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Hybrid Experimental Approaches in Facade Thermal Performance Research: A Systematic Review

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Abstract

Building façades significantly influence building thermal performance and contribute to urban heat mitigation, particularly in hot-humid climates. While field testing, laboratory experiments, numerical modeling, and digital simulations are widely applied in façade research, methodological frameworks for integrating these into hybrid approaches remain limited. This study systematically reviews 32 peer-reviewed articles to analyze the types, sequencing, and disciplinary tendencies in applying hybrid experimental approaches for façade thermal performance research. Seven type of hybrid experimental approach were identified, with combination of field experiments-simulations are most common. Stage sequencing varied by research objectives, while disciplinary background influenced whether studies began with modelling or empirical experimentation. The proposed hybrid experimental research framework offers strategic guidance for approach selection and sequencing, supporting resource efficiency and methodological rigor in sustainable building design.

Keywords: *Building Façade, Experimental Hybrid, Façade Thermal Performance, Research Method, Sustainable*

Pendekatan Eksperimental Hybrid *pada Penelitian Kinerja Termal Fasad Bangunan: Sebuah Review Sistematis*

Abstrak

Fasad bangunan memengaruhi kinerja termal bangunan dan berkontribusi dalam mitigasi panas perkotaan secara signifikan, khususnya di iklim panas-lembap. Meskipun pendekatan eksperimental seperti pengujian lapangan, eksperimen laboratorium, pemodelan numerik, dan simulasi digital banyak digunakan dalam penelitian fasad, kerangka metodologis untuk mengintegrasikan pendekatan-pendekatan ini ke dalam pendekatan hibrida masih terbatas. Penelitian ini melakukan tinjauan sistematis terhadap 32 artikel peer-reviewed *untuk menganalisis jenis, urutan, dan kecenderungan disiplin ilmu dalam menerapkan pendekatan eksperimental hibrida untuk penelitian kinerja termal dinding luar. Tujuh jenis pendekatan eksperimental hibrida diidentifikasi, dengan kombinasi eksperimen lapangan-simulasi paling sering ditemukan. Urutan tahap bervariasi tergantung pada tujuan penelitian, sementara latar belakang disiplin ilmu memengaruhi apakah studi dimulai dengan pemodelan atau eksperimen empiris. Kerangka kerja penelitian eksperimental hibrida yang diusulkan memberikan panduan strategis untuk pemilihan pendekatan dan urutan, mendukung efisiensi sumber daya dan ketelitian metodologis dalam desain bangunan berkelanjutan.*

Kata-kunci: *Berkelanjutan, Eksperimental Hibrida, Kinerja Termal, Fasad Bangunan, Metode Penelitian*

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Introduction

The building sector is the largest contributor to global energy consumption, which is 40% of the total energy consumption [1]. In Indonesia, the building and construction sector consumed 23% of total energy consumption in 2021 and is predicted to increase by up to 40% by 2030 [2]. Buildings consume 38% of the need for mechanical ventilation, making air conditioning the largest energy user in buildings [3]. In country with hot-humid climate such as in Indonesia, the ownership of air conditioning equipment in residential buildings has become a basic need, which is shown by the presence of fans in 78-91% of residential houses and the presence of air conditioners in 14-69% of residential houses [4].

Building facades play an important role in determining the thermal and energy performance of buildings, and can directly affect the sustainability, energy efficiency, and environmental quality of indoor spaces [5], [6]. The façade of the building regulates the exchange of heat, air and the entry of light into the building, thus maintaining comfort in the room. The ability of the building façade to regulate the energy that passes through it is significantly influenced by the selection of wall materials, fenestration systems and the use of shading devices [7]–[12]. Optimal façade design can improve thermal performance, reduce energy consumption, and reduce dependence on mechanical air conditioning systems for air conditioning, thereby improving healthier and more sustainable indoor space conditions [8], [13]. In addition, the configuration of the façade can affect the microclimate, particularly in dense urban canyon areas, contributing to the formation of urban heat islands [14]. Therefore, it is necessary to develop high-thermal performance façade technology to reduce the impact on the thermal environment of indoor and outdoor spaces.

Facade technology research often uses an experimental approach [15]. Experimental research was conducted to evaluate how the thermal performance of a building façade is by manipulating free variables, to see the influence of free variables on the thermal performance of building facades [16]. An experimental approach to physical models in building façade technology research can be conducted in two ways, namely measuring the results of field and laboratory experiment [17], [18]. Field experiments have the advantage that researchers can make direct observations of the performance of the façade under dynamic environmental conditions, where external factors such as solar radiation, wind speed, cloud cover, and temperature, can occur naturally. This allows researchers to explore the response of facades to real-world conditions and test specific treatments or modifications to façade design [19].

However, the complexity and variability of the outdoor environment make it difficult for researchers to examine the role of certain factors on the thermal performance of buildings specifically [20], [21]. In contrast, laboratory-based experimental research has high internal validity, as it allows researchers to determine the impact of manipulation of independent variables on performance, by regulating or eliminating other variables that may exist under real-world conditions that could cause bias [17]. Laboratory-based experiments use equipment such as climate chambers, solar simulators, and wind tunnels to replicate external conditions that are independent variables in research [22]–[24]. However, despite having great control over environmental factors, laboratory experiments face great challenges, especially in replicating the dynamic and complex nature of the outside environment [25].

Another experimental approach that is often used is simulation using numerical and digital models. Numerical models simplify dynamic conditions into steady-state conditions and make it easier to compare façade performance with different design parameters [26]. However, because it is a steady-state that indicates momentary conditions, numerical models are not representative of the thermal performance of building facades over a longer period of time. Simulations using digital models allow simulations of the application of façade technology to different building typologies and model scales and see the consequences, without incurring large costs. However, incorporating initial data into digital modeling needs to be done carefully and carefully to produce accurate findings [27].

Even though there are several prior publications that mentioned types of experimental research approach in building performance study, there has been no article explaining the framework of experimental hybrid approach in façade thermal performance research [18], [23], [28]. There is a difference in the order in which simulations and experiments are conducted in studies that use a combination of the two raises doubts in novice researchers. The differences in method used in each stage are suspected to be due to differences in research objectives and the author's background.

This study will discuss how the framework conducted by the researcher in conducting thermal performance research on building facades with a hybrid approach. The hybrid approach to be studied is research that conducts a combination of laboratory experiments, field experiments, numerical and digital simulations. The combination can consist of two or more approaches. This study will provide an overview of when a researcher conducts a simulation first or a field or laboratory experiment in the initial stage.

Methods

This study conducted a literature review of thermal performance research articles on building facades using a hybrid approach. The hybrid approach referred to in this study is research conducted by combining experiments conducted in the field and laboratory with other approaches, such as simulation or model development. The use of a hybrid approach is already common. Cuce conducted field experiments to see the difference in thermal regulation between conventional walls and those covered by the Hedera helix, conducted simulations using Ecotect to justify the accuracy of the experimental results, and finally calculated the absorption of solar radiation using numerical models. Ibrahim et al. began the research by conducting field measurements of one reference model and one test model, followed by simulation using numerical models to see the performance of pipe-embedded walls. On the other hand, Yu et al. developed a dynamic model based on the response factor method on the wall integrated with a flat plate solar collector, which was then validated through experiments.

A similar literature review method has been conducted in a study on the state-of-the-art review of hybrid simulation modeling in operational research [29]. In the study, articles were selected based on search strategies, then reviewed and sorted based on inclusion and exclusion criteria. The discussion of the results of the review was carried out by describing the type of study based on the type of simulation conducted, conceptual modeling based on the type of article, and the type of hybridization based on the type of simulation technique conducted.

This research was conducted in two stages, such as data collection and data analysis, which are shown in Figure 1. The first stage is data collection. The data collection stage began with a search from the Sciencedirect database to find building façade technology research on the topic of Urban Heat Island (UHI) and energy. To find research paper about building façade technology as UHI mitigation and energy consumption reduction strategy, the terms "urban heat island", "energy", "cooling", "microclimate", "heat", "facade", "envelope", "wall", "experimental", and "pipe" are used as search keywords. Then, the search is performed using the Boolean "AND" and "OR" to sharpen the search results. For paper with UHI related topic, the search was done using keywords (“urban heat island”) AND ("Energy" OR "cooling" OR "microclimate" OR "heat") AND ("facade" OR "envelope" OR "wall") AND ("experimental"), while the energy related topics use keywords ("Energy" OR "microclimate" OR "heat") AND ("facade" OR "envelope" OR "wall") AND ("experimental") AND "cooling" AND ("pipe").

Since the search results show a large number of articles, namely 3,044 articles on UHI topics and 74,867 articles on energy topics, the search is narrowed to research published in the 2015-2025 range and the title must contain the terms "façade" and its synonyms, such as "envelope" and "wall". Based on the selection, 651 articles with UHI topics and 1,313 articles with energy topics were filtered.

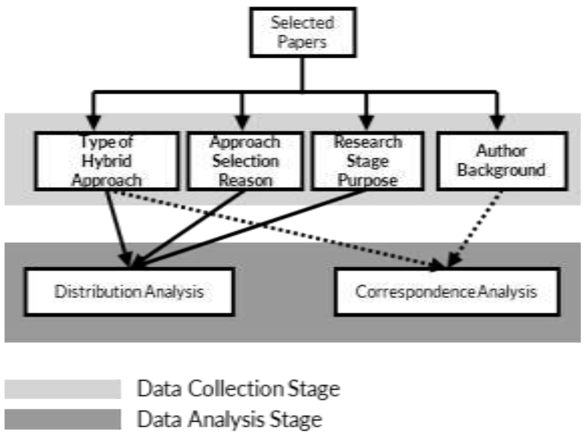

Figure 1. Flow of research method

The selection continued by selecting articles in the form of research articles from quartile journals 1 and 2 in the subject area of "engineering", "energy", "environmental science" or "material science". Articles that appear more than once and that are unrelated regarding strategies to reduce cooling loads or improve microclimate conditions through modification of building facades are removed from the list of articles to be reviewed. From the 76 articles screened, data collection was carried out on the approaches used, and 32 articles were selected using a hybrid approach. Figure 2 shows the PRISMA 2020 flow diagram for this systematic review. Finally, data collection was carried out on the type of hybrid approach, approach selection reason, research stage purpose, and the background of the researcher.

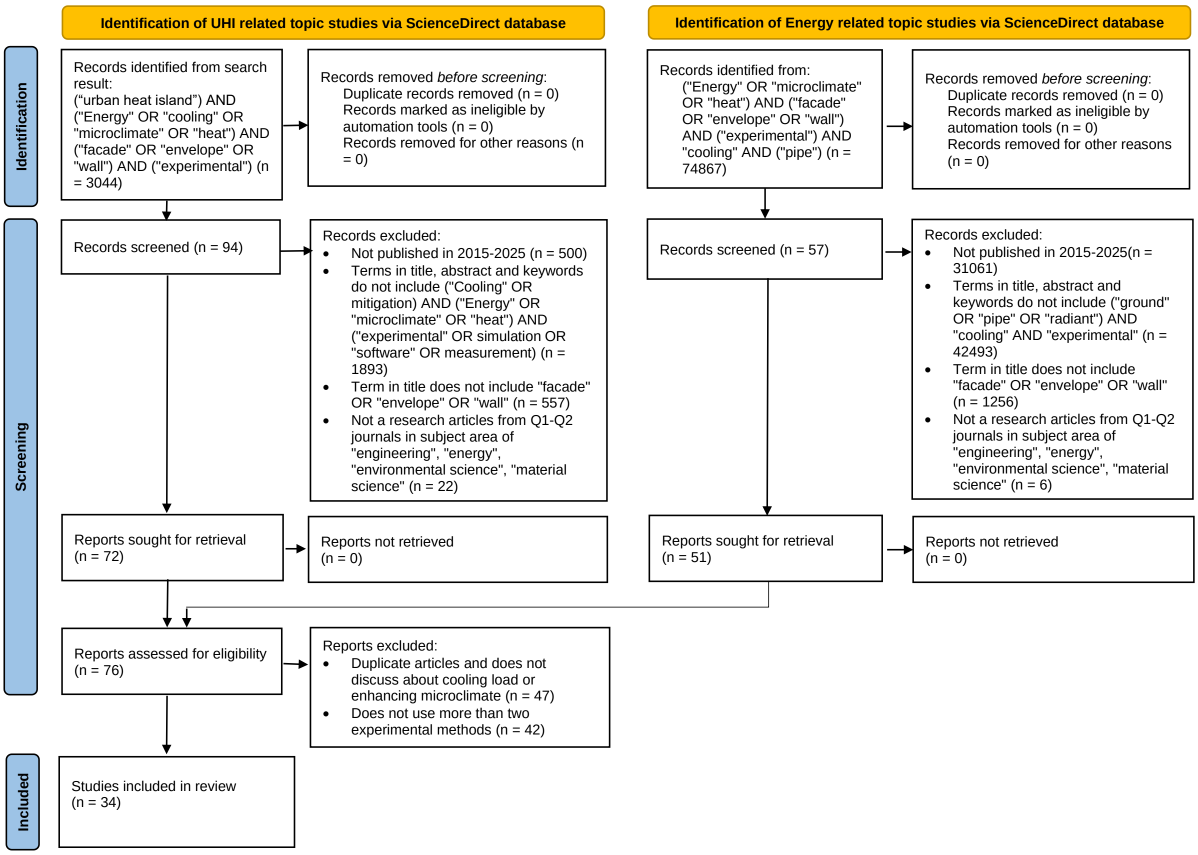

Figure 2. PRISMA 2020 flow diagram for systematic review of research with experimental hybrid approach

In the second stage, the collected data is analyzed. Distribution analysis was performed on the data on the type of hybrid experimental approach, describing the number of research stages and the order of research approaches used in each stage, to identify the most used types of hybrid experimental approaches. Distribution analysis was also conducted on type of hybrid approaches and its selection reason to understand the researcher motives when designing experimental research. Meanwhile, the data on the research stage purpose, the type of hybrid approach, and the researcher's background were processed using correspondence analysis to find out which type of approach for specific research objectives.

Results

Types of Hybrid Experimental Approaches

Based on 34 articles selected from the inclusion and exclusion criteria, a review was conducted by reading the full-paper to understand the type of hybrid experimental approach carried out. Two articles were removed from the review list because they were not hybrid experimental, leaving 32 articles. To determine the types of approaches that are most commonly used, a distribution analysis of the hybrid experimental approach was performed (see Figure 3). Based on the results of the distribution analysis, it is known that there are six types of hybrid experimental approaches, namely; 1) combined field experiment and simulation (FE-S), 2) combined laboratory experiment and simulation (LE-S), 3) combined field experiment and numerical model development (FE-N), 4) combined laboratory experiment and numerical model development (LE-N), 5) combined field experiment, laboratory experiment and simulation (FE-LE-S), 6) combined field experiment, numerical model development and simulation (FE-N-S), and 7) combined four approaches (FE-LE-N-S). Among the six types, the combined field experiment and simulation approach was the most used hybrid approach, accounting for 56%.

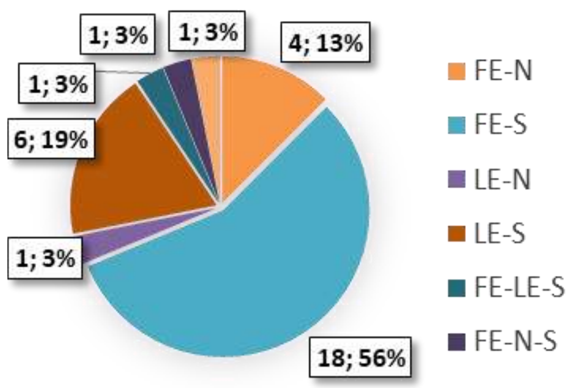

Figure 3. Distribution of hybrid experimental approach types

This finding indicates a strong preference within the researcher for increasing contextual validity and enhance model calibration by integrating empirical data obtained from real-world conditions with simulation tools. The dominance of FE-S approach emphasizes on bridging the gap between experimental observations and predictive modeling in complex environmental and engineering studies.

Approach Type Selection Based on the Research Stage Objective

Based on the mapping of the distribution of the number of stages in 32 articles, it is known that the number of stages in the study consists of two to five stages. Table 1 shows the order of the stages as presented in each article.

Table 1. Summary of method, hybrid approach type, number of stages and stage sequence on 32 articles

No. of Approach	Approach Type	Stages	Approach order
2	FE-N	2	FE-N [34], [35]
			N-FE [36], [37]
	FE-S	2	FE-S [10], [30], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49]
			S-FE [31], [50]
		3	FE-S-S [32]
	LE-N	2	N-LE [51]
	LE-S	2	LE-S [52], [53], [54], [55], [56], [57]
			S-LE [58]
3	FE-LE-S	4	LE-S-FE-S [59]
	FE-N-S	3	N-FE-S [60]
4	FE-LE-N-S	5	N-LE-S-S-FE [33]

From the mapping, it is known that the same type of hybrid can be done with different sequences of stages. Ibrahim et al. conducted field experiments, then conducted numerical simulations [30]. Meanwhile, Sotelo-salas et al. conducted a simulation before conducting field experiments [31]. Both use a combination of field experiments and simulations but in a different order. In addition, one type of approach can also be used more than once in a study, using different tools or scales. Morini et al. conducted two simulations in his research, where in the second stage a simulation was carried out on a scaled urban canyon model, while in the third stage a larger-scale simulation was conducted on a full-size building [32]. Liu integrated two types of simulations, namely energy simulation and computational fluid dynamics simulation to get a complete picture of the effects of thermal mass on the transparent building envelope of water storage and determine its energy performance [33]. This variation reflects the methodological flexibility inherent in hybrid experimental research, enabling adaptation to specific research questions, available resources, and scale of analysis. The diverse sequence also highlights the iterative nature of knowledge generation, where simulations can either guide or validate empirical observations.

Figure 4 shows the distribution of research objectives by hybrid approach types in the first research stage. This chart highlights that research with FE or LE as first approach are predominantly associated with façade performance comparison and validation. Data collection and variable influence identification also appear in moderately in this group. Meanwhile, research that started with N or S approaches is strongly associated with model development. Variable influence identification, validation and performance comparison also appear in this group but not prominent.

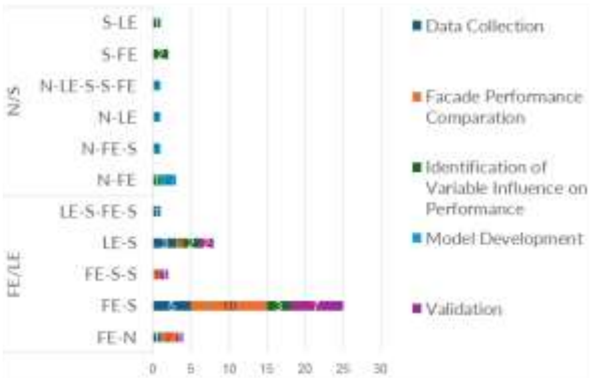

Figure 4. Distribution analysis of research objectives by hybrid approach type, grouped by the first-stage approach to highlight dominant research objectives.

Figure 5 shows the distribution of research objectives by hybrid approach types in the second research stage. In the second research stage, N/S approaches show a diverse range of research objectives. While it is dominated with façade performance comparison, N/S approaches are also used when researchers want to conduct sensitivity analysis, scale-up simulations and validation, although it does not appear as much as the prior objective. Research with FE or LE as second approaches are dominantly used as validation of prior research stage.

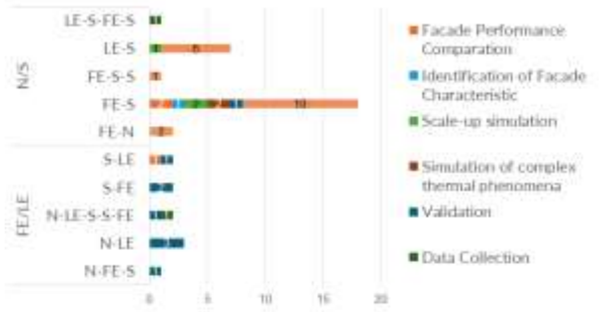

Figure 5. Distribution analysis of research objectives by hybrid approach type, grouped by the second-stage approach to highlight dominant research objectives.

Approach Type Selection Based on the Researcher's Justification

Every researcher must have their own justification when choosing certain approach for each research stage. Figure 6 shows the distribution of researchers' justification in selecting approach type in first research stage. In research that started with FE/LE approach, testing under real-world conditions has become the most dominant reason. Control of variables are dominantly shown in LE approach. Other justifications, such as cost efficiency and data measurement purposes, do not occur as much as the others.

Figure 6. Distribution analysis of researchers' justification by hybrid approach type, grouped by the first-stage approach to highlight dominant researchers' justification

Distribution analysis of researchers' justification on the second stage is shown in Figure 7. When the second stage was conducted with N/S approach, it is strongly associated with the tool's capability and reliability, where parametric study capability, scalability to real-world scale, simplified representation of phenomena, transient simulation capability, and tool validation and reliability are dominating as researchers' justification. Unexpectedly, cost efficiency justification only appears once, in FE-S approach type. On the other hand, model validation is the most dominant reason for using FE/LE approach in the second stage.

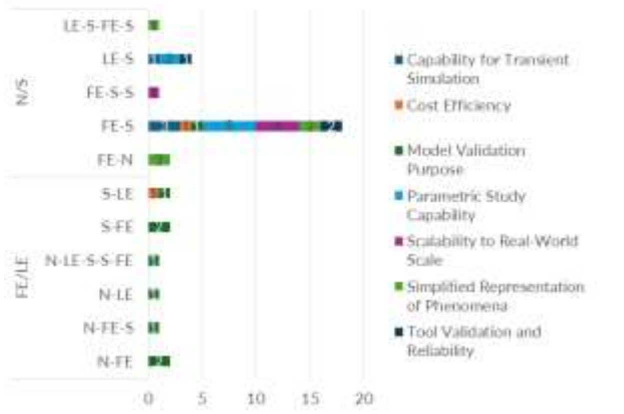

Figure 7. Distribution analysis of researchers' justification by hybrid approach type, grouped by the second-stage approach to highlight dominant researcher's justification

The Relationship between the Research Field and the Research Stage

To understand the justification for the choice of approach type, correspondence analysis was conducted to see the correspondence of the research field to the stage of research conducted (Fig. 8).

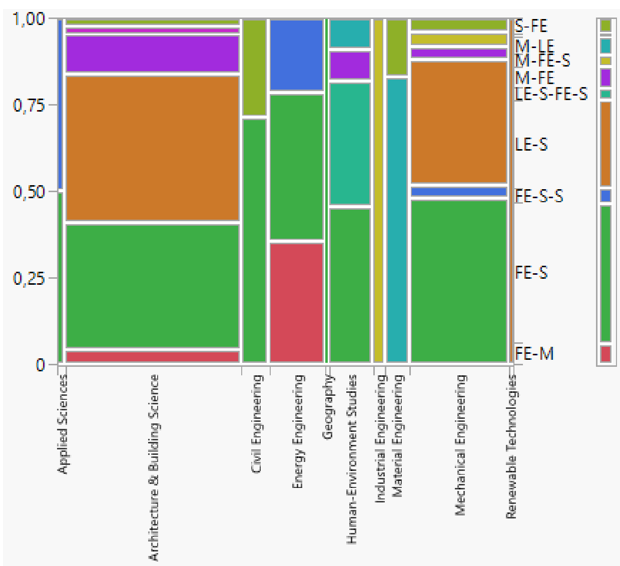

Figure 8. Analysis of correspondence of the type of research stage and the background of the research field

Researchers who used experiments, both field and laboratory, in Stage 1 and simulations in Stage 2 mostly came from the fields of Architecture and Building Science and Mechanical Engineering. Researchers who perform numerical modeling before conducting experiments come from engineering, either Industrial Engineering, Materials Engineering or Energy Engineering. Among researchers from the fields of Civil Engineering, Architecture and Building Science, and Mechanical Engineering, researchers from Civil Engineering have a greater tendency to conduct simulations at the beginning of the study before conducting field experiments.

This finding signifies that disciplinary paradigms influence methodological preferences in hybrid experimental research, where engineers tend to prioritize modeling and simulation for theoretical exploration, while architecture and building science researchers often emphasize empirical grounding through initial experimentation. This disciplinary orientation shapes not only the research workflow but also the epistemological approach to validating thermal performance studies.

Discussion

Although studies that combine experimental methods with numerical modeling and simulation are commonly found, research frameworks that adopt a hybrid experimental approach remain underexplored, particularly among researchers in the fields of Architecture and Building Science. The findings of this study indicate that the selected methods and the number of stages in a hybrid experimental approach are closely related to the research objectives and researcher's justification. Table 2 summarizes the findings, key insights and their implications on research methodology.

In studies aiming to simplify complex thermal phenomena, the research process typically begins with numerical modeling, followed by validation through laboratory or field experiments, as demonstrated by He *et al.* and Zhu *et al.* [36], [51]. In contrast, studies that seek to test new materials or composite façade systems often begin with laboratory experiments to investigate thermal behavior, before proceeding to building- or urban-scale simulations. Field experiments are frequently employed at the initial stage in research involving multiple façade types, where empirical data collected in real-world conditions are later used in simulations to identify variable influence or assess performance at a larger scale. This simulation stage is often necessary because full-scale real-world testing can be prohibitively expensive, as illustrated in the study by Ornam [49].

There is also a significant pattern in researcher's justification on approach type selection. They use field experiments in the first research stage because a real-world context is needed. It is evidenced by the high value of testing under real-world conditions. Laboratory experiments are chosen as the first stage when researchers need control of variables, where in a controlled environment, confounding variables can be ignored. Simulation, digital or numerical, are used as first research stage approach because the researchers need an efficient and reliable predictive modeling before continuing to the next stage, which is indicated by the predictive modeling capability and cost efficiency as the justification. Approach type selection in the second research stage shows different

Table 2. Summary of findings, key insights and implications

Finding Category	Key Insights	Implications
Types of Hybrid Experimental Approaches	- 7 hybrid types identified - FE-S (Field Experiment + Simulation) is most dominant (56%) - Some studies use all 4 methods (e.g., FE-LE-N-S)	Preference for combining real-world validation with simulation for calibration and scale-up application.
Methods Used Based on the Objectives of Each Stage	- Stage 1: 63% use FE for empirical validation, 18% LE for component testing, 12% model development - Stage 2: 69% use simulations for performance analysis, 13% FE for validation - Same methods used for different purposes across stages	Method selection is closely tied to research purpose; simulations often used for sensitivity analysis and scenario testing, while experiments provide grounding data.
Approach Type Selection Based on the Researcher's Justification	- In Stage 1, FE/LE-first studies are primarily justified by 'Testing under Real-World Conditions', especially in FE-S. - LE approaches are specifically associated with 'Control of Variables'. - Justifications like 'Cost Efficiency' and 'Data Measurement Purpose' are less frequent. - In Stage 2, N/S approaches are linked to tool capabilities such as 'Parametric Study', 'Scalability', 'Simplified Representation', and 'Tool Reliability'. - FE/LE approaches in Stage 2 are predominantly chosen for 'Model Validation'.	Researchers select approach types based on strategic justification, balancing the need for empirical grounding, variable control, and real-world testing with the advantages of simulation efficiency, scalability, and predictive capability.
The Relationship between the Research Field and the Research Stage	- Architecture & Building Science: favor early experimentation (FE first) - Engineering (e.g., Industrial, Energy): favor simulation or modeling first - Civil Engineering often starts with simulation, then FE	Disciplinary norms shape research flow: architects prioritize contextual insights, while engineers focus on theoretical model building.

patterns. In numerical modeling and digital simulation approach, the approach selection is primarily influenced by the need for reliable and scalable simulation. Meanwhile, the need for experimental validation appears to be reason in using field or laboratory-based experiments in the second research stage.

Another significant finding reveals that the sequencing of hybrid methods also correlates with the researcher's disciplinary background. Researchers with Science educational background tend to begin with numerical simulations and modeling as they try to figure new variables or variables relationships, whereas researchers from Architecture and Engineering are more likely optimize thermal performance by modifying design variables. This reflects differing epistemological orientations: science disciplines typically prioritize theoretical exploration through modeling and simulation, while architectural and engineering disciplines emphasize empirical grounding to understand thermal performance in a contextual manner.

Therefore, researchers must clearly identify their research objectives, justification and contextual constraints to determine the most appropriate sequence of hybrid methods—both to ensure methodological efficiency and to maximize cost-effectiveness and analytical rigor. Additionally, fostering interdisciplinary understanding of hybrid experimental approaches is crucial, as façade design and thermal performance assessment are not solely technical concerns, but also relate to architectural design strategies and the broader agenda of sustainable building performance.

Unlike previous studies that primarily emphasize what experimental methods are used and how they are implemented [18], [28], [61], this paper advances the methodological discourse by explaining why and when specific hybrid experimental approaches are conducted. Through a systematic examination of researcher justifications and methodological sequences, these study findings demonstrate that the choice and order of hybrid methods are not accidental but are shaped by clearly articulated research aims, disciplinary epistemologies, and contextual constraints. By uncovering these underlying rationales, this study contributes a nuanced understanding of hybrid experimentation in façade and building performance research, thereby providing a valuable reference for future researchers seeking to align their methodological strategies with both scientific rigor and practical relevance.

Conclusion

This study underscores the critical importance of aligning research design with methodologically sound and strategically articulated justifications within hybrid experimental research frameworks. Rather than being arbitrary, researchers' methodological choices across research stages are shaped by deliberate reasoning that reflects their research objectives, disciplinary orientations, and methodological familiarity.

The findings reveal two distinct yet complementary justification logics. Researchers initiating with field or laboratory experiments (FE/LE) tend to emphasize practical and contextual justification, prioritizing empirical observation and control of real-world variables. Conversely, those who begin with numerical or simulation-based (N/S) methods are often motivated by efficient and reliable predictive modelling, utilizing computational tools for parametric studies, scalability and predictive insight. In the second stage, researchers who employ N/S approaches continue to increase external validation and to refine of results through a scalable and reliable simulation, while those using FE/LE approaches focus on experimental validation to confirm and ground earlier predictive findings.

These patterns demonstrate that justification extends beyond technical reasoning to encompass broader epistemological strategies. The sequencing and integration of methods are influenced by disciplinary training and research paradigms, shaping how researchers conceptualize knowledge production and validation. The hybrid approach, therefore, should not be viewed as a mere combination of methods, but rather as a coherent framework where each methodological decision is purposefully justified and contextually situated.

By shedding light on how methodological justification operates across research stages, this study offers a nuanced perspective on the logic of hybrid experimentation. It advocates for greater transparency and reflexivity in research design, encouraging scholars to explicitly articulate the rationale behind their methodological trajectories. This perspective contributes to ongoing discourse in research methodology by positioning justification as a central axis in the integration of diverse methods, ultimately advancing more coherent, rigorous, and adaptive approaches to hybrid experimental research.

In doing so, this study fills a critical gap in the literature by shifting the analytical focus from merely what experimental methods are employed and how they are executed, as commonly explored in previous studies, to *why* and *when* specific methods are combined in experimental hybrid research. This distinction enables a deeper understanding of methodological intent, positioning this study as a foundational reference for future research aiming to refine the strategic use of hybrid experiments in Architecture and Building Science studies.

References

[1] A. Karanafti, T. Theodosiou, and K. Tsikaloudaki, "Assessment of buildings' dynamic thermal insulation technologies-A review," *Appl Energy*, vol. 326, p. 119985, Nov. 2022, doi: 10.1016/j.apenergy.2022.119985.

[2] I. Y. Purnomo, F. Nurfitriani, J. Press-Williams, and A. Haesra, "Financing Green Buildings in Indonesian Cities," Mar. 2024. Accessed: Mar. 06, 2025. [Online]. Available: https://www.climatepolicyinitiative.org/wp-content/uploads/2024/03/Financing-Green-Buildings-in-Indonesia.pdf.

[3] M. González-Torres, L. Pérez-Lombard, J. F. Coronel, I. R. Maestre, and D. Yan, "A review on buildings energy information: Trends, end-uses, fuels and drivers," *Energy Reports*, vol. 8, pp. 626–637, Nov. 2022, doi: 10.1016/j.egyr.2021.11.280.

[4] U. Surahman, D. Hartono, E. Setyowati, and A. Jurizat, "Investigation on household energy consumption of urban residential buildings in major cities of Indonesia during COVID-19 pandemic," *Energy Build*, vol. 261, p. 111956, Apr. 2022, doi: 10.1016/j.enbuild.2022.111956.

[5] F. Tahmasbi, A. I. Khdair, G. A. Aburumman, M. Tahmasebi, N. H. Thi, and M. Afrand, "Energy-efficient building façades: A comprehensive review of innovative technologies and sustainable strategies," *Journal of Building Engineering*, vol. 99, p. 111643, Apr. 2025, doi: 10.1016/j.jobe.2024.111643.

[6] M. Gholampour, M. Taghipour, A. Tahavvor, and S. Jafari, "Retrofitting of building with double skin façade to improve indoor air quality, thermal comfort, and infection control in inpatient wards of a hospital in a semi-hot-arid climate," *Energy Build*, vol. 332, p. 115365, Apr. 2025, doi: 10.1016/j.enbuild.2025.115365.

[7] R. F. Madina, "Outdoor thermal performance comparison of several glazing types," *International Journal on Livable Space*, vol. 4, no. 1, pp. 22–31, Sep. 2019, doi: 10.25105/livas.v4i1.4653.

[8] Y. D. Apritasari, A. Indraprastha, and S. Wonorahardjo, "The role of building mass configuration and material selection for mitigating the intensity of the urban heat island," *Energy Build*, vol. 323, p. 114822, Nov. 2024, doi: 10.1016/j.enbuild.2024.114822.

[9] S. Wonorahardjo *et al*., "Characterising thermal behaviour of buildings and its effect on urban heat island in tropical areas," *International Journal of Energy and Environmental Engineering*, vol. 11, no. 1, pp. 129–142, Mar. 2020, doi: 10.1007/s40095-019-00317-0.

[10] I. Shah, B. Soh, C. Lim, S.-K. Lau, and A. Ghahramani, "Thermal transfer and temperature reductions from shading systems on opaque facades: Quantifying the impacts of influential factors," *Energy Build*, vol. 278, p. 112604, Jan. 2023, doi: 10.1016/j.enbuild.2022.112604.

[11] I. Shah, X. Su, R. Talami, and A. Ghahramani, "Enhancing building envelopes: Parametric analysis of shading systems for opaque facades and their comparison with cool paints," *Energy and Built Environment*, 2024, doi: 10.1016/j.enbenv.2024.04.001.

[12] A. Dutta, A. Samanta, and S. Neogi, "Influence of orientation and the impact of external window shading on building thermal performance in tropical climate," *Energy Build*, vol. 139, pp. 680–689, Mar. 2017, doi: 10.1016/j.enbuild.2017.01.018.

[13] A. Taşer, S. Uçaryılmaz, and Z. D. Arsan, "Effect of Building Envelope and Environmental Variables on Building Energy Performance: Case of a Residential Building in Mediterranean Climate," in *Proc. 9th Int. Conf. Energy Environ. Res*., 2023, pp. 69–80. doi: 10.1007/978-3-031-43559-1_7.

[14] N. Y. Nugroho, S. Triyadi, and S. Wonorahardjo, "Effect of high-rise buildings on the surrounding thermal environment," *Build Environ.*, vol. 207, p. 108393, Jan. 2022, doi: 10.1016/j.buildenv.2021.108393.

[15] E. J. Grant, *Integrating Building Performance with Design*. New York: Routledge, 2017, doi: 10.4324/9781315680071.

[16] L. Groat and D. Wang, *Architectural Research Methods*, 2nd ed. New York: Wiley, 2013.

[17] E. J. Grant, "Research approaches for building enclosure studies," in *Research Methods in Building Science and Technology*, Cham, Switzerland: Springer International Publishing, 2021, pp. 33–49, doi: 10.1007/978-3-030-73692-7_2.

[18] H. Rashed-Ali, "Building energy performance research – Current approaches and future trends," in *Research Methods in Building Science and Technology*, Cham, Switzerland: Springer International Publishing, 2021, pp. 51–70, doi: 10.1007/978-3-030-73692-7_3.

[19] A. Aflaki, N. Mahyuddin, and M. R. Baharum, "The influence of single-sided ventilation towards the indoor thermal performance of high-rise residential building: A field study," *Energy Build*, vol. 126, pp. 146–158, Aug. 2016, doi: 10.1016/j.enbuild.2016.05.017.

[20] E. Barreira, R. M. S. F. Almeida, and J. M. P. Q. Delgado, "Infrared thermography for assessing moisture related phenomena in building components," *Constr Build Mater*, vol. 110, pp. 251–269, May 2016, doi: 10.1016/j.conbuildmat.2016.02.026.

[21] M. P. de Jesus, J. M. Lourenço, R. M. Arce, and M. Macias, "Green façades and in situ measurements of outdoor building thermal behaviour," *Build Environ*, vol. 119, pp. 11–19, Jul. 2017, doi: 10.1016/j.buildenv.2017.03.041.

[22] M. Sudirman, S. Gillmeier, T. van Hooff, and B. Blocken, "Wind tunnel measurements of cross-ventilation flow in a realistic building geometry: Influence of building partitions and wind direction," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 254, p. 105907, Nov. 2024, doi: 10.1016/j.jweia.2024.105907.

[23] M. Kuenstle and H. Rashed-Ali, "Research Methods in Computational Fluid Dynamics," in *Research Methods in Building Science and Technology*, Cham: Springer International Publishing, 2021, pp. 95–114. doi: 10.1007/978-3-030-73692-7_5.

[24] Y. Zhao *et al.*, "Research Methods for Assessing the Thermal and Optical Performance of Building Windows," in *Research Methods in Building Science and Technology*, Cham: Springer International Publishing, 2021, pp. 1–31. doi: 10.1007/978-3-030-73692-7_1.

[25] R. Lionar, D. Kroll, V. Soebarto, E. Sharifi, and M. Aburas, "A review of research on self-shading façades in warm climates," *Energy Build*, vol. 314, p. 114203, Jul. 2024, doi: 10.1016/j.enbuild.2024.114203.

[26] J. Vijayalaxmi, "Methods of assessing thermal performance of buildings," in *Building Thermal Performance and Sustainability*, Singapore: Springer, 2023, pp. 41–52, doi: 10.1007/978-981-19-9139-4_4.

[27] Z. Duan, P. de Wilde, S. Attia, and J. Zuo, "Challenges in predicting the impact of climate change on thermal building performance through simulation: A systematic review," *Appl Energy*, vol. 382, p. 125331, Mar. 2025, doi: 10.1016/j.apenergy.2025.125331.

[28] R. Azari and H. Rashed-Ali, *Research Methods in Building Science and Technology*. Cham: Springer International Publishing, 2021. doi: 10.1007/978-3-030-73692-7.

[29] S. C. Brailsford, T. Eldabi, M. Kunc, N. Mustafee, and A. F. Osorio, "Hybrid simulation modelling in operational research: A state-of-the-art review," *Eur J Oper Res*, vol. 278, no. 3, pp. 721–737, Nov. 2019, doi: 10.1016/j.ejor.2018.10.025.

[30] M. Ibrahim, E. Wurtz, J. Anger, and O. Ibrahim, "Experimental and numerical study on a novel low temperature façade solar thermal collector to decrease the heating demands: A south-north pipe-embedded closed-water-loop system," *Solar Energy*, vol. 147, pp. 22–36, May 2017, doi: 10.1016/j.solener.2017.02.036.

[31] C. Sotelo-Salas, C. E. Pozo, and C. J. Esparza-López, "Thermal assessment of spray evaporative cooling in opaque double skin facade for cooling load reduction in hot arid climate," *Journal of Building Engineering*, vol. 38, p. 102156, Jun. 2021, doi:

10.1016/j.jobe.2021.102156.

[32] E. Morini, B. Castellani, S. De Ciantis, E. Anderini, and F. Rossi, "Planning for cooler urban canyons: Comparative analysis of the influence of façades reflective properties on urban canyon thermal behavior," *Solar Energy*, vol. 162, pp. 14–27, Mar. 2018, doi: 10.1016/j.solener.2017.12.064.

[33] X. Liu, M. Xu, J. Guo, and R. Zhu, "Numerical study on the energy performance of building zones with transparent water storage envelopes," *Solar Energy*, vol. 180, pp. 690–706, Mar. 2019, doi: 10.1016/j.solener.2019.01.044.

[34] C. Zhao et al., "Long-wave infrared radiation properties of vertical green façades in subtropical regions," *Build Environ*, vol. 223, Sep. 2022, doi: 10.1016/j.buildenv.2022.109518.

[35] Z. Azkorra-Larrinaga, N. Romero-Anton, K. Martin-Escudero, G. Lopez-Ruiz, and C. Giraldo-Soto, "Comparative summer thermal performance analysis between open ventilated facade and modular living wall," *Case Studies in Thermal Engineering*, vol. 53, Jan. 2024, doi: 10.1016/j.csite.2023.103919.

[36] Y. He, H. Yu, A. Ozaki, N. Dong, and S. Zheng, "A detailed investigation of thermal behavior of green envelope under urban canopy scale in summer: A case study in Shanghai area," *Energy Build*, vol. 148, pp. 142–154, Aug. 2017, doi: 10.1016/j.enbuild.2017.03.014.

[37] G. Yu, C. Du, H. Chen, and L. Xiong, "A dynamic model based on response factor method and seasonal performance analysis for integration of flat plate solar collector with building envelope," *Appl Therm Eng*, vol. 150, pp. 316–328, Mar. 2019.

[38] E. Cuce, "Thermal regulation impact of green walls: An experimental and numerical investigation," *Appl Energy*, vol. 194, pp. 247–254, May 2017.

[39] F. Olivieri, R. C. Grifoni, D. Redondas, J. A. Sánchez-Reséndiz, and S. Tascini, "An experimental method to quantitatively analyse the effect of thermal insulation thickness on the summer performance of a vertical green wall," *Energy Build*, vol. 150, pp. 132–148, Sep. 2017, doi: 10.1016/j.enbuild.2017.05.068.

[40] L. L. H. Peng, Z. Jiang, X. Yang, Y. He, T. Xu, and S. S. Chen, "Cooling effects of block-scale facade greening and their relationship with urban form," *Build Environ*, vol. 169, Feb. 2020, doi: 10.1016/j.buildenv.2019.106552.

[41] C. Alonso *et al.*, "Effect of façade surface finish on building energy rehabilitation," *Solar Energy*, vol. 146, pp. 470–483, 2017, doi: 10.1016/j.solener.2017.03.009.

[42] A. L. Pisello, V. L. Castaldo, C. Piselli, C. Fabiani, and F. Cotana, "Thermal performance of coupled cool roof and cool façade: Experimental monitoring and analytical optimization procedure," *Energy Build*, vol. 157, pp. 35–52, Dec. 2017, doi: 10.1016/j.enbuild.2017.04.054.

[43] M. Ibrahim, L. Bianco, O. Ibrahim, and E. Wurtz, "Low-emissivity coating coupled with aerogel-based plaster for walls' internal surface application in buildings: Energy saving potential based on thermal comfort assessment," *Journal of Building Engineering*, vol. 18, pp. 454–466, Jul. 2018, doi: 10.1016/j.jobe.2018.04.008.

[44] Y. A, N. Li, J. Long, and Y. He, "Thermal performance of a novel solar thermal facade system in a hot-summer and cold-winter zone," *Solar Energy*, vol. 204, pp. 106–114, Jul. 2020, doi: 10.1016/j.solener.2020.04.050.

[45] S. Summa, G. Remia, C. Di Perna, and F. Stazi, "Experimental and numerical study on a new thermal masonry block by comparison with traditional walls," *Energy Build*, vol. 292, Aug. 2023, doi: 10.1016/j.enbuild.2023.113125.

[46] R. Bakhshoodeh, C. Ocampo, and C. Oldham, "Impact of ambient air temperature, orientation, and plant status on the thermal performance of green façades," *Energy Build*, vol. 296, Oct. 2023, doi: 10.1016/j.enbuild.2023.113389.

[47] Z. Azkorra-Larrinaga, A. Erkoreka-González, K. Martín-Escudero, E. Pérez-Iribarren, and N. Romero-Antón, "Thermal characterization of a modular living wall for improved energy performance in buildings," *Build Environ*, vol. 234, Apr. 2023, doi: 10.1016/j.buildenv.2023.110102.

[48] W. G. Báez-García, E. Simá, M. A. Chagolla-Aranda, L. Carlos Sandoval Herazo, and L. G. Carreto-Hernandez, "Numerical-experimental study of the thermal behavior of a green facade in a warm climate in Mexico," *Energy Build*, vol.

311, May 2024, doi: 10.1016/j.enbuild.2024.114156.

[49] K. Ornam, S. Wonorahardjo, and S. Triyadi, "Several façade types for mitigating urban heat island intensity," *Build Environ*, vol. 248, p. 111031, Jan. 2024, doi: 10.1016/j.buildenv.2023.111031.

[50] T. Singh Rajput, V. C. Padmanabhan, and A. Thomas, "Analyzing the thermal performance of walling systems in low-income housing through computational fluid dynamics approach," *Energy Build*, vol. 319, p. 114480, Sep. 2024, doi: 10.1016/j.enbuild.2024.114480.

[51] Q. Zhu, A. Li, J. Xie, W. Li, and X. Xu, "Experimental validation of a semi-dynamic simplified model of active pipe-embedded building envelope," *International Journal of Thermal Sciences*, vol. 108, pp. 70–80, Oct. 2016, doi: 10.1016/j.ijthermalsci.2016.05.004.

[52] M. Zinzi, "Characterisation and assessment of near infrared reflective paintings for building facade applications," *Energy Build*, vol. 114, pp. 206–213, Feb. 2016, doi: 10.1016/j.enbuild.2015.05.048.

[53] W. Chen, S. Liu, and J. Lin, "Analysis on the passive evaporative cooling wall constructed of porous ceramic pipes with water sucking ability," *Energy Build*, vol. 86, pp. 541–549, 2015, doi: 10.1016/j.enbuild.2014.10.055.

[54] L. Mauri, G. Battista, E. de Lieto Vollaro, and R. de Lieto Vollaro, "Retroreflective materials for building's façades: Experimental characterization and numerical simulations," *Solar Energy*, vol. 171, pp. 150–156, Sep. 2018, doi: 10.1016/j.solener.2018.06.073.

[55] X. Zhang et al., "The early design stage for building renovation with a novel loop-heat-pipe based solar thermal facade (LHP-STF) heat pump water heating system: Techno-economic analysis in three European climates," *Energy Convers Manag*, vol. 106, pp. 964–986, 2015, doi: 10.1016/j.enconman.2015.10.034.

[56] J. Shen et al., "Characteristic study of a novel compact Solar Thermal Facade (STF) with internally extruded pin–fin flow channel for building integration," Appl Energy, vol. 168, pp. 48–64, 2016, doi: 10.1016/j.apenergy.2016.01.021.

[57] M. A. Gálvez, T. Gil, R. Barraza, and P. Kapstein, "Analysis of the influence of the position of the reflective layer on the thermal performance of a multi-layer lightweight wall panel," *Journal of Building Engineering*, vol. 48, p. 103849, May 2022, doi: 10.1016/j.jobe.2021.103849.

[58] W. Chen, S. Zhang, and Y. Zhang, "Analysis on the cooling and soaking-up performance of wet porous wall for building," *Renew Energy*, vol. 115, pp. 1249–1259, 2018, doi: 10.1016/j.renene.2017.08.024.

[59] J. Yuan, K. Emura, C. Farnham, and H. Sakai, "Application of glass beads as retro-reflective facades for urban heat island mitigation: Experimental investigation and simulation analysis," *Build Environ*, vol. 105, pp. 140–152, Aug. 2016, doi: 10.1016/j.buildenv.2016.05.039.

[60] A. Buonomano, C. Forzano, S. A. Kalogirou, and A. Palombo, "Building-façade integrated solar thermal collectors: Energy-economic performance and indoor comfort simulation model of a water-based prototype for heating, cooling, and DHW production," *Renew Energy*, vol. 137, pp. 20–36, Jul. 2019, doi: 10.1016/j.renene.2018.01.059.

[61] J. M. Lirola, E. Castañeda, B. Lauret, and M. Khayet, "A review on experimental research using scale models for buildings: Application and methodologies," *Energy Build*, vol. 142, pp. 72–110, May 2017, doi: 10.1016/j.enbuild.2017.02.060.