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Application of Parametric Design and Artificial Intelligence in Energy Analysis of Buildings – A Review

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In an era where sustainability and energy efficiency are paramount in architecture, advanced technological tools, and analytical methodologies are restructuring the design and construction of buildings. Energy analysis methods, including parametric modeling and artificial intelligence, offer architects unprecedented capabilities to comprehensively assess and optimize energy performance throughout a building's lifecycle. This paper reviews a wide range of energy analysis methods, including dedicated software tools, in-built applications, parametric tools, and artificial intelligence. It highlights the benefits and limitations of each method, emphasizing model-based methodologies. Dedicated software simplifies energy studies but requires manual data input, limiting flexibility and scalability. In-built applications, such as ArchiCAD or Autodesk Revit, enable automatic energy analysis but rely on detailed models. Parametric tools like Rhinoceros-Grasshopper enable flexible design variations but demand specialized knowledge. Artificial intelligence-driven tools like CoveTool and Autodesk Forma leverage AI algorithms for rapid energy modeling but are still evolving. In this review article, we would like to highlight the importance of energy analysis in building design and the need for architects to learn about new technologies. All these are necessary for a sustainable future.

1. Introduction

In the dynamic world of architecture, where sustainability and energy efficiency have become paramount (Dyudnev et al., 2021), the integration of advanced technological tools and analytical methodologies is transforming the way of designing and constructing buildings. Energy analysis methods, including generative design, parametric modeling, and artificial intelligence, offer architects unprecedented capabilities to comprehensively assess and optimize energy performance throughout the lifecycle of a building. By harnessing the power of data-driven insights and cutting-edge technologies, architects can shape environmentally conscious structures that not only reduce energy consumption but also enhance occupant comfort and well-being. Energy analysis methods encompass a range of sophisticated techniques that allow architects to delve into the intricate details of a building's energy dynamics. Among these, generative design stands out as a revolutionary approach that employs algorithmic descriptions to explore a vast design space, generating numerous design alternatives (Caetano et al., 2020). By integrating energy performance parameters into the generative design process, architects can automatically generate and evaluate multiple design options, identifying those that achieve optimal energy efficiency while meeting other design objectives.

Parametric modeling, another powerful technique also belonging to the wide range of computational design, allows architects to create flexible and adaptive design models that respond to changing parameters. By linking the building's geometry, materials, and environmental factors, architects can analyze and optimize energy performance through parametric simulations. This iterative process enables the exploration of design variations, helping architects identify the most energy-efficient configurations and strategies for a given context.

Artificial Intelligence (AI) has also emerged as a game-changer in energy analysis methods for architecture (Bundela, 2023). Machine learning algorithms can analyse vast amounts of data from building sensors, historical energy consumption, and environmental conditions, identifying patterns and correlations that humans may overlook. AI-powered predictive models can forecast energy usage, optimize building systems, and suggest

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energy-saving measures, providing architects with valuable insights to inform design decisions and enhance energy efficiency. Advancements in computational power and simulation technologies have further revolutionized the capabilities of these energy analysis methods. Architects can now take advantage of generative algorithms, parametric modelling, and AI techniques to create virtual models of their designs and simulate real-world energy scenarios. These simulations provide valuable insights into factors such as energy consumption, thermal comfort, daylighting, and HVAC (Heating, Ventilation and Air conditioning) system performance, empowering architects to optimize their designs for maximum energy efficiency and occupant well-being. Moreover, these energy analysis methods enable architects to explore the integration of renewable energy systems seamlessly. Generative design algorithms can automatically optimize the placement and configuration of renewable energy components, such as solar panels considering the factor of solar exposure. Parametric modelling can assist in evaluating the impact of renewable energy integration on energy performance, while AI algorithms can optimize energy production and storage systems, maximizing the utilization of renewable resources.

The initial building energy models primarily focused on thermal energy and HVAC systems, providing insights into building energy performance. With the introduction of computers and advanced mathematical modeling techniques, energy analyses evolved to include complex system-level assessments. One effective method for utilizing and managing the information content of 3D models is Building Information Modeling (BIM), which has become increasingly important in the construction industry (Sacks et al., 2018). However, several studies (Chong et al., 2017) have pointed out that seamless data exchange between BIM software and energy analysis tools is not fully resolved. This presents a significant obstacle to the realization of federated BIM models, which should be a single source of truth. According to Forouzandeh et al. (2021) the majority of available tools for building energy analysis uses simplified numeric input data, which does not allow the data-driven nor the BIM-based design. Furthermore, there are no relevant study in this field, which includes all the aforementioned techniques.

Additionally, building performance simulations, such as energy analysis, are often neglected in the early design stages due to high levels of uncertainty and lack of detailed information (Tkeshelashvili, 2021). Nevertheless, it is a recognized fact that the most significant impact on building performance can be achieved through decisions made in the early design phases (Wang et al., 2002), leading to increased interest in new methods capable of overcoming these shortcomings.

Based on these research gaps this article reviews the wide range of energy analysis methods available for architects today. We examined the software according to the following grouping: dedicated and in-built software solutions, parametric modeling, and artificial intelligence. In this paper, the key techniques and tools used for energy simulation are examined, highlighting their benefits and limitations and focusing on model-based methodologies. Furthermore, it is important to emphasize that this article is dedicated to the exploration of the aforementioned innovative work methodologies and unconventional approaches in energy analysis. The manuscript serves as a foundational investigation, with the primary objective of providing an exposition of software tools currently available in the market and their suitability within contemporary methodological frameworks.

The research methodology relied on a comprehensive literature review with the primary objective of investigating current technological solutions for building energy analysis. Since this study focuses on model-based techniques, the main keywords were the following: building energy analysis; BIM; model-based; parametric building performance; and artificial intelligence in architecture. Furthermore, data was also collected from descriptions provided by software vendors.

2. Results and discussion

There are three primary approaches for energy analysis: (1) using dedicated software solutions or integrated applications and plugins; (2) employing parametric design; and (3) utilizing artificial intelligence. The choice of method depends on the available inputs, desired outcomes, and knowledge of the process. In the following sections, we examine these three main methods, including their advantages and disadvantages, and highlight situations in which they can be applied.

In the article, it was considered important to present as many programs as possible that fall within the three primary methodological categories defined for energy analysis. Accordingly, the article aims to succinctly showcase programs, delineating their advantages, disadvantages, and primary areas of applicability within each defined methodology.

2.1 Dedicated software tools

Today, one of the most common methods used in energy assessments is the application of numerical software with manual data input. These software solutions have made it possible to simplify and speed up energy studies. The input and output data of dedicated software tools is usually numerical. The calculations are based both on international and country-specific standards. One example of this method is Auricon Energetic software whose workflow is described below.

The essence of these calculations is to manually input various data of the building into the software. This process can be time-consuming, as different layers need to be entered one by one, and the thermal bridges of the structures need to be manually set. Each different window and door must be specified individually. The building's HVAC systems, energy sources, and potential renewable energy sources must be determined. The software then calculates the heat loss coefficients, energy consumption, and other energy-related characteristics. Additionally, the building's energy performance classification is received based on current regulations determined by national law and practice. However, the disadvantage is that the data must be entered manually into these programs. Nowadays, BIM plays a significant role in the construction industry and allows us to simplify or speed up any processes, such as material calculation. Therefore, even if a BIM model is created with the appropriate level of detail, it cannot be used for energy assessments with this method. As a result, despite advancements, energy assessments remain a time-consuming and labor-intensive process. Another drawback is that the model cannot be continuously analyzed from an energy perspective since comprehensive calculations can only be performed on a finalized building. Furthermore, if any changes occur, the energy calculations need to be repeated, and the parts of the input data that changed need to be figured out. These limitations hinder the possibilities of energy optimization for a specific building.

2.2 In-built applications

The workflow of the built-in analyses is very similar to the workflow of software dedicated to energy analysis, but with the advantage that any changes to the building are automatically reflected in the energy analysis. The only changes that need to be made manually are changes to the building services systems or the geographic location.

Nowadays, simulation is the most widely used methodology for performance assessment and analysis of buildings, both in the design and renovation processes. Within this topic, the built-in energy analysis tools of two CAD (Computer Aided Design) - BIM software are presented, Graphisoft ArchiCAD and Autodesk Revit. Graphisoft ArchiCAD Energy Evaluation (formerly known as EcoDesigner) is a software tool developed by Graphisoft, a leading provider of BIM solutions. It is specifically designed to extend the environmental analysis capabilities of ArchiCAD, their flagship BIM software. This built-in energy assessment tool integrates energy assessment and simulation capabilities directly into the BIM workflow. For energy assessment in ArchiCAD, the input data is the building model, which includes at least the main multi-layer structures, openings, and zones. The tool also allows the use of templates for operating profiles according to DIN 18599 (series of preliminary standards, method of calculating the overall energy balance of buildings) (Tkeshelashvili, 2021). The MEP (mechanical, electrical and plumbing) systems used (i.e., heating, cooling, hot water production, and ventilation) can be assigned to the thermal blocks and the energy source can be specified. The final step is to define environmental settings such as location, wind protection, soil type, and climate data (Ali et. al., 2022). The output is a report that includes the hourly energy balance of the building, annual structural consumption, structural performance, and carbon footprint. The results can be exported to five different formats, including Green Building XML (gbXML), an open schema for energy analysis tools implemented in multiple software applications. Autodesk Revit is a widely used design software with BIM capabilities. In addition to its many features, it is complemented by other Autodesk software and cloud services. The possibility to perform energy audits is also provided through Autodesk Revit. This requires the creation of a model with a high level of detail in the software, the definition of openings, and multi-layered structures. It is necessary to provide data on the geographical position of the building and the building services systems. Once all the necessary data is given in the software, the energy study can be applied using Autodesk Insight, which is compatible with Revit. Autodesk Insight can also be used for detailed energy simulation, daylighting analysis, environmental optimization, and thermobalance calculation. It is a cloud-based tool available to users with an Autodesk subscription (Deepa et. al, 2019).

2.3 Parametric tools

One of the main advantages of parametric design is the ease with which different architectural variants can be generated. By investing a little extra work in the initial design phase, a model can be created that can be easily adapted. Once the parametric model is developed, generating further design alternatives becomes almost effortless. Because of the high cost of modifications in later phases, various initiatives are being taken to generate more decisions early in the design phase. The intention is to bring design efforts forward to earlier stages to reduce costs. In architecture, optimization using analytical methods is an iterative process consisting of four general steps: inputting parameters, performing calculations, outputting results, and optimization. In the fourth step, the output is evaluated to check that it meets the objectives of the analysis. It is worth pointing out that optimization tasks are usually focused on a certain value of the building, but that, independently of this, all other aspects and requirements (structural, aesthetic, etc.) related to the building must be met. Once these are met, the process is over and the solution is found. If not, the input parameters are modified, and the cycle runs iteratively until the goal is reached. There are several parametric design software currently on the market, but in this case, we focus on the Rhinoceros-Grasshopper software pair. There are several add-ons available that can help you run energy studies, such as Archsim Energy modelling. This is the first add-on to bring full EnergyPlus simulations to Rhino/Grasshopper, combining the EnergyPlus simulation engine with a powerful parametric design and CAD modelling environment. Since ClimateStudio is a Grasshopper add-on, modelling and testing runs directly in Rhino, allowing data to be exported to any Rhino-compatible BIM software or saved in DDX (Device Data Exchange) or IFC (Industry Foundation Classes) format. Archsim allows users to easily create complex, multi-zone energy models, simulate them and visualize the results without ever having to switch between devices. Archsim supports advanced sunlight and shading control, ventilation modules such as wind and stacked natural ventilation, airflow networks, simple HVAC systems, photovoltaics, and phase change materials (Elbeltagi and Wefki, 2021).

There are several other software solutions on the market, for example, the most widely used energy testing addon is Ladybug which enables to display and analyze weather data in Grasshopper. This includes charts such as the solar path, wind rose, psychrometric chart, etc., as well as geometric studies such as radiation analysis, shadow studies, and view analysis. Honeybee combines Grasshopper3D with validated simulation engines including EnergyPlus/OpenStudio (for building energy, HVAC sizing, thermal comfort, etc.) and Radiance (for daylight and glare simulation). Dragonfly enables the creation and manipulation of large-scale EnergyPlus and Radiance models by exploiting an abstracted 2D representation of building geometry, where each room is assumed to be a stretch of floor slab. Butterfly links Grasshopper to the OpenFOAM engine, which can be used to run advanced computational fluid dynamics (CFD) simulations. The use of these programs is extremely wide. In addition to the energy tests, a wide range of test types are available, such as climate analysis, advanced natural ventilation tests, lighting optimization, or even natural air flow analysis. However, within these test types, it is also possible to run more specific tests. For the daylight analysis tests, the simulation can run for a fixed time or for a specific time interval. For different tests, the time interval to be tested can naturally differ, so daily, monthly, or even yearly simulations can run. These studies require much more computational and backup capacity for accurate computation, which has become available mostly in the last few years.

2.4 Artificial intelligence

The technological revolution is ushering in a proliferation of transformative technologies, including artificial intelligence, machine learning, IoT, and neural network architectures. These advancements hold immense promise for architects, promising streamlined workflows, efficient time management, and heightened precision (Ghobakhloo, 2019). Architects must embrace these opportunities and stay attuned to technological developments to harness their potential advantages. As these technologies gain prevalence, they are evolving to process data akin to human intelligence, offering increasingly accurate solutions. While AI solutions in architecture are still in their infancy (Goh and Wang, 2022), they are already instigating profound industry transformations (Farzaneh et al., 2021). In this chapter, some of these web-based software tools are investigated that primarily rely on artificial intelligence and can be utilized for energy analysis. The first examined software application is CoveTool (Tkeshelashvili, 2021), a multifunctional web-based platform with a wide array of capabilities. These functionalities simplify highly intricate tasks, encompassing activities such as communication, documentation, 3D modeling, and notably, building performance analysis. Currently, our research focuses on the analysis tool component within the platform. This tool employs an artificial intelligence algorithm that operates on a 3D model base, enabling rapid and efficient modeling of the building's energy performance. Of particular interest is its ability to conduct daylighting simulations, optimize costs, and model water consumption, providing sufficient data inputs. The developers have designed and continue to enhance the program to alleviate architects' workload, achieving cost-effectiveness, and contributing to the establishment of a more sustainable future.

Sidewalk Labs, a sub-company of Google, specializes in the development of generative algorithms powered by machine learning for smart cities. One of their programs is Delve, designed to offer multiple optimal solutions for diverse urban design tasks while considering the specific characteristics of the city. The algorithm considers factors such as zoning regulations and project parameters to provide the most suitable proposal for a development that ensures both high quality of life and economic viability.

Another software worth mentioning is Spacemaker AI (Kyle, 2021), primarily designed to assist with building placement in urban environments. While offering fewer options compared to Cove.Tool (Tkeshelashvili, 2021), this AI provides a specific focus on optimizing sunlight exposure for both urban areas and building facades. Additionally, it measures the ventilation between buildings, addressing a significant challenge in modern cities. The software also includes a feature for proposing building placements and generating building forms to aid decision-making in the early stages. However, Autodesk acquired this software and incorporated it into a more extensive multifunctional program called Autodesk Forma, enhancing its further development.

Autodesk Forma is considered a major rival to Cove.Tool. Its algorithm can conduct various analyses like Cove.Tool, but with a notable advantage that potentially makes this program superior: it can establish continuous real-time communication with design software. Once the 3D environment is established, the program can continuously monitor the planned building and its conditions, ranging from sunlight exposure and cost optimization to external views and internal perspectives modeling. However, a significant drawback of the program is its current high cost, but considering the potential facilitation of decision-making processes, this aspect might be justifiable.

The last software, that will be briefly introduced is Digital Blue Foam. This AI is relatively advanced and possesses an intriguing capability – it can establish live connections with ArchiCAD, Revit, and Grasshopper. This extensive interoperability suggests a significant potential for interdisciplinary applications, leveraging the positive and developmental attributes of each software. The program shares similarities with Delve, developed by Sidewalk Labs, and is also well-suited for urban development, rapidly evolving to incorporate building analysis from an energy perspective. In our opinion, it harbors immense potential and merits close monitoring of its progress and development.

3. Conclusions

The current global energy landscape is characterized by a growing demand for strict energy standards and improved building energy performance. This pressing need highlights the importance of focusing on the study and development of energy analysis software tools. In today's context, there exists a wide range of alternative software solutions for energy analysis, encompassing various methodologies such as parametric design and artificial intelligence. Despite the abundance of available programs, there is a noticeable gap in the literature, with a lack of comprehensive publications that consolidate both traditional and innovative software tools within these methodologies. The primary objective of this study has been to thoroughly investigate and elucidate both emerging and conventional working methodologies. Within this article, we conducted an in-depth examination of several software programs situated within dedicated, parametric, and artificial intelligence-based methods. Throughout our analyses, we made concerted efforts to highlight the most significant advantages and, where relevant, potential drawbacks of these software tools. Our intention has been to present these programs in a manner that empowers future researchers, users, or enthusiasts to make informed decisions regarding the most suitable tool for their specific tasks, whether it involves running an analysis or evaluating the robustness of a particular methodology. The study's exploration of software tools encompassed three key methodologies. Firstly, we discussed dedicated or embedded software tools, which represent the most fundamental programs. While still widely used, these tools demand significant expertise and substantial time investments due to their non-model-based workflows. Secondly, we delved into parametric software tools, where innovation lies in dynamic change tracking and parameter adjustability. This model-based approach streamlines processes, saving time by minimizing data import requirements and operating on algorithmic foundations. Furthermore, the availability of plug-in modules for IFC export and seamless integration with various BIM software platforms further enhances its appeal. Lastly, the study ventured into artificial intelligence-driven software solutions, representing a cutting-edge approach to energy analysis. Artificial intelligence, with its rapid learning capabilities, enables precise analysis and optimization, both in terms of model and numerical aspects. Although this methodology is relatively new and its credibility is evolving, it has yet to match the reliability of traditional methods or even parametric approaches. In summary, this article has aimed to underscore the pivotal importance of energy analysis and the profound influence of decisions made during the early design phases of building projects. By presenting and examining these software programs, our goal has been to inspire and encourage architects to embrace and experiment with these innovative working methodologies. As the world grapples with ever-increasing energy challenges, the knowledge and utilization of these diverse tools become crucial in achieving sustainable and energy-efficient built environments.

Finally, the article also has a purpose that will form the basis for a later study. The programs and working methods mentioned in the article will be tested with 3D building models in the future. The aim of these studies is to prove the usability and competitiveness of the methods and programs found and to map their accuracy.

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