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EVALUATION OF CAD-INTEGRATED BUILDING ENERGY SIMULATION TOOLS FOR THE EARLY DESIGN STAGE

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Abstract: The background of this study lies in the urgent need for building energy simulation (BES) tools that can be used by architects during the early design stage to support the achievement of nearly zero-energy buildings (nZEB) targets. This research aims to identify and evaluate CAD-integrated BES tools that are suitable for the conceptual design phase of buildings within the Swedish context. The methodology includes a literature review, screening of BES tools, testing on a *Stockholmshus* case using industry-standard values, and multi-criteria analysis through the Delphi method. The results indicate that EcoDesigner (ArchiCAD), Energy Evaluation, designPH (SketchUp), and Sefaira are the most relevant tools, although limitations persist regarding simulation assumptions, result consistency, and compliance with local regulations. The findings highlight the need for model calibration and further development to enhance the reliability of energy simulation outcomes during the early design stage.

Keywords: Building Energy Simulation, Performance-Based Design, Early Design Stage, CAD-BIM Integration

1. Introduction

In recent decades, the issues of climate change and energy resilience have driven a global shift toward sustainable development. The building sector, as a major energy consumer accounting for approximately 40% of global final energy consumption and 36% of energy-related CO_2 emissions [1], is under significant pressure to transform. In response, the European Union has enacted the Energy Performance of Buildings Directive (EPBD), mandating that all new buildings must meet the nearly Zero-Energy Building (nZEB) standard by the end of 2020 [2]. As an EU member state, Sweden has incorporated these ambitious targets into its national regulatory framework. The Swedish building code, *Boverkets byggregler* (BBR), has been continuously tightened, with the January 2017 draft redefining building energy performance and imposing stricter limits on the maximum allowable specific energy demand [3]. To comply with these stringent requirements—particularly the obligation for heat recovery ventilation systems (FTX) with a minimum efficiency of 75% in all new buildings—integrating energy considerations from the earliest stages of design has become essential.

Traditional building design processes are often fragmented and linear. Architects typically develop designs based on aesthetics, functionality, and site context, while energy analyses are performed later by engineering consultants after the architectural design is nearly finalized [4]. At that stage, the ability to modify inefficient design features—such as poor orientation, high aspect ratios, or suboptimal building envelopes—is significantly limited, requiring costly and time-consuming design revisions. This reactive approach has proven to be a substantial barrier to consistently achieving high-performance buildings.

The MacLeamy Curve (Figure 1) clearly illustrates this paradigm [5]. It shows that the ability to influence project outcomes and value is highest during the pre-design and conceptual phases, while the cost of implementing design changes is lowest. Conversely, during the construction documentation (CD) phase, the cost of changes is very high, but their impact on building value and performance is minimal. As a result, compared to the traditional process, the preferred design workflow shifts the primary workload from the CD phase to the Schematic Design (SD) and Design Development (DD) phases. Alternatives are explored before final decisions are made, allowing for optimized project outcomes. This paradigm shift underscores the urgent need for tools that can evaluate design options during the conceptual phase.

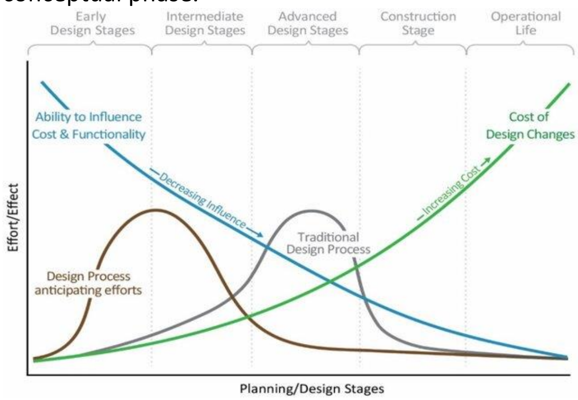

Figure 1: The MacLeamy Curve [5]

The need to evaluate design options in the conceptual phase has driven the development of Building Energy Simulation (BES) tools that operate in virtual environments. Over the past two decades, BES software has been used by professionals to predict and monitor building energy performance [6]. These tools have been classified in various ways. From a theoretical standpoint, Schlueter & Thesseling [7] distinguish between physical calculation models, which replicate physical processes within the building, and statistical models, which apply empirically derived factors. From a computational standpoint, Tronchin & Fabbri [8] differentiate between static methods, based on actual energy consumption, and dynamic methods, which use fluctuating parameters for thermal simulation.

From a practical perspective, Maile et al. [9] separate thermal simulation engines (such as DOE-2 and EnergyPlus) from their user interfaces (such as RIUSKA, eQUEST, and DesignBuilder). These interfaces rely on the same thermodynamic principles but offer accessible input and intuitive output formats. However, most BES tools adopt a *post-decision* evaluative approach and are intended for use by engineers and researchers with a deep understanding of building technologies. They often require highly detailed and high-quality input data to fully leverage their customization capabilities [10].

The early design stage, however, is characterized by a lack of such high-quality data. Jensen [11] defines high-quality datasets as comprehensive, validated, cleaned, and well-documented—conditions rarely present in the conceptual phase. As a result, conventional BES tools are often unusable or produce unreliable outputs due to the use of arbitrary data merely to make the software operable. Architects, on the other hand, require *pre-decision* informative tools that provide indicative energy consumption rather than precise energy load quantification. They typically lack the time and resources to engage in complex early-stage modeling [12].

As Attia et al. [13] state, architects prioritize intelligence, usability, process interoperability, and adaptability over detailed component-level simulation and accuracy. Therefore, decision-support simulation tools specifically designed to support simple, transparent, and energy-conscious design are required. An ideal performance-based tool for the early design stage should deliver rapid feedback, highlight problem areas, identify responsible parameters, and assess the magnitude of these issues [3].

Several promising tools have been developed. Ochoa & Capeluto [14] created *NewFacades*, a recommendation tool utilizing EnergyPlus to generate intelligent façade designs based on energy and visual comfort strategies. Urban [15] describes the *MIT Design Advisor* as a simple and fast energy simulation tool aimed at early-stage building design. Petersen & Svendsen [16] confirm the usefulness of such tools but note that they fail to provide constructive feedback, forcing designers to iteratively revise designs until acceptable performance is achieved. They later proposed *iDbuild*, a performance-based simulation tool that offers design suggestions through parameter variations.

The integration of Building Information Modeling (BIM) has emerged as another pathway to address performance-based design challenges. As explained by Azhar et al. [17], BIM represents buildings as integrated databases of coordinated information. Its integration with performance simulation tools simplifies analysis and provides real-time feedback to architects during the conceptual design phase. File exchange formats such as Industry Foundation Classes (IFC) and green Building XML (gbXML) have been developed to promote interoperability between different software platforms and actors within Architecture, Engineering, and Construction (AEC) projects.

Another significant challenge is the validation and calibration of BES tools. These programs face several intrinsic limitations: low predictive value [18], error-prone conversions from geometric models to simulation models [19], complex workflows, and poor external validity [20]. The IEA Solar Heating and Cooling Program Task 34 conducted empirical validation of BES tools in the context of innovative

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low-energy buildings by developing a comprehensive BESTEST (Building Energy Simulation Test) case suite [21]. However, as noted by Hensen & Radošević [22], deviations from BESTEST results persist, often due to implicit assumptions and uncommon definitions in the underlying computational methods. Evidence-based calibration using hourly measured operational data has been proposed [20], but such data is rarely available during the conceptual phase, highlighting the need for tailored calibration methods.

This study aims to identify existing energy simulation tools that can be integrated into the early design process of urban planning, particularly within the Swedish context. These tools must be capable of accounting for relevant building energy features—such as climate envelopes and solar radiation—while remaining user-friendly for architects. Through the screening of available BES programs, the most promising tools will be tested on a typical *Stockholmshus* case using industry-standard values from Swedish building practices. Each tool will then be evaluated against a set of assessment criteria proposed by key stakeholders involved in the process.

2. Research Method

The research method began with the identification and screening of various building energy simulation (BES) software tools available in both national and international markets, conducted through an extensive literature review. The selected tools were subsequently tested using a *Stockholmshus* case study—a model of multi-family residential buildings located in Stockholm—applying industry-standard construction values from Sweden, such as U-values, air leakage rates, solar heat gain coefficients, and heat recovery efficiency.

The building model, formatted in IFC, was simulated across three major CAD environments: Autodesk Revit, Graphisoft ArchiCAD, and SketchUp, along with their respective integrated energy plug-ins, including Energy Analysis, Insight, Green Building Studio, Energy Evaluation, EcoDesigner, Sefaira, OpenStudio, and designPH.

Each tool was evaluated based on a comprehensive set of criteria, including simplicity, prerequisite requirements, input options, reliability, licensing cost, program adaptability, output categories, usability, and result presentation. The evaluation employed a multi-criteria decision analysis using the Delphi method to minimize bias and ensure a balanced perspective. The Delphi panel consisted of urban planners, energy experts, and academics. Simulation results from the different tools were compared to assess their consistency and accuracy.

3. Discussion

This study reveals the complexity and challenges of implementing Building Energy Simulation (BES) tools integrated with CAD in the early design phase. The key findings indicate that although several promising tools exist—such as EcoDesigner, Energy Evaluation, designPH, and Sefaira—none emerges as universally superior across all evaluation criteria. Simulation results from different tools applied to the same Stockholmshus model showed significant variation, corroborating previous findings regarding disparities in output across simulation platforms [23]. These discrepancies are primarily attributed to underlying simulation assumptions, energy calculation methodologies, and the regulatory contexts for which the tools were originally developed.

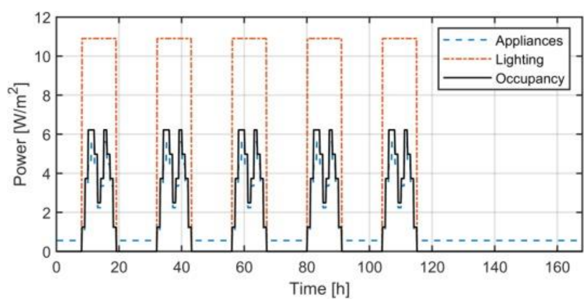

Figure 2: Comparative Simulation Results for the Stockholmshus Case

One of the most critical challenges lies in the underlying simulation assumptions. Each BES tool comes with a default set of parameters and calculation methods, which are often not transparent to end users—typically architects. For example, a stark contrast between Energy Evaluation (26 kWh/m²/year) and EcoDesigner (43 kWh/m²/year) in the same ArchiCAD model highlights the significant impact of a hidden parameter: surface heat transfer. Although Energy Evaluation's online guide recommends using default values, this study manually calibrated them to 7.69 W/m²K for internal convection and 25 W/m²K for combined external conditions based on empirically derived factors. Such opacity creates a "black box" effect that may compromise the integrity of evidence-based design processes if not addressed carefully. This reinforces the argument by Bazjanac et al. [23] regarding the unavoidable use of arbitrary data in early design stages, often leading to arbitrary outcomes.

Furthermore, differing energy modeling approaches serve as another major source of variation. Tools based on EnergyPlus or DOE-2 (e.g., Sefaira) differ methodologically from those using simplified heat balance methods (e.g., designPH). Tools like designPH, developed to meet Passive House standards, employ highly simplified yet robust calculations for specific heat demand, ideal for rapid comparative analysis but limited in representing complex HVAC systems. In contrast, tools like Sefaira Systems offer detailed energy breakdowns by end-use (heating, cooling, fans, pumps, lighting, equipment), yet often rely on undisclosed calculation methods and standards such as ASHRAE 90.1. Contextual sensitivity is crucial here, as highlighted by Petersen & Svendsen [24], because tools developed for specific climates and regulatory frameworks may fail to accurately reflect conditions in other regions without significant calibration.

Legislative context and terminology also hinder interoperability. Most of the tested tools were originally developed to comply with specific energy codes—BBR in Sweden, ASHRAE 90.1 in the U.S., or Passivhaus in Germany. For instance, Autodesk's Green Building Studio (GBS) offers a comprehensive HVAC equipment library, yet references American standards and terminology (e.g., VAV, DOAS, BTU, CFM), which may be unfamiliar to European designers and misaligned with Swedish FTX systems. EcoDesigner stands out by explicitly supporting BBR 22 and BFS 2015:3, including built-in comparisons against BBR performance categories. These mismatches create additional friction for architects, who must translate between disparate terminologies and make assumptions about system equivalencies—ultimately undermining result reliability.

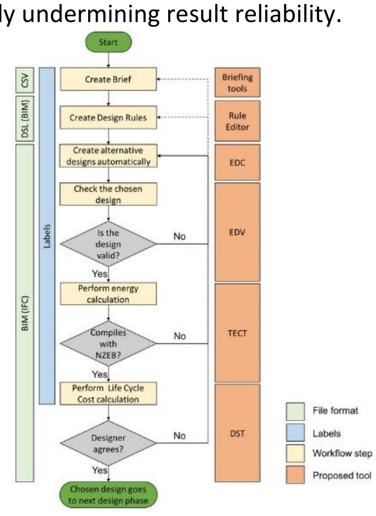

Figure 3: Ideal Workflow for Early-Stage Simulation

From a usability standpoint, the tested tools exhibited clear trade-offs between analytical depth and ease of use. Tools such as Insight 360 and Sefaira Architecture aim to streamline interfaces down to core elements, offering near real-time feedback and visually engaging sensitivity analysis widgets. However, this simplification often comes at the cost of input control, as many critical parameters are hidden or locked at default values. Conversely, tools like the OpenStudio Application provide extensive customization capabilities but demand substantial technical expertise and are prone to instability, making them impractical under tight project deadlines. designPH offers a balanced interface and rapid outputs but lacks the ability to model ventilation airflow and heat recovery—parameters critical in the Swedish context—which can only be configured in the more complex PHPP. These findings echo the work of Attia et al. [25], who observed that architects often value "good-enough" and easy-to-use tools over highly accurate but complex ones.

Model validation is another central concern. Simplifying geometry—such as merging rooms on the same floor or replacing 3D components with 2D planes—to make IFC models compatible with all tools introduces uncertainty. Testing revealed that differences between the original Revit IFC model and a simplified SketchUp model remained within a 10% confidence interval, suggesting that such simplifications are acceptable for early-stage analysis. Nevertheless, caution is warranted, particularly given the conceptual limitations inherent in these models. The "one thermal zone per floor" approach, used in several simulations due to the absence of detailed partition information, is a necessary proxy but fails to capture temperature gradients and uneven internal gains across a floor.

Looking ahead, several steps must be taken to realize the full potential of early-stage energy simulation. First, transparency must improve. Software developers should make default assumptions, calculation methods, and data sources clearly accessible. Second, tools must become more context-aware, automatically detecting project location and adjusting defaults accordingly (e.g., HVAC systems, operating schedules, terminology preferences). Third, smoother integration with BIM workflows is essential to minimize geometry rework and information loss. The long-term vision is for a system that can be automatically calibrated using real-world building performance databases—offering fast, user-friendly, yet statistically robust feedback to support confident design decisions. As suggested by Negendahl [26], the future lies in dynamic, integrated models that evolve seamlessly from conceptual sketches to fully calibrated operational models.

The practical implication of this study is that architects and practitioners should not accept the output of any single simulation tool as absolute truth. A more prudent approach involves using multiple context-appropriate tools and comparing their outputs, focusing on relative differences between design scenarios rather than absolute values. Moreover, investing in the early-stage calibration of selected tools using local case studies or known benchmarks is strongly recommended to enhance reliability. This aligns with the recommendations of Raftery et al. [27] on the importance of evidence-based model calibration, even at early design stages.

Finally, this research underscores the urgent need for improved training and education for architects in the use of BES tools. As noted by Hensen & Radošević [28], understanding the basic principles behind energy simulation is essential to correctly interpret results and avoid modeling errors. Architectural curricula should incorporate modules not only on software use, but also on the underlying assumptions, limitations, and calibration methodologies.

From a software development perspective, these findings indicate the need for closer collaboration between BES tool developers, building policy makers, and practitioners across different regions. Such collaboration could foster the development of more robust and context-sensitive data exchange standards, along with internationally standardized yet locally adaptable building component and HVAC system libraries. As highlighted by Maile et al. [29], interoperability and effective data exchange between different platforms remain critical challenges in the energy simulation workflow.

4. Conclusion

This study successfully identified and evaluated a range of CAD-integrated building energy simulation (BES) tools with potential for use during the early design stage, focusing specifically on the Swedish context. Based on a comprehensive multi-criteria analysis, it was concluded that no single tool excels universally across all criteria prioritized by architects. However, four tools proved to be the most relevant: EcoDesigner (ArchiCAD), Energy Evaluation, designPH (SketchUp), and Sefaira. These tools produced relatively realistic outcomes for the *Stockholmshus* case and offered the best combination of simplicity, speed, and usability.

The key findings of the study reveal that significant variations in simulation results across tools are primarily due to differences in underlying simulation assumptions, energy modeling approaches, and the regulatory context for which each tool was developed. The opacity of default parameters and mismatches in terminology present substantive obstacles for architects. The research also highlights an inherent trade-off between analytical depth and ease of use, where the most user-friendly tools often obscure critical calculation complexities.

The practical implications of this research emphasize the importance of calibrating tools to local contexts and known benchmarks, as well as adopting a multi-tool comparative approach rather than relying on a single platform. For future development, the study recommends improving algorithm transparency, enabling smoother integration with BIM workflows, and developing automatic contextualization capabilities that adjust default settings according to local standards. In doing so, early-stage BES tools can become truly robust and trustworthy decision-support systems for achieving sustainable building targets.

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