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Comparative Validation of Building Energy Simulation Results: Using Cross-Software Analysis for Enhanced Accuracy

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Introduction

The accurate prediction of building energy performance is crucial for sustainable design and operation. Building Energy Simulation (BES) software offers a powerful tool for this prediction, but the accuracy of these simulations depends heavily on the software's underlying algorithms and the quality of input data. Therefore, rigorous validation methods are essential to ensure the reliability of BES software results. This literature review examines the use of comparative validation, specifically employing one BES tool to verify the results of another, as a key methodology for assessing the accuracy and reliability of building energy simulation software.

Comparative Validation Methods in BES Software

Comparative validation involves comparing the results of a target BES software against those of a reference software or a set of established benchmarks. The choice of reference software is critical; it should ideally be a well-established and widely accepted tool with a proven track record of accuracy (Nouri, 2021). Several studies have employed this approach, using various metrics to quantify the agreement or disagreement between the software outputs.

One common approach involves using standardized test cases, such as those defined in the Building Energy Simulation Test (BESTEST) (Pernigotto, 2013), (Gasparella, NaN). BESTEST provides a set of reference buildings and their associated energy performance data, allowing researchers to compare the results of different BES tools under controlled conditions. This approach ensures a consistent basis for comparison and facilitates the identification of systematic biases or errors in the target software (Gonzalo, 2023).

Beyond standardized test cases, researchers have also compared BES software results against actual building energy consumption data (Lee, NaN). This empirical validation approach offers a more realistic assessment of software performance, as it considers the complexities of real-world building operation and environmental conditions. However, collecting accurate and comprehensive building energy data can be challenging and expensive, limiting the applicability of this method in some cases (Tomruku, 2024).

Another approach involves comparing the results of different BES tools when modeling the same building under identical conditions (Alfano, 2023). This method can highlight discrepancies arising from differences in algorithms, calculation methods, or input data processing. By systematically varying input parameters, researchers can investigate the sensitivity of each software to different factors and identify areas where improvements are needed (Gonzalo, 2023). This approach is particularly useful for identifying potential sources of error and uncertainty in BES software (Nouri, 2021).

Statistical indices play a vital role in quantifying the agreement between the results of different BES tools. Commonly used metrics include the Mean Bias Error (MBE), Root Mean Square Error (RMSE), and Coefficient of Variation of the Root Mean Square Error (CVRMSE) (M, 2021), (Nouri, 2021). These indices provide a quantitative measure of the deviation between the simulated and reference values, allowing researchers to assess the overall accuracy and reliability of the target software (Barone, 2019). The selection of appropriate statistical indices depends on the specific research question and the nature of the data being analyzed. For instance, hourly data might require different metrics than annual data (Gonzalo, 2023).

Software Comparisons and Validation Results

Several studies have directly compared the results of different BES software tools. Marwan Abugabbara's work on TEKNOsim 5, for instance, validated the software against various other simulation tools using BESTEST cases and three European Standards (Abugabbara, NaN). The results indicated accurate peak sensible cooling load estimations, with deviations of no more than 12% compared to other tools (Abugabbara, NaN). However, the study also suggested modifications in defining outdoor climate setup to enhance result accuracy (Abugabbara, NaN), highlighting the ongoing need for refinement in both software and validation methodologies.

Sang-Soo Lee and G. Maxwell compared DOE2, HAP, and TRACE, finding that these programs performed better in predicting heating energy than cooling energy, particularly in non-dynamic building operations (Lee, NaN). They also observed significant differences in energy predictions when using different HVAC systems (Lee, NaN), emphasizing the importance of considering system type in validation processes. This highlights the need for comprehensive validation studies that consider a wide range of building configurations and operational scenarios (Gasparella, NaN).

Fernando del Ama Gonzalo et al. compared various BES tools to assess heating and cooling loads, finding good agreement in annual heating and cooling demand but more significant deviations at monthly and hourly levels (Gonzalo, 2023). This underscores the importance of considering both yearly and more granular analyses to fully understand discrepancies among software results (Gonzalo, 2023). The use of ASHRAE Guideline 14-2014 thresholds for acceptable levels of disagreement provided a valuable framework for evaluating the reliability of simulations (Gonzalo, 2023).

G. Pernigotto and A. Gasparella compared TRNSYS 16.1 and EnergyPlus 7, analyzing over 1600 configurations with varying envelope variables and climatic conditions (Pernigotto, 2013). Their method for evaluating relative inaccuracies from using different simulation codes provided valuable insights into the impact of different software choices (Pernigotto, 2013). Similarly, A. Gasparella and G. Pernigotto conducted a detailed comparison of TRNSYS and EnergyPlus, highlighting the limitations of existing validation standards and the need for more comprehensive testing across diverse building configurations (Gasparella, NaN).

F. D. dAmbrosio Alfano et al. compared IDA ICE and Design Builder/EnergyPlus, finding significant differences in temperature predictions but more consistent energy predictions (Alfano, 2023). This highlights the importance of careful model preparation and the definition of input data and boundary conditions for accurate comparisons (Alfano, 2023). The discrepancies observed emphasize the need for thorough validation procedures before relying on simulation results for design decisions (Alfano, 2023).

Magni M et al. presented hourly simulation results from multiple BES tools, including EnergyPlus and TRNSYS, for a reference office building (M, 2021). They employed statistical indices such as MBE, MAE, and RMSE to evaluate the accuracy of different tools (M, 2021), providing a detailed dataset and evaluation methods to facilitate cross-validation efforts by other researchers (M, 2021). This emphasizes the value of open data and reproducible research in enhancing the reliability of BES software validation.

S. Shrestha's study compared empirical data from controlled test rooms with EnergyPlus simulation results, examining performance at zone, system, and plant levels (Shrestha, NaN). Discrepancies between measured and predicted values highlighted the importance of validation and provided insights into potential reasons for these differences (Shrestha, NaN). This approach combines empirical and comparative validation, strengthening the reliability of the findings (Shrestha, NaN).

G. Barone et al. validated an in-house simulation tool (DETECt) against measurements from a real test room, demonstrating very good agreement between simulated and experimental data (Barone, 2019). This study showcases the importance of empirical validation in conjunction with comparative methods, providing a robust validation approach (Barone, 2019).

Piljae Im et al. focused on providing reliable empirical data for validating BEM tools according to ANSI/ASHRAE Standard 140, generating cooling season test plans and comparing experimental datasets with EnergyPlus (Im, NaN). Their emphasis on reliable empirical validation data sets highlights the importance of consistent and validated simulation engines across software vendors (Im, NaN).

S. Sehnalek et al. used the IEA BESTEST methodology for validating SolidWorks Flow Simulation 2012 against twelve test cases related to ground-coupled heat transfer (Sehnalek, NaN). This illustrates the application of established benchmarks and methodologies in comparative validation, providing a structured approach for assessing software accuracy (Sehnalek, NaN).

L. Pompei et al. compared TRNSYS 16 and Grasshopper/Archsim using a real case study, validating simulated results against real consumption data (Pompei, NaN). Their emphasis on real-world data for validation underlines the need for moving beyond theoretical comparisons to ensure the practical applicability of BES software (Pompei, NaN).

Hong Xian Li et al. explored interoperability issues between BIM tools and energy simulation software (Autodesk Revit and EnergyPlus), proposing a framework for transferring building information and comparing results with HOT2000 and monitored data (Li, 2020). This work highlights the importance of using multiple tools to cross-check and enhance the reliability of simulations (Li, 2020).

Abdullahi Muhammed Gambo et al. validated IES-VE software by comparing simulated air temperature to measured values in a Malaysian office building (Gambo, 2022). Their findings, with a percentage discrepancy of 11.03% below the acceptable threshold of 20%, affirm the validity and applicability of IES-VE for building performance simulation (Gambo, 2022).

Elena Catto Lucchino et al. validated the performance of double skin facades (DSFs) in various BES tools, finding that no single tool significantly outperformed others (Lucchino, 2021). This highlights the need for a comparative validation approach when modeling complex building components, emphasizing the limitations of current simulation methods in capturing short-term dynamic behaviors (Lucchino, 2021).

Marie-Lise Pannier et al. discussed the application of DBES and LCA using Pleiades+COMFIE and novaEQUER, emphasizing the importance of validating results through comparisons with other software and experimental data (Pannier, 2016). They employed sensitivity analysis to assess reliability and identify influential parameters (Pannier, 2016), highlighting the impact of different sensitivity analysis methods on the validation process (Pannier, 2016).

N. Tayari and M. Nikpour investigated the validity of DesignBuilder by comparing its results with empirical measurements of heat gain in a courtyard house (Tayari, NaN). The difference of less than 10% between simulation and field measurements indicated a high level of accuracy for this specific application (Tayari, NaN).

Shui Yuan and Zheng ONeill applied ASHRAE Standard 140-2004 for testing a Modelica-based dynamic building model, comparing results with EnergyPlus and DOE-2 (Yuan, NaN). They emphasized the importance of standard thermostat control schemes for accurate validation (Yuan, NaN).

Vicente Gutirrez Gonzlez et al. proposed a novel calibration methodology for building energy models, employing empirical and comparative validation methods referencing IEA Annex 58 (Gonzlez, 2020). Their focus on simplicity and cost-effectiveness makes this methodology more accessible for practical applications (Gonzlez, 2020).

F. Tahmasebinia et al. used BIM and regression models to predict energy performance, validating Autodesk Green Building Studio (GBS) results against Monte Carlo simulation results (Tahmasebinia, 2022). Most differences were within 5%, indicating high accuracy, though limitations in the linear regression model for predicting EUI were noted (Tahmasebinia, 2022).

Javier Garca-Lpez et al. presented a standardized validation process for GIS-UBEM models using open data, showing that heating and cooling demands fell within confidence bands required for approval of alternative simulation methods for energy certification (Garca-Lpez, 2024). This highlights the potential of open data in addressing challenges in UBEM validation (Garca-Lpez, 2024).

Sei Ito et al. discussed the development of a test procedure for evaluating building energy simulation tools, focusing on HVAC systems in commercial buildings and highlighting discrepancies in energy consumption results between different tools (Ito, 2017). This contributes to efforts to create standardized evaluation protocols for BES tools (Ito, 2017).

J. Villarino et al. compared a ground-coupled heat pump system with other HVAC technologies using EnergyPlus, validating the model using experimental results from a monitored building (Villarino, 2019). This combined approach provides a comprehensive evaluation of system performance (Villarino, 2019).

Benedetto Grillone et al. proposed a data-driven methodology for measuring and verifying energy savings, using EnergyPlus alongside real-world monitoring data (Grillone, 2021). Improvements of up to 10% in CV(RMSE) were observed compared to traditional models (Grillone, 2021).

Rosaura Castrilln-Mendoza et al. emphasized model selection in energy efficiency assessments, using EnergyPlus and Design Builder for scenario analysis and performing statistical validation and error analysis (Castrilln-Mendoza, 2024). This highlights the importance of rigorous validation in ensuring reliable energy performance assessments (Castrilln-Mendoza, 2024).

K. Orehounig et al. discussed CESAR-P, a tool generating EnergyPlus input files, enabling comparative analysis of energy results between the two tools (Orehounig, 2022). The detailed output allows for validation against other energy modeling tools (Orehounig, 2022).

E. Stamponi et al. modeled the Loccioni Leaf Lab using DesignBuilder and EnergyPlus, validating the model against internal database data according to ASHRAE guidelines (Stamponi, 2021). The validated model was then used to propose optimization strategies (Stamponi, 2021).

Rimvydas Adomaitis et al. analyzed a single-family Passive House, comparing results from PHPP, Aquarea Designer, and Swegon ESBO Light against operational data (Adomaitis, 2024). The close alignment between modeled and operational heat consumption supported the reliability of the BPS software (Adomaitis, 2024).

Xinyue Zhang and Xue Fan compared FEM and FDM for simulating heat transfer in buildings with PCMs, using FreeFEM++ and COMSOL Multiphysics (Zhang, 2023). FEM provided higher accuracy, and the use of open-source software offered economic and flexible solutions (Zhang, 2023).

Laura Maier et al. discussed AixLib, an open-source Modelica library with automated quality management for simulation results, using continuous integration to compare simulation results with existing validation data (Maier, 2023). This ensures high-quality outputs (Maier, 2023).

Koldobika Martn-Escudero et al. calibrated a BES model using detailed operational data and energy monitoring systems, comparing simulated outputs against monitored data (Martn-Escudero, 2021). Tuning building envelope parameters achieved a model fitting ASHRAE accuracy criteria (Martn-Escudero, 2021).

Syed Monjur Murshed et al. developed a model integrating ISO 13790:2008, validating it using TRNSYS (Murshed, 2018). Sensitivity analysis assessed the impact of various factors on building energy modeling results (Murshed, 2018).

Suwon Song and C. Park developed an algorithm for automatically determining best-fit building energy baseline models, validating it against the ASHRAE Inverse Model Toolkit (Song, 2019). Statistical analysis assessed accuracy (Song, 2019).

Majdi T. Amin evaluated a grid-connected solar PV system using Helioscope and PVsyst, comparing annual energy production, performance ratio, and energy injected into the grid (Amin, 2024). PVsyst showed a higher performance ratio (Amin, 2024).

Gke Tomruku et al. presented a systematic approach to validate building energy simulation models, using MBE and CV(RMSE) to compare simulation outputs with actual measurements (Tomruku, 2024). Case studies demonstrated practical applications (Tomruku, 2024).

D. Palladino and I. Nardi investigated validating building energy models using energy bills and monitored indoor environmental parameters, finding that indoor environmental parameters provided a better fit for actual consumption data (Palladino, NaN).

H. E. Huerto-Cardenas et al. investigated the moisture buffering effect in historical building energy models using two different models in EnergyPlus, highlighting the impact of model choice on simulation accuracy (Huerto-Cardenas, 2020).

Ali Maboudi Reveshti et al. compared building energy consumption estimates using different generated TMY2 weather data files in EnergyPlus, observing a 10% difference in Tehran (Reveshti, 2023). They emphasized using recent weather data for improved accuracy (Reveshti, 2023).

D. Beltran et al. compared MCDM and BES for selecting PCMs for building wallboards and roofs, finding discrepancies between rankings obtained from the two methods (Beltran, 2017).

M. A. R. Shafei et al. employed a Fuzzy Logic Control scheme validated using DesignBuilder and EnergyPlus, comparing results with traditional ON/OFF control schemes (Shafei, 2020).

Xu Jun et al. conducted energy consumption simulations using ECOTECT and BECH for different building layouts, finding the row-column layout most energy-efficient (Jun, NaN).

Daphene C. Koch et al. compared energy efficiency practices in residential construction between Switzerland and the U.S., using REM/Rate for simulation (Koch, NaN).

Mohammad Hasan Ghodusinejad et al. compared thermal and cooling load calculations using HAP Carrier software against Iran's national building code, finding a 6% difference in cooling loads and a 34% difference in heating loads (Ghodusinejad, 2022).

X. Tan et al. analyzed energy performance in Malaysian government office buildings using SketchUp, identifying air-conditioning systems as the major energy consumer (Tan, NaN).

Hagar Elarga validated DIGITHON simulation software against experimental data and a simplified transient numerical model, also using TRNSYS for analyzing innovative photovoltaic module placements (Elarga, 2017).

Andy Berres and Y. Ye discussed methodologies for assessing building performance, including using empirical data for validating energy use predictions and comparative analysis between simulation tools (Berres, 2024).

M. ekon et al. presented a study on a novel solar facade element, finding good consistency between simulation results and experimental data during the cooling period (ekon, 2020).

A. El Hokayem et al. evaluated a simplification algorithm for building energy modeling, comparing simplified models with detailed building energy models (Hokayem, 2023).

Andrs Gallardo and U. Berardi presented a method for validating a simulation model of a radiant ceiling panel with thermal energy storage, using a heat flow meter for enthalpy measurements (Gallardo, 2021).

Ali El Saied et al. presented a new model integrating heat and humidity conditions for slab on grade houses, validated against benchmark analytical results (Saied, 2021).

Fatemeh Boloorchi utilized Autodesk Insight 360 and Autodesk Green Building Studio for energy analysis of a single-family house, highlighting the importance of window factors in energy load minimization (Boloorchi, 2022).

Alsaad H et al. presented validation data for ENVI-met, comparing simulation outputs with collected measurement data, investigating the impact of facade greening on the urban microclimate (H, 2022).

V. Richter et al. discussed a tool for validating and correcting geometric input data for BEPS in EnergyPlus (Richter, 2022).

Ibrahim DM et al. focused on predicting building energy consumption using machine learning and statistical tools (DM, 2022).

Abdoul-Razak Ali-Tagba et al. used EnergyPlus to simulate energy consumption, emphasizing design parameter optimization for energy savings (Ali-Tagba, 2024).

Fan Zhang discussed predicting future energy consumption using the BP_AdaBoost algorithm (Zhang, 2023).

Hou D et al. developed an automated Bayesian Inference calibration platform for building energy model calibration (D, 2023).

Mana Alyami and S. Omer used DesignBuilder to simulate energy performance in residential buildings in Saudi Arabia, validating results against collected data (Alyami, 2021).

Aysegul Tereci et al. discussed the impact of urban form on building energy demand and highlighted the use of software tools to calculate mutual shading (Tereci, NaN).

Challenges and Limitations

While comparative validation offers a valuable approach to assessing BES software, several challenges and limitations need to be acknowledged. One significant challenge is the selection of an appropriate reference software. Different BES tools employ different algorithms and assumptions, making direct comparisons difficult (Gasparella, NaN). The choice of reference software can significantly influence the results of the comparative validation (Nouri, 2021).

Another challenge is the availability of reliable benchmark data. While standardized test cases like BESTEST offer a consistent basis for comparison, they may not fully represent the diversity of real-world building types and operating conditions (Gasparella, NaN). Empirical validation using actual building data is more realistic but can be challenging due to data availability, quality, and cost (Tomruku, 2024).

The complexity of building systems and the numerous input parameters involved in BES can also introduce uncertainties into the validation process. Differences in input data, model assumptions, and user interpretation can all contribute to discrepancies between the results of different software tools (Ito, 2017). Careful attention to detail in model development and data preparation is therefore crucial (Alfano, 2023).

Furthermore, the choice of statistical indices used to quantify the agreement between software outputs can influence the interpretation of the validation results. Different indices may emphasize different aspects of the discrepancies, leading to potentially conflicting conclusions (Nouri, 2021). The selection of appropriate indices should therefore be carefully considered based on the specific research question and the nature of the data (Gonzalo, 2023).

Finally, the computational cost of running detailed BES simulations can be significant, especially for large-scale models or complex building systems. This can limit the feasibility of conducting comprehensive comparative validation studies (Hokayem, 2023). The development of efficient simplification algorithms can help to mitigate this challenge (Hokayem, 2023).

Future Research Directions

Future research should focus on addressing the challenges and limitations discussed above. This includes developing more comprehensive and representative benchmark datasets, improving the interoperability of BES software, and refining validation methodologies to account for uncertainties in input data and model assumptions. The development of standardized protocols for comparative validation, incorporating a wider range of statistical indices and considering the influence of different factors, is also needed (Ito, 2017).

Further research is needed to investigate the sensitivity of different BES tools to variations in input parameters and to develop methods for quantifying and reducing uncertainties in simulation results (Nouri, 2021). The exploration of new validation techniques, such as machine learning approaches, may also offer valuable insights (DM, 2022).

Finally, efforts should be made to promote open data sharing and reproducible research practices in the field of BES validation. This will facilitate collaboration among researchers, enhance the transparency of validation studies, and ultimately improve the reliability of BES software results (M, 2021). The development and wider adoption of open-source BES tools and validation platforms could significantly contribute to this goal (Maier, 2023).

Conclusion

Comparative validation using another BES software as a reference is a valuable methodology for assessing the accuracy and reliability of building energy simulation results. While challenges and limitations exist, this approach offers a powerful tool for identifying systematic biases and errors in BES software and for improving the quality of energy performance predictions. Future research should focus on refining validation methodologies, developing more comprehensive benchmark datasets, and promoting open data sharing and reproducible research practices to enhance the trustworthiness and practical applicability of BES software for sustainable building design and operation. The consistent use of standardized metrics and a thorough understanding of the limitations of each software are crucial for accurate and reliable interpretations of comparative validation studies. The integration of empirical data, where feasible, further strengthens the validation process and increases confidence in the simulation results.

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