INTERNATIONAL BUILDING PERFORMANCE SIMULATION ASSOCIATION ENGLAND

Proceedings of BSO-V 2020
5th Building Simulation and Optimization Virtual Conference
21-22 September 2020
Loughborough, UK

A Comparative Analysis of Energy Simulation Tools for Architectural Research: A Case Study of a Typical House in Saudi Arabia

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Abstract

The building sector is responsible for over 30% of the energy consumption worldwide, and in Saudi Arabia in particular, the building sector consumes double that when compared to US, UK, and EU. The residential buildings are responsible for half of this consumption mainly for cooling. Energy simulation tools are an important aid in understanding a buildings performance and in optimising the architectural designs to be more energy efficient. However, there are hundreds of building performance simulation (BPS) tools in the market, which makes the choice of design tool very challenging. In this study, a systematic approach was used to filter the most commonly evaluated and compared energy simulation tools in literature, concluding by evaluating the Usability and Information Management (UIM) of four tools: IES-VE, DesignBuilder, Green Building Studio (GBS), and Insight 360, using a case study of a typical house in Saudi Arabia. The objective of this paper is to help the architects and building designers in their decision making of the most suitable tool that serves to optimise their designs.

Introduction

There is a growing need to build energy efficient buildings in Saudi Arabia, as the building sector alone is responsible for more than 80% of the consumed electricity in the country. The current Saudi Vision 2030 encourages energy efficiency in buildings for a future that is less dependent on oil and releases less CO_2 emissions (Felimban et al. 2019). An improved level of building energy performance is one of the most common approaches to achieve this goal and that can be guided through the use of energy simulation tools.

Energy simulation tools enable deeper understanding of buildings efficiency through the visualisation of different design proposals and simulating their performance and energy consumption. However, there is a large number of energy simulation tools in the market with different features and capabilities. According to the survey done by Attia et al. (2009), architects prefer tools with graphical interface over text interface, as well as the tools that have high interoperability with building information modelling (BIM).

A systematic scoping review of literature was conducted in order to determine the most common tools that have been evaluated in the past two decades. The resulting list of tools was filtered based on their type of interface (graphical or text), and their level of interoperability with BIM. Insight 360 was added to the compared tools as it is a new tool by Autodesk under GBS, that targets architects as the main users according to the developers (Autodesk, 2020), and it wasn't reviewed in literature previously, which makes it an interesting candidate to be added in the comparison.

An overview of the tools (GBS- IESVE- DesignBuilder- and Insight360) is given, then their Usability and Information Management (UIM) are evaluated in depth using the criteria that was developed by Farzaneh et al. (2015) based on the survey results of Attia et al. (2009), using a case study of a typical Saudi house that's modelled in Autodesk Revit Architecture.

Systematic Scoping Review:

This scoping review follows the framework developed by Arksey and O'Malley (2005), which is consisted of five stages that focus mainly on transparency, allowing the search protocol to be repeated and the research results to be more reliable. The five stages of Arksey and O'Malley's framework are: (1) identifying the initial research questions, (2) identifying relevant studies, (3) study selection, (4) charting the data, and (5) collating, summarising and reporting the results. These stages are now elaboarated on in the context of this analysis.

1. Identifying the initial research questions

The focus of this review is to investigate the reviews of the available building energy analysis tools. To ensure that a significant range of literature was captured relating to the topic of interest, the following initial research questions were considered to guide the search:

- What are the BPS tools that had been assessed? And how frequently was each tool mentioned?
- What are the key assessment criteria of these tools?
- What is the methodology used to review the energy analysis tools in these studies ?

2. Identifying relevant studies

A broad description of key words for search terms should be introduced in order to obtain a wide coverage of available literature as proposed by Arksey and O'Malley (2005). Key search terms were developed and tested before choosing the final combination of key terms in order to capture the widest range of the literature that review building energy analysis and simulation tools. The search criteria included the use of search tools such as 'OR' between words that are similar in meaning, 'AND' to combine the parts of the search scope, and 'TITLE' as only phrases that appeared in the titles are considered in this search. The linked descriptive key search terms that have been developed to guide the search are outlined in Table 1, as well as the search inclusion parameters: Review method, Type of studies, Terms location, and the chosen search engines and databases.

Table 1: Parameters implemented in the scoping review

Unit of Analysis	Reviews of building energy analysis tools .
Review methods	Literature review, Case studies, Surveys.
Type of included studies	Journal articles, theses and dissertations, conference proceedings and research reports.
Search terms and criteria	"Energy" OR "Building" OR "Dynamic Thermal" OR "Thermal"
	AND
	"Analysis" OR "Simulation" OR "Performance" OR "Model" OR "Modelling"
	AND
	"Tools" OR "Applications" OR "Software" OR "Programs" OR "Programmes"
	AND
	"Compare" OR "Comparison" OR "Comparative" OR "Contrast" OR "Review"
Search terms location	Title
Search Engines and Databases	Web of Science Core collection, Scopus, Engineering Village, UCC library Onesearch
Publication Year	Last two decades

3. Study selection:

1066 studies were identified after using the parameters mentioned in Table 1, excluding the following types from UCC library Onesearch: Book reviews, Magazine articles, Newsletters, and Newspaper articles, and excluding the irrelevant subject areas from Scopus: Med – Nurs – Psy– Vet -Phar- Chem. A significant number of duplicated studies were excluded automatically when importing the documents to Mendeley, however, Mendeley and Endnote only remove the 100% match duplicates and ignore the rest, so a manual check was needed to remove the rest of the duplicates using Rayyan, an online based tool for managing documents, that automatically calculates the percentage of the match but needs a manual action to remove the excluded documents (Rayyan, 2020). Then reviewing the titles revealed many irrelevant studies that have used the same terminologies in their titles but within a different field or hold a different meaning for the term (for example: the term 'Applications' was added to the search terms as it is being used widely as a noun to refer to 'Computer tools and software programs', but in a number of the excluded studies it meant 'Use' or 'Request' (Cambridge dictionary, 2020). Figure 1 illustrates the process of articles selection.

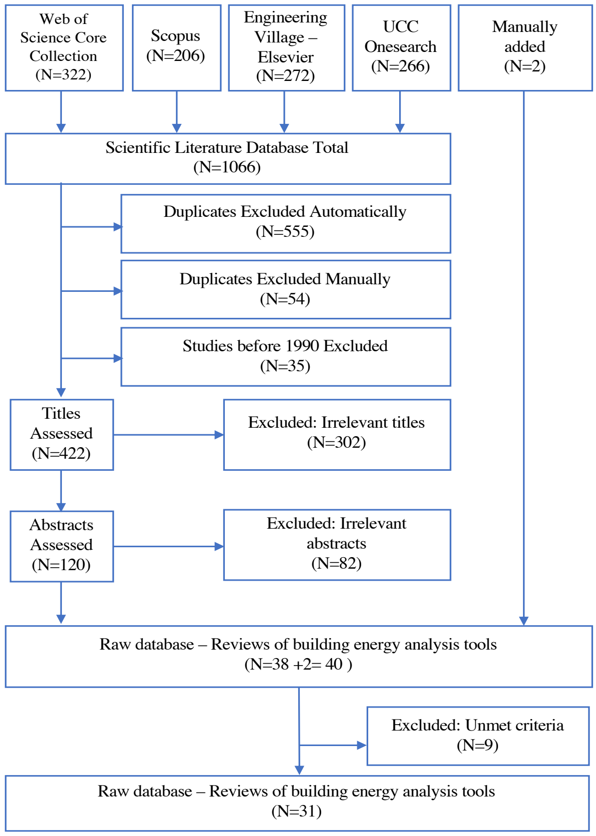


Figure 1: Flow diagram for scoping review inclusion and exclusion

4. Data charting and collation:

This stage of the framework charts and organises the selected studies. A summary of the final list of the studies is provided in Table 2, where a summary is developed for each study presenting the author, year, and method/s used in each review paper.

5. Summarising and reporting findings:

The scoping review resulted in 31 included studies from four different databases that evaluated and compared the energy analysis tools. 10 of which are based on literature review, while only two of these were systematic reviews. Two studies used analysis framework approaches, two used surveys, and one study used interviews. The remaining 16 used case studies as the main methodology.

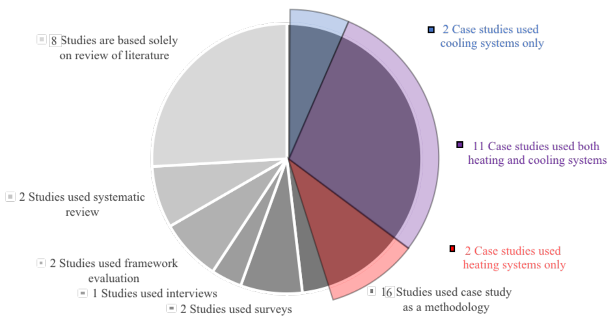


Figure 2: Used methodologies in the included studies, and the chosen HVAC systems in the case studies.

Table 2: The resulted included articles of the systematic scoping review.

Reference	Methodology
(Solmaz, A. 2019)	Literature review
(Al Ka'bi, A. 2019)	Literature review + Case study: One-floor residential building model.
(Lucchino, E. et al. 2019)	Systematic literature review
(Han, T. et al. 2018)	Literature review + framework
(Wena, L. and Hiyamaa, K. 2016)	Literature review
(Nadarajan, M. and Kirubakaran, V. 2016)	Literature review
(Mantesi, E. et al. 2015)	Literature review + BESTEST buildings 600 and 900.
(Yang, Z. and Becerik, B. 2015)	Systematic literature review
(Farzaneh, A. et al. 2015)	Case study of a four-story hotel + Interviews with architects and engineers.
(Han, Y. et al, 2014)	Literature review
(Buonomano, A. and Palombo, A. 2014)	BESTEST Case studies in various climatic conditions.
(Christensen, J. et al. 2013)	Model of an actual commercial building in Denmark.
(Manke, P. et al, 2013)	Literature review.
(Jarić, M. et al. 2013)	Literature review + Case study of a one-floor residential building model.
(Kensek, K. et al. 2013)	Case study (a model of an actual institutional building in the US.)
(Salmon, S. 2013)	Case studies of six actual buildings
(Bahar, Y. et al. 2013)	Literature review
(Sousa, J. 2012)	Literature review
(Sang-Tae, N. and Jae-Yeob, K. 2012)	Case study of a designed office building
(Attia, S. et al. 2012)	Literature review and two online surveys
(Weytjens, L. et al. 2011)	Literature review and application of an existing comaparison framework.
(Attia, S. and De Herde, A. 2011)	Literature review + experts evaluation.
(Rallapalli, H. 2010)	Case study: a Medium Sized Office Building located in New Mexico.
(Hoque, S. and Sharma, A. 2009)	Case study: a LEED certified single-story detached house in the US.
(Attia, S. et al. 2009)	Survey:gathering information from beginner simulation tools users.
(Hong, T. et al. 2008)	Case studies: Three building prototype (Office building, School, & hospital).
(Hopfe, C. et al. 2007)	Case study chosen is the BESTEST case 600.
(Crawley, D. et al. 2005)	The comparison is based on information provided by the program developers
(Mills, E. 2004)	Case studies: Web-base tools: A benchmark house, located in San Francisco Bay Area. Desk based tools: A benchmark house, located in Ohio.
(Sat, P. and Yik, F. 2003)	Case study - four existing commercial office buildings in Hong Kong.
(Lomas, K. 1991)	Case study: actual building for tools validation

Since the context of this paper is Saudi Arabia and its hot climate all year round, further analysis of these papers was conducted to know whether they considered cooling systems in the case studies, and a gap in this area was found as most papers considered either both systems or just heating (Figure 2) but only two studies considered cooling systems in isolation.

The second main finding of the scoping review is the most frequently assessed tools in these studies. It was found that EnergyPlus and IES-VE are the most common, followed by eQuest. After those tools, ESP-r, GBS, ECOTECT, and DesignBuilder came third. HEED, DOE-2, TRNSYS, Openstudio, Risuka, HTB2, and Vasari were mentioned in less than 25% of the studies, while the rest of the evaluated tools were mentioned only once each.

Energy Simulation Tools Comparison Criteria:

The following criteria is considered in comparing the tools for this study, and are illustrated in Figure 3:

1- Graphical interface: Architects prefer easy-to-use tools that have a user-friendly graphical interface (Attia, S. et al. 2009), so only tools with graphical interface were included and the text-based interface tools were excluded.

2- Interoperability: Architects use of BIM for their designs has increased dramatically, therefore the chosen simulation tool in this comparison should have direct and easy interoperability with BIM in order to be easily integrated within the design process

3- Most common: The systematic scoping review showed 7 tools that were reviewed most frequently (appeared in at least 25% of the total number of the papers), yet only 3 (IES-VE, DesignBuilder, and GBS) match with the previous two points. EnergyPlus was excluded as it is not user-friendly and has difficult interoperability with BIM models on its own, eQuest (Difficult interoperability with BIM models on its own), ESP-r (not user friendly, no interoperability with BIM) (Moon, H. et al. 2011), and ECOTECT (Discontinued in 2015).

Insight 360 was added to the compared tools as it is a new tool by Autodesk under GBS, that's targeting architects as users according to the developers, and it hasn't been reviewed in literature previously, which makes it an interesting candidate to be added to the comparison.

These BPS tools are compared in the following section to further understand their capabilities in terms of the Usability and Information Management (UIM) using the developed criteria by Farzaneh et al. (2015) that is based on the survey results of Attia et al. (2009). A 3-bedroom typical Saudi house was selected as the case study and it is modelled in the BIM software Autodesk Revit Architecture.

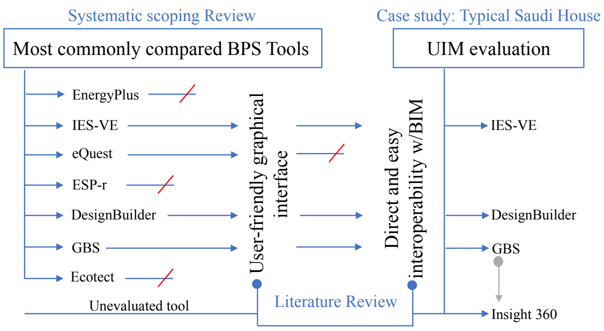


Figure 3: Criteria of choosing the tools for the Usability and Information Management (UIM) comparison.

Overview of the Four Tools:

IES-VE: Is a simulation tool that provides a number of variables in simulation analysis of buildings. ApacheSim is one of the IES-VE analysis tools that is intended for dynamic thermal simulation of heat transfer processes of buildings, it uses its own independent energy simulation engine (Sousa, J. 2012) and (Kamel and Memari, 2019).

DesignBuilder: Is a graphical user interface to EnergyPlus simulation engine. It can be considered as an architect-friendly tool despite being based on a complex simulation program, as it uses visual interface and provides different levels of detail of data input. (Manke et al., 2013).

Green Building Studio (GBS): Is a cloud-based service simulation tool that runs energy analysis for Revit, Insight 360, and Formlt 360.And it is based on the DOE-2.2 simulation engine. It creates the energy model in one step as it reads building information and geometry from Revit and other BIM programs automatically (Solmaz, A. 2019) and (Han, T., et al. 2018).

Insight 360: Is a cloud-based energy simulation plug-in tool in Revit that is run by GBS, it examines the building input parameters and has input adjustment sliders to check the alternatives energy performance (Autodesk, 2020).

Usability and Information Management:

UIM consists of two main criteria: (Usability) and (Information Management). Usability means mainly the overall friendliness and ease of using the tool (Bevan, 1999). The tools' usability also includes the graphical interface of the tool, representation of data input and output results, flexible navigation, as well as learnability and error diagnostics. Furthermore, data exchange and interoperability is another important aspect of the usability of the tool, as it creates easier and efficient simulations (Crawley et al. 2008). The Information Management criteria includes the organisation of data within the tool, possibility to validate the results, and providing design optimisation suggestions (Farzaneh et al. 2015).

Case study – Typical Saudi House:

The residential sector is accounted for about 40% of total electricity consumption in Saudi Arabia (Felimban et al. 2019), mostly as a cause of the excessive use of air conditioners due to heat transmittance through the building's envelope, as most of the existing buildings lack thermal insulation. A typical Saudi modern villa that represents the vast majority of residential buildings in the country (Asif, M. et al. 2017) was chosen as a case study for this comparison, it is a rectangle 3-bedroom house with a gross floor area of (449 m2), front elevation facing east, and the chosen location is Jeddah, Saudi Arabia. According to a survey study conducted by (Opoku and Abdul-Muhmin, 2010) in major cities of Saudi Arabia, the single-family detached house known as 'villa' represents 40% of the building stock in Saudi Arabia. Moreover, the design of the typical house in this study was chosen on the basis of a survey that was conducted by (Alaidroos and Krarti, 2015) to determine the preferred dwelling type in different regions of Saudi Arabia. The majority of the respondents have described their preferred future home to be a villa with a total site area between 400 m2 and 600 m2. The thermal properties of the building are explained in Table 3.

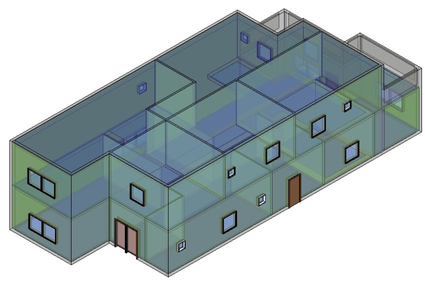


Figure 4: Energy model of the typical Saudi house created in Revit Architecture.

Table 3: Thermal properties of the case study's building features.

Building Feature	**Description**	**U-Value $(w/(m^2.k))$**
External walls	Plaster 15mm – Concrete hollow blocks 200mm – Plaster 15mm	4.7
Roof	Concrete tiles 40mm – Concrete (cast in place) 300mm- Screed 50mm- Polystyrene insulation 50mm – Plaster 15mm	0.56
Ground Floor	Concrete (cast in place) non-insulated 150mm	6.9
Windows	Double glazing – Domestic – Aluminium frames	3.1
External Doors	Solid core wood	2.6

The chosen location of the case study is Jeddah, Saudi Arabia, where the climate is hot and humid all year long, with a mean temperature of 27.9 C°, mean relative humidity of 64.7, mean wind speed of 2.6, and annual solar radiation of 257 W/m^2. (Alrashed and Asif, 2015). The cooling degree-days of Jeddah stands at 6587 with Zero heating degree-days (Alaidroos and Krarti, 2015). The main used HVAC system in Jeddah is "split mechanical cooling system (A/Cs)" and no heating is used all year long. In Autodesk Revit architecture, this system can be found in the early design phase, yet when moving to the energy settings, the list of HVAC systems that overrides the previous design settings doesn't include this/ nor a similar system. So an HVAC system that includes cooling was chosen, moreover, this is overridden again in some of the energy simulation tools at a later stage.

Table 4 presents the entered energy settings in Autodesk Revit Architecture. In a recent survey that was conducted in Jeddah by (Felimban et al., 2019), it was found that the preferred room temperature by the majority of respondents is between 22 and 24 C°, and as this case study simulates a typical house under the environmental conditions of Jeddah as one of the major cities of Saudi Arabia; 23 C° was chosen as the cooling set-point.

Table 4: Energy settings of the case study in Autodesk Revit Architecture.

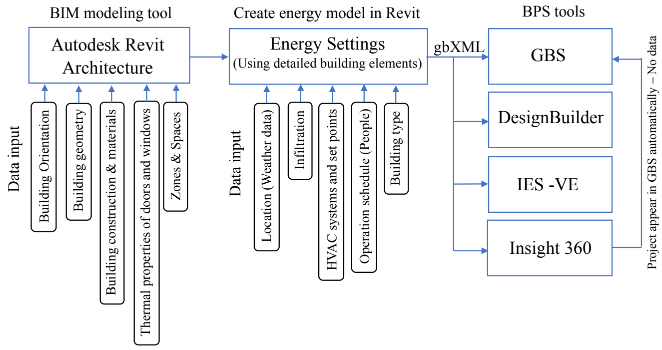
Energy settings	**Description**
HVAC system	Split system - mechanical ventilation with cooling.
Cooling set point	23 C°
Operation schedule	24-Jul
Building Type	Residential
Location / Weather data	Jeddah– Saudi Arabia (21.543333, 39.172779) Winter: 21C° – Summer: 47 C°
Infiltration	Medium

Exporting to gbXML from Revit gives two options (Use energy settings or Use room/space volumes), the first option is selected as it provides more accurate data for analysis in the gbXML file.

Tools Comparison:

In order to check the usability, a quick check on the file transfer from BIM tool, in this case Revit, to the selected tools had to be done as a first step, it was found that some of the gbXML elements that were supposed to be automatically converted to the receiving analysis tools, such as (Building type) were found to be missing in all four tools, and the location (weather data) had to be reentered as well in all the tools except for Insight 360. Although the chosen tools were mentioned in literature to have high and easy interoperability with BIM, some of the elements of the gbXML file still had to be fixed manually in each tool to match the entered data in Revit before running the energy simulation. Figure 5 illustrates the process of exporting BIM to the energy simulation tools.

Figure 5: Process of exporting and importing BIM files into the chosen BPS tools.



The gbXML file of the BIM model was imported into the tools at the same time in order to compare their UIM, (Insight 360 is a built in plugin within the Revit environment which automatically sends the BIM file to the tool's cloud, so there is no need/possibility to export and import the gbXML file into it).

The UIM evaluation applied in this comparison is developed by Farzaneh et al. (2015), it is divided into two main categories: (Usability) and (Information Management), the first category includes the following criteria: Representation of input data and output results, graphical 3D results, flexibility of use and navigation, follow-up structure, and learnability. And the second category includes: Assumptions and default values, flexibility of data storage, input review and modification, quality control of simulation input, and the creation of alternatives reports.

When the gbXML file is imported into the tools, a wizard screen appears in all compared tools (except for Insight360) presenting and offering options for the weather data, building type, HVAC systems, and even error diagnosis (in IES-VE and DesignBuilder), which allowed the evaluation of the data input of each tool.

After insuring the same data were entered in the four tools, the energy simulation was started, and the processing time was recorded. After simulations are completed, the output results were compared and evaluated, and options of optimisations were noted where available.

Table 5 and Table 6 shows the UIM evaluation and comparison results of the tools, where Green=Yes, Yellow=Partially, and Orange/red=No. The four energy simulation tools can be arranged in terms of their usability and information management as follows: DesignBuilder and IES-VE are equally in the first place in their UIM, followed by GBS, and lastly Insight360.

Discussion and results:

This experiment attempts to provide an overview of the usability of four of the tools that are considered architect-friendly. As many architects model their designs in a BIM software, it was important to investigate the usability of the method of exporting the BIM design into the energy analysis tool, as it appears to be the easiest and fastest way to run the energy simulation in order to understand the building performance and to optimise the designs.

It was found that importing a design (the typical Saudi house in this case study) that includes interior walls and different heights was troublesome, as it was found that some of the elements in Revit like the walls joining points (with other walls and with the roof/ceiling) should follow particular instruction to insure the validity of the created energy model and to be imported without many error messages. To solve the issue in this case study, the interior walls were replaced with space separators to differentiate between the different zones.

The different heights in this case study was also an issue and had to be adjusted couple of times in order to be interpreted correctly into the tools, at the first attempt for example, there was a low level wall surrounding the western low roof so it can be enjoyed as an outdoor space. Yet when the building was imported, some of the tools completed the wall to create a full block and considering it as a full zone. So the low level wall had to be removed completely in Revit in order to be correctly read by the tools.

Autodesk Insight 360 is a good tool to be used by architects and designers at the early schematic design stage or (pre-design), as it doesn't require much details to run the energy analysis. It is beneficial to be used when making early decisions with the client regarding the building mass, envelope, glazing, orientation. After running the analysis, which would take around 15 minutes to process, it becomes possible to instantly see the result (energy loads or cost) of any modifications by simply using the sliding bars on the tool's cloud

Table 5: Usability comparison between four energy simulation tools =Yes. =Partially. =No.

	CATEGORY	CRITERIA	IES-VE	DesignBuilder	GBS	Insight 360
1	Representation of input data	Data exchange proficiency	Yes	Yes	Yes	Yes
		Graphical input capability	Yes	Yes	Yes	Yes
		Support both SI/IP	Yes	Yes	Yes	Yes
2	Representation of output results	Short running time	Yes	Yes	Yes	Partially
		Error diagnostics	Yes	Yes	No	No
		Clear text report	Yes	Yes	Yes	No
		Graphical report	Yes	Yes	Yes	Yes
		Flexible graphs	No	No	No	Yes
		Finding easily key output	Partially	Partially	Yes	Yes
3	Graphical 3D results		Yes	Yes	No	Yes
4	Flexibility of use and navigation		Yes	Partially	Yes	Yes
5	Easy follow-up structure		Yes	Yes	Yes	Yes
6	Easy learnability	Short learning curve period	Partially	Partially	Yes	Yes
		Help support (online, forum, guidelines)	Yes	Yes	Yes	Yes

Table 6: Information management comparison between four energy simulation tools =Yes. =Partially. =No.

	CATEGORY	CRITERIA	IES-VE	DesignBuilder	GBS	Insight 360
1	Allowing assumptions and default values to facilitate data entry	Data entry tree	Yes	Yes	Partially	No
		Library of construction properties	Yes	Yes	Yes	Partially
		Library of central plant and HVAC system	Yes	Yes	Yes	Partially
		Range of default values	Yes	Yes	Yes	Yes
		Simple input options	Yes	Yes	Yes	Yes
2	Flexible data storage and user customizable	Tools adaptability to different design phase	Yes	Yes	Partially	Partially
		Tools adaptability to different user	Yes	Yes	Yes	Yes
3	Simple input review		Partially	Yes	Partially	Yes
4	Simple input modification		Partially	Partially	Yes	Yes
5	Quality control of simulation input		Yes	Yes	Yes	No
6	Enhancing building performance	Creation of comparative reports for multiple alternatives	Yes	Yes	Yes	Yes
		Generation of optimisation reports/options	Yes	Yes	Partially	Yes

interface.
GBS is most useful in the early design stage. The needed input data are not as detailed as other energy simulation tools (when compared to IES-VE and Designbuilder), yet still not as simple as Insight 360. It provides useful insights when designing an energy efficient and carbon-neutral building and deciding on the best construction methods and materials. GBS provides the best level of output details that is required by the architects.
IES-VE and Designbuilder both require a great amount of input data, yet they also provide some default settings that can be used to simplify the process. Both tools give detailed reports on many analysis aspects, and a good level of knowledge of the tool should be obtained before attempting to use it to analyse any project. These tools are best used in the late design stages to asses and optimise a certain aspect specifically, retrofitting stage, and they are most useful when the building is aiming for a green building certification like LEED.

Overall, it is possible to run the energy analysis of the building successfully using the method of detailed building elements in BIM into the BPS, however, a level of understanding of how the building should be modelled in BIM for energy analysis, should be achieved first. Moreover, It was found that Insight 360 provides the easiest overall energy consumption of the designed buildings without further calculation details, yet it depends solely on its cloud graphical interface and doesn't offer any reports which is a major disadvantage. GBS is also a good and easy option if a little further analysis and reports are required for the building's energy consumption. Both GBS and Insight 360 are Autodesk products and therefore have higher compatibility with Revit when compared to the other tools. They are best used in early design phases, and provide comparison option between the entered designs.

IES-VE and DesignBuilder provide more professional input options and output results, they can provide detailed performance simulations, and both are approved by LEED, and they both provide an optimisation option for the analysed model.

The provided lists of HVAC systems in all four tools were found to be unsatisfactory when it comes to separate cooling systems.

Conclusion and Future work:

This study aimed to help the architects and building designers in their decision making of the most suitable tool that serves in creating energy efficient buildings at each of the design stages. UIM evaluation of four energy simulation tools was conducted using a case study of a typical Saudi house. This study is the start of this research journey, other studies will be conducted to further evaluate the tools' reliability using actual data in a similar climatic condition, moreover, a survey is be conducted to capture the architects' current usage and expectations of energy simulation tools in the middle east.

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