

# Discussion on the Hybrid Models for Building Energy Consumption Modeling and Prediction

Qianqian Wang \*

The Bartlett Faculty of the Built Environment, University College London, London, United Kingdom

\* Corresponding Author Email: [ucbvqqw@ucl.ac.uk](mailto:ucbvqqw@ucl.ac.uk)

**Abstract.** Building Energy Consumption Modeling and Prediction (BECMP) gradually become more and more significant in architectural engineering construction process in dealing with energy efficiency, sustainability and environmental-friendly development goals. Based on recent research on BECMP, this paper mainly focuses on the hybrid model combining the physic-based model and the AI-driven model, to discuss improvement on simulation result accuracy, prediction on residence activity, elimination on performance gaps, and optimization on Artificial Intelligence (AI) algorithm selection in improving building performance simulation rather than the other two types of prediction models, following the recent specific application examples and evidence. It also discusses opposing development concepts of models in BECMP among scholars and the limitations of building performance prediction, including corporation of residence behavior models, low popularity of the topic and the high education requirements of users. Lastly, this paper highlights the importance of real-time data system monitor and management, suggests multidisciplinary collaboration, and appeals widespread attention on BECMP.

**Keywords:** Building Energy Consumption Modeling and Prediction; Artificial Intelligence Algorithm; Residence Behavior; Performance Gap; Homogeneous Assembly Model.

## 1. Introduction

Building Energy Consumption contributes 30% of global ultimate energy utilization and 26% global energy emission with 18% output from electricity and heating [1]. Building operation and construction management occupy over one third of CO<sub>2</sub> emission with increased tendency. It is far away from 2030 Net Zero Mission that downgrades building energy consumption below 25% [2]. Building Energy Consumption Modeling and Prediction (BECMP) is important to respond to residence comfort, urbanization development and increasing energy consumption challenge [2]. Utilizing Artificial Intelligence (AI) to upgrade old system can provide considerable energy saving results [3]. Under the background of synthesize smart basic construction, data-driven techniques depending on data analysis and machine learning (ML) provide flexible solution for BECMP.

Technology plays reform function on engineering and architectural industry. To achieve the maximum profit and deal with low efficiency and complicated project management problems, enterprises combine data-driven technology with construction process, such as AI and Building Information Model (BIM) [4]. BIM is the process between engineering, facility planning, construction, and management process with building information, taking three-dimension, simultaneous, dynamic models to provide geometric, space, geographical information and different construction component properties with material information [5]. AI and BIM create more possibilities for digital construction, promoting standardized safety environmental regulation [6]. AI has a major impact on development of building performance prediction, but the application of BIM environment and BECMP in architecture and engineering industry is not sufficient to exploit the contained building information and the potential of AI with unsolved significant basic challenge [7].

This essay mainly describes the recent applications of AI on BECMP model. The 2<sup>nd</sup> part explains the different computation model type of BECMP: physics-based model, AI-driven model and hybrid model. The 3<sup>rd</sup> part concentrates on how hybrid models optimize simulation precision, residence behavior, and performance gap, proposing a homogeneous assembly model. The 4<sup>th</sup> part of this paper

points out the other limitation on the current application of BECMP and development with future potential direction.

## 2. The Classification of BECMP Models

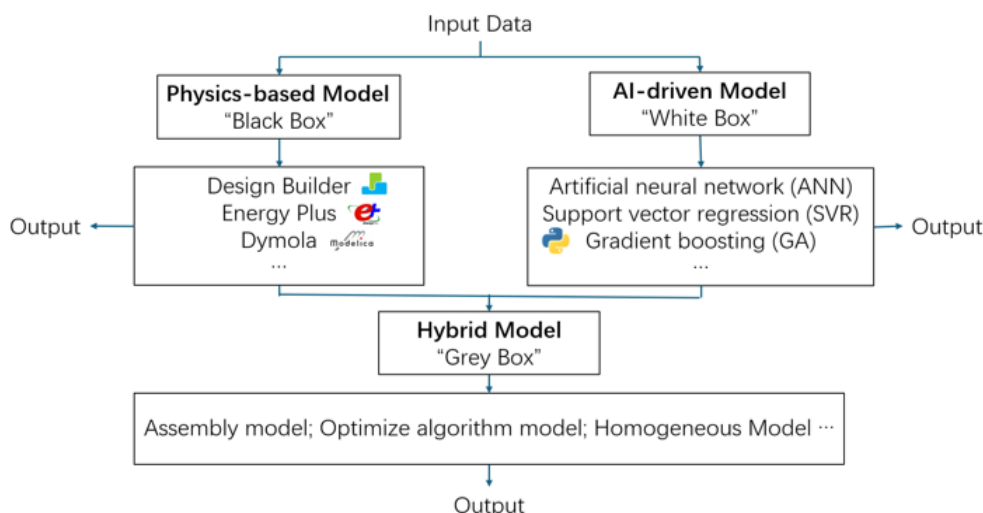
The classification of BECMP is not based on building type and energy end-use, but modelling process and application of building [8]. The three main methods of BECMP are illustrated in Fig. 1: physics-based, data-driven and hybrid models with unique methodologies, strengths, and limitations. The Physics-based model is based on physical equations to represent the building energy consumption, called “white box” [9]. The data-driven model depends on time series statistical analysis and ML algorithm to assume and predict BECMP, regarded as “black box”. The hybrid model is the combination of physics-based models and data-driven models as “gray box”.

The physics-based model (“white box”)’s internal logic is known as taking detailed manufacture material, building system and surrounding environment information to simulate internal energy consumption. The calculation process is sophisticated since it takes a lot of time and requires professional experts. The limitation on collection of material data, mechanical system dimensions and specifications improves the difficulty of the application of this model.

The data-driven model (“black box”) has large flexibility and well predictive performance, using statistics and ML to analysis historical energy consumption and predict future trends. It has low requirements on physical information, taking multiple linear regression (MLR), artificial neural networks (ANN), and support vector regression (SVR), response surface methodology (RSM) and other algorithms [2, 10, 11]. For this kind of AI-based model, there are four steps: data collecting, data preprocessing, model training, and model testing. The accuracy of model simulation depends on the selection of input data, which means high influence and related input data provide more accurate simulation results [10].

The hybrid model (“gray box”) combines “the black box” and “the white box”, taking the optimization methods to enhance single data-driven technology and integrated ML algorithms. “The gray box” keeps the balance between previous two methods, combining advantages, minimizing the limitations, and applying to realistic phenomenon [2].

The application of BECMP happens primarily before the construction in modern building design for performance optimization, cost savings, and risk reduction to create a resilient, efficient, and sustainable building, but all of three methods have certain limitations. They need sufficient data to support the result and ensure prediction quality. Because of geographic location, material modification, and user’s activity, these uncertain variables impact the performance gap between simulation results and reality construction process.



**Fig 1.** BECMP Framework  
 (Picture credit: Original)

### 3. Hybrid Model's Optimization on BECMP with Recent Applications

#### 3.1. Improvement in Energy Efficiency

In machine learning, Assembly model is defined as a method using multiple learning algorithms to receive a better function prediction model than single learning algorithm or model [12]. Considering the significance of building reacting to environment condition, Luong optimized building facade and envelop structure design to alleviate energy crisis and cost in an early design stage of building envelop structure project in Vietnam [13]. He created a new assembly model to provide solutions for building envelope structures, meeting different stakeholders' requirements and saving 7.52% cost and 8.48% energy. Among this model, the weight of cost saving and energy saving is adjustable to provide different project plans, such as when focusing on saving cost, it can provide 21.17% cost saving and 0.4% energy saving. This hybrid model contains three parts: simulated model (for different stakeholders like architects and engineers), predict model (modern ML algorithm), optimize model (new AI algorithm). It combines different modern AI algorithms, like ANN, deep neural network (DNN), SVM, random forest (RF), and gradient boosting (GB), and take GB for adjustment on hyperparameters. Then, this energy prediction model assembles to multi-optimize model, combining modern ML algorithm like nondominated sorting genetic algorithm II (NSGA-II), differential evolution strategy (DSE) and multi-objective particle swarm optimization (MOPSO) to create the best pareto front align with energy and cost standard. It optimizes the defect of energy efficiency, cost efficiency and architectural beauty on early stage of project with multi alterations. Luong thought that multi-algorithms can provide better results since there is no single AI algorithm satisfying all environmental situations, especially for complement AI algorithms [13].

Furthermore, Seraj et al. combined ANN and RSM to make smart decisions on heating, ventilation and air condition (HVAC) by collecting history and real-time data like temperature, air quality and occupancy level through communication sensor and internet of things and processing data with AI algorithm [11]. This hybrid model optimizes HVAC settings, satisfies conciseness and energy-saved temperature adjustment, predicts potential system breakdown and low efficiency, reduces maintenance cost, and deals with dynamic characteristic problems of indoor environment conditions. It improves 16% efficiency of the controlled room and saves 15% cost benefits. According to investigations on recent 72 studies about the combination of ML and BECMP, Elwy and Hagishima also suggested model hybridization and ensemble learning to optimize prediction accuracy [14].

#### 3.2. Prediction on Residence Behavior Effects

Occupant behavior is a crucial variable affecting building energy consumption of simulation precision [15]. It even causes negative effects as most related data only consider schedule timetable for residence [4]. Some recent research start evaluating and specifying user's normal activities [16]. Xu et al. applied Energy plus and ANN to develop an integrated inter-building model consisting of building networks, occupant social networks and neighborhood amenities to assess the impact of the community around the building and its occupants on energy consumption patterns [17]. They found that the sense of place, dependence and identity that comes from patronizing neighborhood facilities creates a social network amongst the occupants. This closeness of the social network encourages friendly environmental behavior which leads to a reduction in energy consumption of 1.3-11.3% from retrofitting the neighborhood without taking into account the impact between residents, to a potential additional energy saving of 11.7-31.1%.

#### 3.3. Reduction in Performance Gap

There is a difference in performance gap between black box and white box. On Energy demand forecasting for the administration building of the University of São Paulo, the physic-based model has a margin of error of 13% in 80% of the databases tested, while the ANN of the AI-driven model has a good agreement between the predicted and actual values of energy consumption with average error of 10% [18]. Hernandez and Fiorelli thought that physics model provides perspective in

reducing building energy consumption and ANN model has limitation on recorded data to predict future, so the two methods can be appropriately integrated and adapted to make the black and white boxes effective tools for BECMP, which is grey box [18]. Mazuroski et al. also proposed that combining physical accuracy with ANN-based predictive modelling of buildings can effectively alleviate the problem of time-consuming simulations [19].

### 3.4. Homogeneous Assembly Model

Wang and Srinivasan compared three main single AI algorithm prediction methods for BECMP (MLR, ANN and SVR) with assembly prediction method principle and proposed homogeneous assembly model [10]. Single AI algorithms are easy to run in real-time with fast computation speed, but they lack the accuracy and reliability of prediction. The ensemble prediction method reduces the prediction error of the system by using multiple base models, which can significantly improve the prediction precision and stability with stronger generalization ability than that of the single model [10]. For different cases, both single and ensemble methods require the user to choose the appropriate learning algorithm according to the corresponding situation, for example, in predicting residential space heating electricity consumption, among back propagation neural network (BPNN), radial basis function neural network (RBFNN), general regression neural network (GRNN), and SVR, SVR is more powerful in this case [20]. Whereas homogeneous ensemble models have commonality and do not require selection of applicable algorithms because each algorithm is trained with the same training data in the third step of model training to give the optimal solution. Homogeneous ensemble models can be widely used as a framework to improve prediction performance.

## 4. Other Limitations and the Future Research

There is some controversy over the usage of different approaches of AI-driven model and hybrid model, Wang et al. argued that both grey and white boxes suffer from the drawback of slow operation, whereas AI driven black box can give fast and efficient solutions that are adaptable, which is especially important for engineering especially for the initial hypothesis phase [10]. On the other hand, Bourdeau et al. stated that future research direction should be the synthesis of the physical model and the AI-driven model to enhance black-box technology driven techniques [2].

Residence's behavior is one of most effective elements to BECMP variability. Even though recent research detailed, digitated and visualized users' activity, like space activity schedule and room occupancy level change from day to night, summer to winter or an integrated inter-building model, it still needs the integration of behavior model with BECMP into more comprehensive building groups to maximize the solution to tackle with residence activity variability [2, 17]. It is recommended to have interdisciplinary study, considering behavior models even from gender, age, and education level to analyze the effect from user to building energy consumption.

Points on performance gap, researchers cannot underestimate or ignore the significance of improving real-time monitor and control systems. The creation and simulation of any type of boxes in BECMP emphasize the accuracy of data input. This is one of the most effective approaches to optimize design plan, trace building degradation, and predict future trends.

Currently, further research on BECMP is still scarce with less attention [10]. There is still a gap between scientific researches to widespread popularity under development. The local government building regulation is needed to assist in promoting the trend for building energy consumption reporting. For instance, the state of Florida introduced a professional college team to participate in pre-construction and post-construction with BECMP [7].

Last but not least, the lack of a uniform input data format for the application of AI-driven model, as well as the high level of knowledge and computational requirements of the users make it difficult to be widely used in practice [10]. Based on the existing BIM construction models, there is still a communication gap between different professional disciplines, construction phases and stakeholders.

It is necessary to encode the building information in a form suitable for machine learning to aid multidisciplinary collaboration [7].

## 5. Conclusion

BECMP is a method using digital technology to assist construction, digitize building, save energy consumption, strengthen connection between stakeholders, and protect the environment during early design stages, operation phase, and future follow-up. This paper first analyzes three main simulation methods of BECMP with advantages, shortages and examples: physic-based model, AI-driven model, and hybrid model.

Then, focusing on the hybrid model which combines physic-based model and AI-driven model, this paper integrates recent research data and application to summarize the optimization of hybrid model on BECMP. It discusses how hybrid models improve simulation energy efficiency in Vienna Building Envelop Case and HVAC integrated system with prominent energy saving outputs. The hybrid model also improves the prediction on occupancy activity with an integrated inter-building model, effecting building energy estimation. Furthermore, it minimizes performance gaps by adopting appropriate complement algorithms. Finally, the proposal of homogeneous Assembly model simplifies the professional selection on AI algorithm by input data in all simulation models to compute the most favorable and efficient one or two.

There are still unsolved limitations on research and suggestions on possible future direction including the combination of residence activity model and BECMP, limited related research, and insufficient uniform input format with high requirement of users. It suggests the collaboration between interdisciplinary teams and promotion of government policies. Besides different future research direction, there is the necessity of tracking performance data and making BECMP become an irreplaceable phase in architecture engineering construction industry.

## References

- [1] International Energy Agency. Tracking clean energy progress 2016. June 2016. Retrieved on December 18, 2024. Retrieved from: <https://www.iea.org>.
- [2] Bourdeau Mathieu, Zhai Xiaoqiang, Nefzaoui Elyes, Guo Xiaofeng, Chatellier Patrice. Modeling and forecasting building energy consumption: A review of data-driven techniques. *Sustainable Cities and Society*, 2019, 48: 101533.
- [3] Bagheri Ali, Genikomsakis Konstantinos N., Koutra Sesil, Sakellariou Vasileios, Ioakimidis Christos S.. Use of AI Algorithms in Different Building Typologies for Energy Efficiency towards Smart Buildings. *Buildings*, 2021, 11: 1-17.
- [4] Blanco Jose Luis, Mullin Andrew, Pandya Kaustubh, Sridhar Mukund. The new age of engineering and construction technology. *Capital Projects and Infrastructure*, 2017.
- [5] Huang Yu, Liu Haiyang, Chang Haijun, Yang Yuansong. Potential Applications and Realization of AI Tools in BIM Technology Based on ChatGPT Working Mode. *Technology Innovation and Application*, 2024, 14(26): 181-184+188.
- [6] He Xiaoxu, Han Meng, Deng Jie, Sun Mingyu. Human-machine Symbiosis: Research on Digital Construction Framework System Based on "BIM + AI". 2023 National Academic Symposium on Teaching and Research of Digital Technology in Architecture for Architecture Faculties and DADA2023 Academic Symposium on Digital Architecture, 2023, 474-477.
- [7] Sacks Rafael, Girolami Mark, Brilakis Ioannis K... *Building Information Modelling, Artificial Intelligence and Construction Tech. Developments in the Built Environment*, 2020, 4: 100011.
- [8] Dong Bing, Li Zhaoxuan, Rahman Md Saifur, Vega Rolando E... A hybrid model approach for forecasting future residential electricity consumption. *Energy and Buildings*, 2016, 117: 341–351.
- [9] Tardioli Giovanni, Kerrigan Ruth. Oates Michael R., O'Donnell James, Finn D.P... Data driven approaches for prediction of building energy consumption at urban level. *Energy Procedia*, 2015, 78, 3378–3383.

- [10] Wang zeyu, Srinivasan Ravi Shankar. A review of artificial intelligence-based building energy use prediction: Contrasting the capabilities of single and ensemble prediction models. *Renewable and Sustainable Energy Reviews*, 2017, 75: 796-808.
- [11] Seraj Mohammad M., Parvez Mohd, Khan Osama, Yahya Zeinebou. Optimizing smart building energy management systems through industry 4.0: A response surface methodology approach. *Green Technologies and Sustainability*, 2024, 2(2): 100079.
- [12] Opitz Daniela, Maclin R... Popular ensemble methods: An empirical study. *Journal of Artificial Intelligence Research*, 1999, 11: 169–198.
- [13] Luong Duc Long. An AI-driven model for predicting and optimizing energy-efficient building envelopes. *Alexandria Engineering Journal*, 2023, 79: 480-501.
- [14] Elwy Ibrahim, Hagishima Aya. The artificial intelligence reformation of sustainable building design approach: A systematic review on building design optimization methods using surrogate models. *Energy and Buildings*, 2024, 323: 114769.
- [15] Pisello Anna Laura, Asdrubali Francesco. Human-based energy retrofits in residential buildings: A cost-effective alternative to traditional physical strategies. *Applied Energy*, 2014, 133: 224–235.
- [16] Zhang Chuan, Cao Liwei, Alessandro Romagnoli. On the feature engineering of building energy data mining. *Sustainable Cities and Society*, 2018, 39: 508-518.
- [17] Xu Xiaoqi, Taylor John Eric, Pisello Anna Laura, Culligan Patricia J... The impact of place-based affiliation networks on energy conservation: A holistic model that integrates the influence of buildings, residents and the neighborhood context. *Energy and Buildings*, 2012, 55: 637-646.
- [18] Hernandez Neto Alberto, Fiorelli Flávio Augusto Sanzovo. Comparison between detailed model simulation and artificial neural network for forecasting building energy consumption. *Energy and Buildings*, 2008, 40(12): 2169-2176.
- [19] Mazuroski Walter, Berger Julien, Oliverira Ricardo, Mendes Nathan. An artificial intelligence-based method to efficiently bring CFD to building simulation. *Journal of Building Performance Simulation*, 2018, 1-16.
- [20] Wang Zeyu, Srinivasan Ravi S., Shi Jonathan. Artificial Intelligent Models for Improved Prediction of Residential Space Heating. *Journal of Energy Engineering*, 2016, 142(4): 04016006.