • Title 24 in California	• Does not support building codes/certification compliance checking • Does not offer modeling capabilities of human-building interaction • Does not support city/urban scale building energy modelling and analysis • Does not support an evaluation of the building stock's energy use and CO_2 emissions
Open Studio	• Having an Application Programming Interface (API) feature-accessible via a several scripting languages such as Ruby, Python, C#, JavaScript-allows it to be customized and extended easily. Ability to execute scripts written in these languages. • Ability to create a 3D geometry and energy model in SketchUp. • Ability to provide OpenStudio scripts library and component content in the public Building Component Library database that allows these elements to be approved by and shared with a community. • Having committed support from DOE.	• Only content types like constructions and schedules can be imported from .IDF file • gbXML and IFC files	• OpenStudio file (.osm) • EnergyPlus (.IDF) file	International Weather for Energy Calculations (IWEC), Typical Meteorological Year (TMY), TMY-2, Weather Year for Energy Calculations (WYEC),	• ANSI/ASHRAE Standard 140-2014 (OpenStudio v2.7.0 with EnergyPlus v9.1.0) • ASHRAE 90.1-2007	• Requires good knowledge of building technology and scripting • Does not support building codes/certification compliance checking • Does not offer modelling capabilities of human-building interaction • Does not support city/urban scale building energy modelling and analysis • Does not support an evaluation of the building stock's energy use and CO_2 emissions
TRNSYS	• Ability to simulate behavior of transient systems focusing on the performance of thermal and electrical energy systems. • Ability to execute several applications ranging from central plant modeling, building simulation, solar thermal processes, coupled multi-zone thermal/airflow modeling to wind and PV systems, data and simulation calibration, optimization. • Ability to model a variety of energy systems in different complexities using its modularity • Ability to easily modify existing components or write their own • Ability to provide extensive documentation on component routines (e.g. explanation, typical uses, supplied time step, starting and stopping period) • Graphical interface named SimulationStudio • Ability to integrate with several programs such as COMIS, CONTAM, EES, FLUENT, GenOpt and Matlab	• Standard TRNSYS input file known as deck file (.dck) • TRNSYS Project File (.tpf) • ASCII text file • EnergyPlus input file (.idf) by TRNSYS3D	• TRNSYS basic output format is ASCII • TRNBuild can generate Radiance files (.rad), (.dds)	Any user-specified format, Monthly average data, EnergyPlus Weather file (.epw), ESP-r Climate Formatted File (CLM), European Test Reference Year (TRY), Typical Meteorological Year (TMY), TMY-2, Japan Automated Meteorological Data Acquisition System (AMeDAS) weather data	• ANSI/ASHRAE Standard 140-2014 • ASHRAE 90.1-2007	• Requires detailed knowledge about the building and HVAC system in order to create a building energy model. • Does not support building codes/certification compliance checking • Does not offer modelling capabilities of human-building interaction • Does not support city/urban scale building energy modelling and analysis • Does not support an evaluation of the building stock's energy use and CO_2 emissions

design space and guide the design rather than just evaluate the performance of design. Main functionalities are parametric analysis for creating geometry and automatically making rapid design changes for the geometry, statistical analysis such as sensitivity/uncertainty analysis for identifying the most influential design parameters on performance criteria within a wide range of parameter set, single/multi-objective optimization for automatically searching an optimal set of design solution within a large solution space in order to optimize the performance criteria, and lastly cloud computing for helping to overcome time consuming process of performance based design to increase the usability of BPS in design process. Through the review of selected BPS tools, it is deduced that only a very limited number of these tools have aforementioned functions. It is believed that this limitation leads software industry to focus more on developing different types of applications such as plugins, GUIs by third-party developers to encapsulate this challenge.

Lastly, model customization during evaluation of the building performance allows expanding the design limits and propose suitable solutions according to the project requirements. Among selected tools, some of them (e.g. DesignBuilder, EnergyPlus, IES-VE) allow users to customize the model via several ways such as scripting. Therefore, customization of BPS tool is a good feature to add for the future in order to extend, customize and automate the design applications.

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