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Review Article

Energy Efficiency and Comfort Performance of Airport Terminal Buildings: A Systematic Review

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ABSTRACT

Airport terminal buildings (ATBs) exhibit highly dynamic occupancy patterns and extended operating hours, leading to notably higher energy consumption and carbon emissions than other building types. Among the various energy-intensive systems, review findings indicate that heating, ventilation, and air conditioning (HVAC) systems, the most energy-intensive in ATBs, account for approximately 40–60% of total energy consumption, underscoring the need for efficiency improvements, notably during cooling periods. This study systematically reviews 63 studies from 2003 to 2024 to evaluate energy efficiency and thermal comfort performance in ATBs, identifying key research trends and gaps. Despite their significant impact, real-time variations in passenger density and movement patterns pose significant challenges to HVAC optimization, yet existing studies have overlooked mainly their influence on energy performance. The findings reveal that research on ATB energy efficiency has shifted towards integrated approaches that balance energy efficiency and passenger comfort, rather than optimizing either factor independently. Regarding optimization methods, two dominant approaches have been identified: physics-based and data-driven methods, with the latter being the most popular, adopted in 49% of the reviewed studies. Future research should focus on hybrid approaches that integrate physics-based and AI-driven optimization models to improve predictive accuracy and computational efficiency. Additionally, incorporating real-time occupant behaviour into energy optimization strategies is crucial for balancing efficiency and passenger comfort. Advancing robust datasets and enhancing model interpretability will be key to next-generation ATB energy management.

Keywords: Airport terminal building, data-driven energy modeling, energy efficiency, HVAC optimization, systematic review, thermal comfort assessment

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INTRODUCTION

Built environments play a crucial role in supporting the Paris Agreement's goal of limiting the increase in the average global temperature to 1.5 °C above pre-industrial levels (International Energy Agency [IEA], 2021) Moreover, achieving the global net-zero emissions goal by 2050. Building

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operations are responsible for > 30% of global final energy consumption and 26% of global energy-related emissions (i.e., direct emissions constitute 8%, while indirect emissions resulting from electricity generation and heat consumption constitute 18%) (IEA, 2023). Moreover, carbon dioxide emissions account for almost 25% of the global total emissions (González-Torres et al., 2022). Airport terminal buildings (ATBs) are among the most energy-consuming commercial buildings owing to their complicated and multiple space features and operation characteristics (i.e., check-in area, departure area, arrival area, public service area, and baggage handling area) (Xianliang et al., 2021). The average energy consumption per unit of terminal floor area is 180 $kWh/m^2 \cdot yr^{-1}$, roughly 2.9 and 8.0 folds higher than those of normal public buildings and city residential buildings, respectively (Gu, Xie, Huang, Ma, et al., 2022; Xianliang et al., 2021; Z. Li et al., 2023). In addition, Ahn et al. (2015), Kim et al. (2020), and Xianliang et al. (2021) indicated that terminal buildings are one of the most energy-intensive building types. In this context, Strategies to enhance energy efficiency in ATBs while simultaneously maintaining occupant comfort are urgently required.

As essential public infrastructure and transportation hubs (Z. Li et al., 2023). ATBs accommodate a range of stakeholders and activities, accompanied by dynamic occupancy patterns (Mary Reena et al., 2018) and long operational hours (Kotopouleas et al., 2018). Within this context, related equipment operates almost round-the-clock at a constant or maximum capacity, particularly cooling and lighting, to maintain comfortable and satisfactory environments for occupants (Abdallah et al., 2021; Rupcic et al., 2023). In addition, the unique designs of ATBs involve a large window-to-wall ratio, particularly glass curtain walls, resulting in significant solar radiation infiltration and finally exacerbating indoor temperature fluctuations (B. Chen et al., 2024). Moreover, lighting, along with the dynamic passenger occupancy, generates heat, and the cooling system must compensate for this heat gain. These factors contribute to an increased cooling load. Therefore, HVAC systems are the primary sources of power consumption in ATBs, which account for close to 40–60% of the total energy consumption (Xianliang et al., 2021).

In addition, HVAC systems contribute more than 50% of the total carbon dioxide emissions in buildings (Xu et al., 2024). Given this significant impact, extensive research has been conducted to explore strategies for optimizing HVAC systems to enhance energy efficiency and mitigate carbon emissions in airport terminals. Parker et al. (2011) performed a simulation-based analysis on the correlation between HVAC system performance and carbon emissions in East Midlands Airport, United Kingdom, demonstrating that targeted HVAC interventions can substantially reduce carbon dioxide (CO_2) emissions. Similarly, Perdamaian et al. (2013) conducted an energy consumption and emission simulation for Terminal 3 of Soekarno-Hatta International Airport, revealing that HVAC optimization can effectively decrease energy consumption and carbon emissions. Furthermore, Yıldız et al. (2022) examined the relationship between HVAC energy consumption and CO_2 emissions in Erzurum Airport terminals, highlighting that lowering the heating setpoint temperature not only reduces space heating energy demand but also minimizes the energy consumption of pumps and fans, thereby enhancing overall system efficiency while simultaneously reducing CO_2 emissions. Considering this phenomenon, optimizing HVAC is key to reducing energy demands, energy costs, and CO_2 emissions in ATBs.

In recent years, several efforts have been made to enhance energy efficiency, thermal comfort, and daylighting performance of ATBs, focusing on reducing their total energy demand without compromising the comfort and health of occupants. The parameters for assessing ATB performance are numerous and complex, typically involving three aspects: external environmental, passenger occupancy, and electricity usage, which complicate its energy optimization. However, despite active research in this field, the findings are still fragmented. This study involved a comprehensive review of previous related studies to identify research trends and gaps. To comprehensively review these studies, the following research questions were developed:

1. What are the current widely used strategies and approaches for optimizing the energy performance of ATBs?
2. What are the primary parameters used to evaluate the energy performance of ATBs across different purposes (energy efficiency *vs*. comfort conditions)? How are these parameters measured or estimated?
3. What are the main results observed for energy performance across different purposes (energy efficiency *vs*. comfort conditions)?

Therefore, the expected results will open new research avenues and opportunities for ATB energy strategy optimization, particularly in the post-coronavirus disease pandemic era, as the demand for air passengers could exceed 10 billion journeys by 2050 (International Air Transport Association [IATA], 2025). This study structure allows for a thorough examination of the topics. It began with the screening of high-quality and pertinent research papers for systematic review, followed by examining current research trends using bibliometric analysis, and concluded by assessing the limitations of existing research and delineating potential directions for future research.

MATERIALS AND METHODS

This study employed a systematic literature analysis, following the PRISMA guidelines (Page et al., 2021) to ensure a structured and transparent selection of relevant publications on ATBs. The following sections outline the methodological steps, including literature search, study screening, and data extraction and synthesis.

Literature Search Process

Relevant publications were identified through citation database searches based on predefined eligibility and relevance criteria. The study commenced on 15 July 2024, using Scopus and Web of Science (WoS), two leading academic databases, to ensure a systematic and comprehensive analysis of research on the energy efficiency of ATBs. The search covered studies published up to 15 July 2024. The search involved titles, abstracts, and keywords to attain optimal and maximal retrieval outcomes. In addition, the Boolean operator "AND" included all focus areas, and the operator "OR" was used to gather keywords with equivalent meanings. In addition, wildcards were used to increase flexibility in the search process, i.e., the "*" symbol was used to replace all possible characters when searching for one or more entries, and "?" was used to substitute for a single character. Two keyword sets were used (Table 1).

Table 1
Keywords for literature search on energy efficiency in airport terminal buildings in Scopus and Web of Science

Focus	Keywords
Building type	"airport terminal*" OR "terminal building*" OR "airport terminal building*"
Research purpose	"energy efficien*" OR "energy? saving*" OR "energy consumption*" OR "energy demand*" OR "energy reduction*" OR "energy performance*" OR "energy utili?ation*" OR "energy flexibili*" OR "energy conservation*" OR "energy optimi?ation*" OR "comfort"

Screening Criteria

Overall, 333 records were cumulatively generated based on keyword searches, with 54% from Scopus and 46% from WoS (Figure 1). To ensure relevance and quality, an initial screening was performed based on predefined inclusion and exclusion criteria. The specific criteria applied for filtering and screening the results are as follows:

- English must be the language of publication.
- International Scientific Indexing journal papers (i.e., articles and conference papers) must only be in the final version available or "In Press".
- The chosen research topics must fall within energy, engineering, or environmental science.
- The research must involve either energy efficiency, comfort level, or both.
- The research should focus on systems for end-use energy purposes (therefore, scholarly articles focusing on energy-producing systems, such as photovoltaics or solar energy, were excluded).
- Research should focus on the energy efficiency of the entire ATB, excluding single or isolated components (e.g., glass wall, door and window system, and ceiling system).

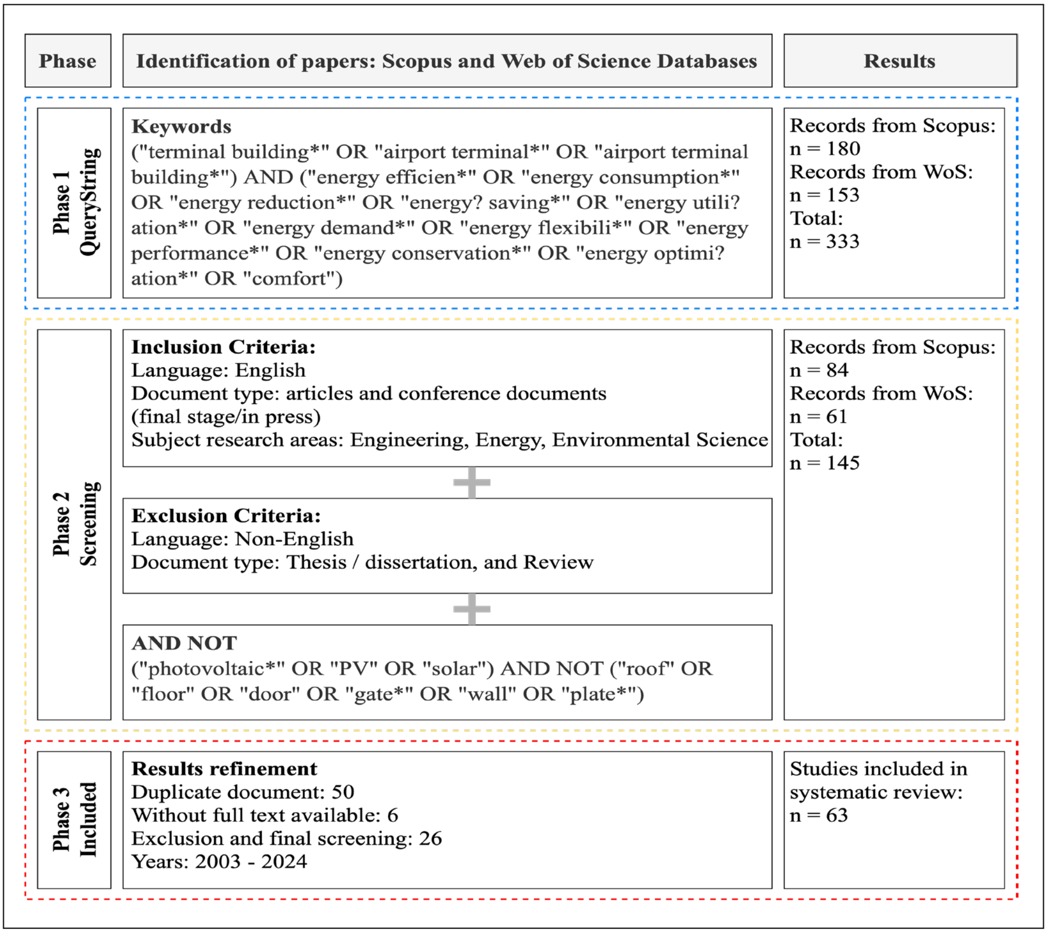

Figure 1. Flow diagram of the systematic review based on the PRISMA guidelines
Note. WoS = Web of Science

- The search engine used the Boolean operator "AND NOT" to eliminate additional specific keywords.

After this phase, 56% of the initial records were excluded based on the filtering and screening criteria, resulting in 145 records being selected for further assessment (84 from Scopus and 61 from WoS).

For further refinement, these records underwent additional screening based on their titles, abstracts, and keywords, leading to the removal of 56 records, including 50 duplicates from both databases and six that lacked full-text availability. A full-text review of the remaining 89 records resulted in the exclusion of 26 papers that did not align with the research scope, since they did not cover ATB's energy consumption. As a result, 63 documents, including 42 research articles (67%) and 21 conference papers (33%), were included in the systematic analysis (Table 2).

Table 2
Overview of authors, publication years, and document types in the systematic review

References	Country	Document type		Building type
		Research article	Conference paper	
B. Chen et al. (2024)	China	✓		Terminal
L. Yang et al. (2024)	China	✓		Terminal
Y. Yang et al. (2024)	China	✓		Terminal
Ma et al. (2024)	China	✓		Terminal
Xu et al. (2024)	China	✓		Terminal
Lin et al. (2023)	China	✓		Terminal
Yue et al. (2023)	China	✓		Terminal
X. Li and Zhao (2023)	China	✓		Terminal
Ma et al. (2023)	China		✓	Terminal
Z. Li et al. (2023)	China	✓		Terminal
Z. Chen et al. (2023)	China		✓	Terminal
Tang et al. (2023)	China	✓		Terminal
Esmaeilzadeh et al. (2023)	United Stated	✓		Terminal
Jia et al. (2022)	China	✓		Terminal
Gu, Xie, Huang, and Liu (2022)	China	✓		Terminal
Jia et al. (2022a)	China	✓		Terminal
Jia et al. (2022b)	China	✓		Terminal
Gu, Xie, Huang, Ma, et al. (2022)	China	✓		Terminal
da Costa et al. (2022)	Brazil	✓		Terminal
Yıldız et al. (2022)	Turkey	✓		Terminal
Yan et al. (2022)	China	✓		Terminal
Hu et al. (2022)	China		✓	Terminal
Akyüz et al. (2021a)	Turkey	✓		Terminal
Xianliang et al. (2021)	China	✓		Terminal
Yıldız et al. (2021)	Turkey	✓		Terminal
Jia et al. (2021)	China	✓		Terminal
Faizah et al. (2021)	Indonesia		✓	Terminal
Akyüz et al. (2021b)	Turkey	✓		Terminal
Dong et al. (2021)	China	✓		Terminal
Liu, Liu, et al. (2021)	China	✓		Terminal
Lin et al. (2021)	China	✓		Terminal
Abdallah et al. (2021)	Egypt	✓		Terminal
Liu, Zhang, et al. (2021)	China	✓		Terminal
Y. Huang et al. (2021)	China	✓		Terminal
Kim et al. (2020)	South Korea	✓		Terminal
Shafei et al. (2020)	Egypt	✓		Terminal
Pasaribu et al. (2019)	Indonesia		✓	Terminal
Sinha et al. (2019)	India		✓	Terminal
Shafei et al. (2019)	Egypt		✓	Terminal

Table 2 *(continue)*

References	Country	Document type		Building type
		Research article	Conference paper	
Lin et al. (2019)	China		✓	Terminal
Liu et al. (2019)	China	✓		Terminal
Mary Reena et al. (2018)	India	✓		Terminal
Kotopouleas et al. (2018)	United Kingdom	✓		Terminal
Miao et al. (2018)	United Stated		✓	Terminal
Malik (2017)	India	✓		Terminal
Weng et al. (2017)	China		✓	Terminal
Zhang et al. (2017)	China	✓		Terminal
B. Li et al. (2017)	China		✓	Terminal
Jiying (2016)	China		✓	Terminal
Kotopouleas et al. (2016)	United Kingdom	✓		Terminal
H. Huang et al. (2015)	Australia	✓		Terminal
Ahn et al. (2015)	United Stated		✓	Terminal
Falvo et al. (2015)	Italy		✓	Terminal
H. Huang et al. (2014)	Australia		✓	Terminal
Wang (2014)	China		✓	Terminal
Gowreesunker and Tassou (2013)	United Kingdom		✓	Terminal
Perdamaian et al. (2013)	Indonesia		✓	Terminal
Sun et al. (2013)	China	✓		Terminal
Danjuma Mambo et al. (2012)	United Kingdom		✓	Terminal
Dai et al. (2012)	China		✓	Terminal
Lau et al. (2011)	Australia		✓	Terminal
Meng et al. (2009)	China	✓		Terminal
Balaras et al. (2003)	Greece	✓		Terminal

RESULTS AND DISCUSSION

Bibliometric Analysis

Based on the bibliometric analysis of the 63 gathered data points (Appendix), summaries of the graphical trend analysis were provided, including publications, countries, variations in paper counts, and network maps generated by VOSviewer.

Publishing Journals

Research Article

Figure 2 and Appendix show that "Building and Environment" was the most prominent journal regarding the topic of energy in ATBs (seven documents), followed by "Energy and Buildings" and "Energy" (each with five documents). While Figure 2 does not provide

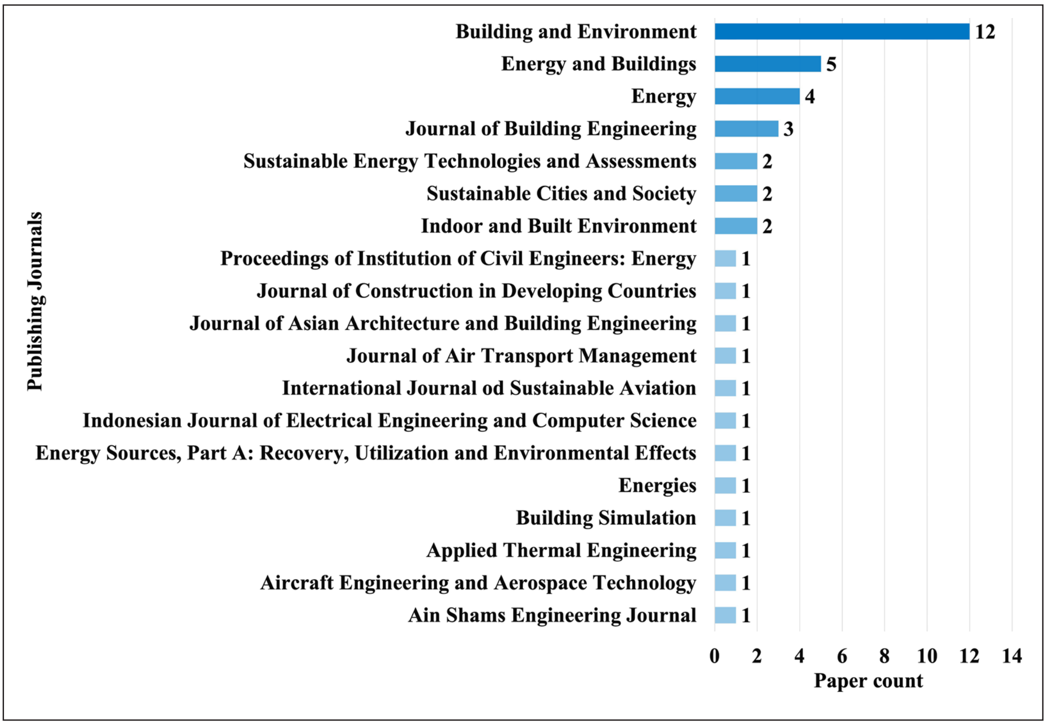

Figure 2. Journal publication distribution of research papers on energy use in airport terminal buildings (up to 15 July 2024)
Note. Darker shades of blue indicate higher values

details on the publisher, most of the selected research articles were published by Elsevier. Refer to the Appendix for further details.

Conference Papers

The International Conference Proceedings contain 21 selected conference papers related to research on ATBs, which span the period from 2011 to 2023. In particular, the International Building Performance Simulation Association (IBPSA) accounts for the highest amount of reviewed conference papers addressing ATBs, close to 24%. The other international conference proceedings, including the International Conference on Environment and Electrical Engineering, the International Symposium on Heating, Ventilation, and Air Conditioning, and the International Conference on Energy, Environment, and Materials Science, account for only one paper each (Appendix).

Study Regions

Figure 3 highlights that publications on the energy efficiency and comfort performance of ATBs are primarily concentrated in countries from the Northern Hemisphere (i.e., eight

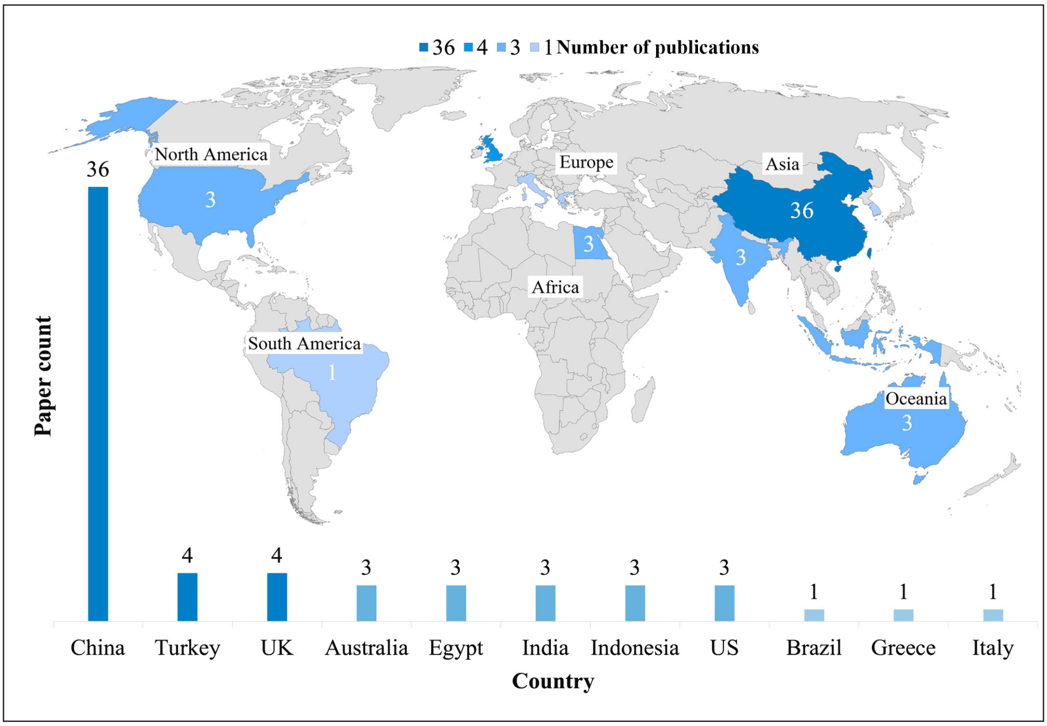

Figure 3. Geographic distribution of research papers on energy use in airport terminal buildings (ATBs) (Up to 15 July 2024)
Note. Darker shades indicate higher numbers of publications; UK = United Kingdom; US = United States

out of eleven published countries). Of the 63 selected studies, 36 (58%) were conducted in China, four (6%) in Turkey, four (6%) in the United Kingdom, and three (5%) in Australia, Egypt, India, Indonesia, and the United States. Only one study was conducted in Brazil, Greece, Italy, and South Korea.

Literature Sources

Figure 4 illustrates the fluctuations in the number of papers published in 2003–2024 (indicated by yellow dashed lines). The starting point of the review paper dates to 2003, as Balaras et al. (2003) was the first relevant and available publication. Additionally, there is currently no single review paper on the energy performance of ATBs. Therefore, this study has covered the past 20 years. Since 2003, the number of research papers on energy and comfort in ATBs has gradually increased, peaking at 12 (11 articles and one conference paper) in 2021. Despite a slight decline in the number of publications since 2021, the overall level remains significantly higher than that recorded in the years prior to 2021. This tendency indicates that there is ongoing interest in the research domain within the academic community, necessitating further in-depth studies in the future.

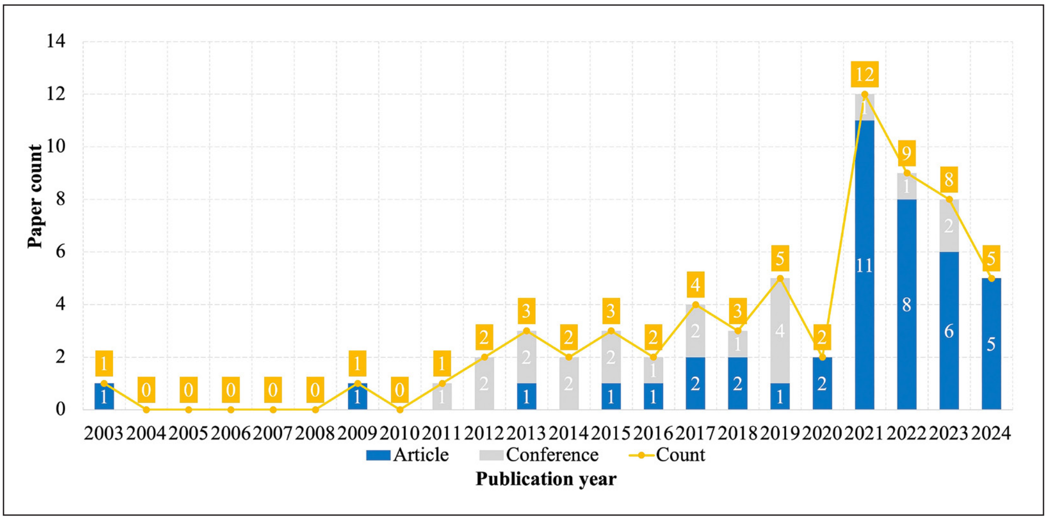

Figure 4. Annual trends in the number of publications on energy performance research of airport terminal buildings (2003–2024)

Keyword Co-Occurrence

Figure 5 presents a keyword co-occurrence analysis map created by VOSviewer, visualizing terms occurring ≥3 times in the keywords and abstracts of 63 reviewed papers. Clusters were identified using the visualization of similarities (VOS) clustering technique, which groups terms with high co-occurrence frequency into distinct categories. In the network map, four colours correspond to four clusters, the node size reflects term recurrence, and terms within the same cluster exhibit strong co-occurrence. The thickness of the links between nodes represents the strength of co-occurrence, with thicker links indicating stronger relationships.

In addition, according to Figure 5, several prominent terms could be identified: “airport terminal building,” “energy efficiency,” “air conditioning,” “thermal comfort”, “ventilation” and “cooling” were emphasized and precisely positioned, emphasizing the deep and intrinsic connections between these terms. Moreover, the keyword co-occurrence analysis map offered additional information. The interconnectedness of all the clusters, with the keyword “energy utilization” at the center, suggested that it was the most extensively researched objective purpose in ATB research. Air conditioning was the second focus, and as expected, the energy demand of ATBs was often associated with air conditioning.

Thematic Synthesis

This subsection provides an overview of the relevant literature. First, the identified papers were categorized according to their research objectives, including energy efficiency, occupant comfort, and both energy efficiency and comfort conditions (Figure 6 and

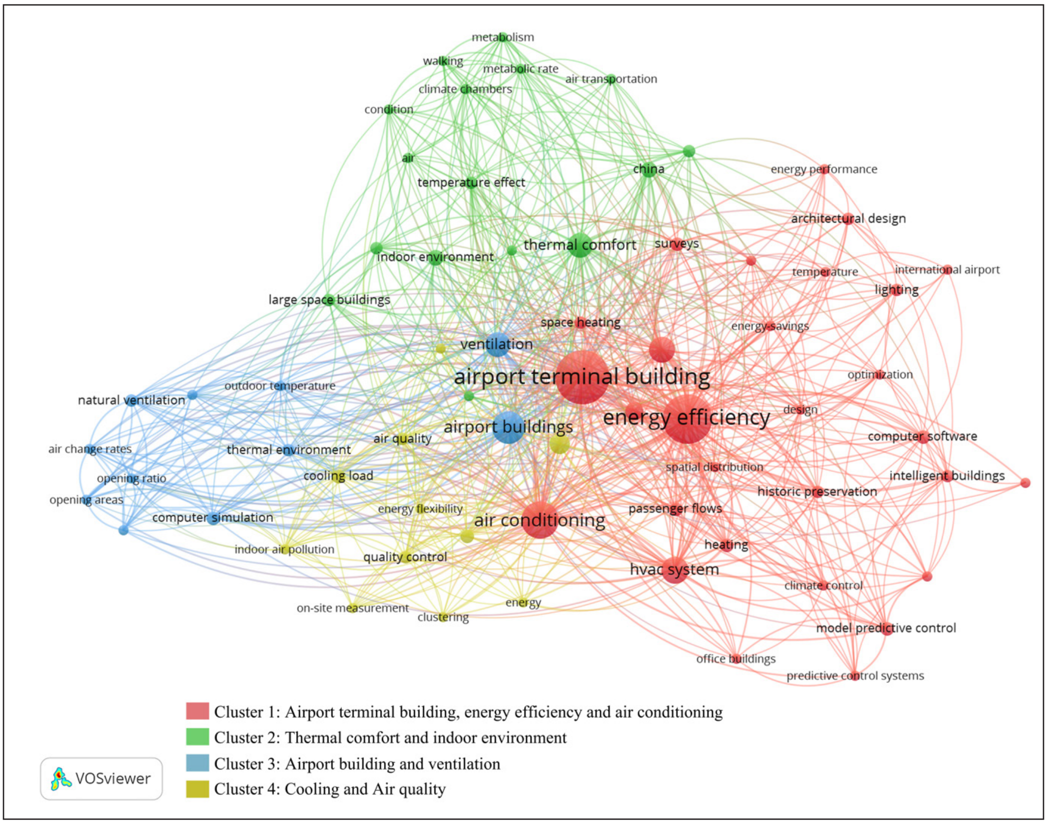

Figure 5. Co-occurrence analysis of keywords (≥3 occurrences) in the reviewed papers using VOSviewer

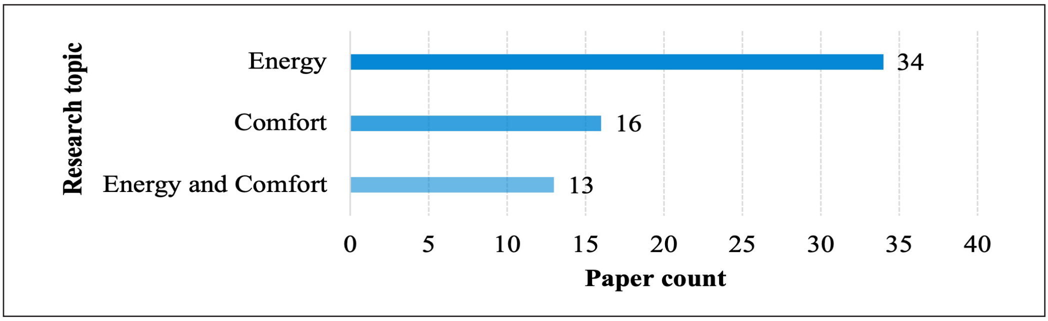

Figure 6. Classification of reviewed papers by research focus: Energy, thermal comfort, and both (n = 63)

Appendix). Among them, 34 (54%) studies concentrated on energy optimization in ATBs, and 16 (25 %) focused on indoor comfort conditions. Only 13 (21%) studies encompassed improved energy efficiency without jeopardizing occupant comfort. Based on the results, we further explored trends in energy performance optimization and the primary parameters evaluated in ATBs in the subsequent section.

Energy Performance Optimization Approach in Terms of Energy Efficiency

Among the 63 studies reviewed, 32 specifically focused on the energy consumption of ATBs, including 22 articles and 11 conference papers (Table 3). Among them, HVAC systems received the most attention, accounting for approximately 40% of the total (25 documents, including 18 articles and seven conference papers). In contrast, only 6% of the reviewed studies (five documents, including one article and four conference papers) examined lighting control systems. Additionally, four studies explored other factors influencing energy consumption.

Besides that, Table 3 presents the energy-saving potential, which varies across different systems. Specifically, previous studies have reported that optimizing the HVAC system can achieve total energy savings between 5 and 57%, depending on the optimization strategies employed. Specifically, these strategies include temperature setpoint adjustments, cooling load parameter optimization, advanced equipment control strategies, fresh air system optimization, and improvements in energy-saving calculation algorithms, among others. For instance, Lin et al. (2023), Malik (2017), and Yıldız et al. (2022) investigated the optimization of air temperature setpoints, with Yıldız et al. (2022) achieving the highest reported energy savings, reaching a 57.24% reduction in energy consumption. Similarly, Lin et al. (2021) and Liu, Liu, et al. (2021) analyzed the impact of adjusting cooling load parameters on overall system performance, with Liu, Liu, et al. (2021) reporting a 34% reduction in HVAC system energy consumption. Additionally, Gowreesunker and Tassou (2013), H. Huang et al. (2014), Liu, Zhang, et al. (2021), Sun et al. (2013), Tang et al. (2023), Z. Li et al. (2023), and Zhang et al. (2017) explored energy-saving strategies for ATBs through advanced control optimizations, among which Tang et al. (2023) reported the highest energy savings, achieving a 38.3% reduction in total energy consumption. Furthermore, Gu, Xie, Huang, and Liu (2022), Gu, Xie, Huang, Ma, et al. (2022), Liu, Zhang, et al. (2021), and Xianliang et al. (2021) optimized cooling load based on passenger distribution, also achieving energy savings. In particular, Gu, Xie, Huang, and Liu (2022) reported a 17.14% reduction in HVAC system energy consumption.

In addition, optimizing the lighting control (LC) system can enhance energy efficiency, particularly with the implementation of an advanced lighting control system. For instance, Wang (2014) reported that adopting such a system led to a total energy consumption reduction of up to 13%. Additionally, Z. Chen (2023) adopted human detection and path planning techniques to adjust terminal internal lighting, ultimately achieving 54.4% energy savings in this system.

Only a limited number of studies (4 out of 63) have explored alternative approaches beyond the two optimization strategies to enhance the overall energy efficiency of ATBs. Among these, Kim (2020) as well as Ahn and Cho (2015) investigated the impact of optimizing relevant parameters on ATB energy consumption, highlighting the critical role

Table 3
Categorization of the reviewed papers by the optimization energy savings factor/system

Optimization factor/system	**References**	**Paper type**		**Max energy saving (%)**			**Number of retrieved articles**
		Article	**Conference**	**HVAC**	**LC**	**Total**	
HVAC	B. Chen et al. (2024)	✓		-	-	-	26
	Xu et al. (2024)	✓		-	-	-	
	Lin et al. (2023)	✓		-	-	-	
	Tang et al. (2023)	✓		-	-	38.3	
	Z. Li et al. (2023)	✓		-	-	-	
	Gu, Xie, Huang, and Liu (2022)	✓		17.14	-	-	
	Gu, Xie, Huang, Ma, et al. (2022)	✓		11	-	-	
	da Costa et al. (2022)	✓		-	-	13	
	Yıldız et al. (2022)	✓		-	-	57.24	
	Yıldız et al. (2021)	✓		-	-	11	
	Lin et al. (2021)	✓		-	-	-	
	Liu, Liu, et al. (2021)	✓		34			
	Xianliang et al. (2021)	✓		-	-	-	
	Liu, Zhang, et al. (2021)	✓		-	-	-	
	Liu et al. (2019)	✓		-	-	-	
	Sinha et al. (2019)		✓	-	-	-	
	Miao et al. (2018)		✓	-	-	17	
	Malik (2017)	✓		30	-	-	
	Zhang et al. (2017)	✓		-	-	8	
	Falvo et al. (2015)		✓	77		-	
	H. Huang et al. (2014)		✓	-	-	18	
	Gowreesunker and Tassou (2013)		✓	-	-	30	
	Sun et al. (2013)	✓				19	
	Perdamaian et al. (2013)	✓		-	-	5.16	
	Dai et al. (2012)		✓	-	-	-	
	Lau et al. (2011)		✓	-	-	-	
	Meng et al. (2009)	✓		21	-	-	
LC	Z. Chen et al. (2023)		✓	-	54.4	-	4
	Faizah et al. (2021)		✓	-	-	-	
	Malik (2017)	✓		-	-	-	
	Wang (2014)		✓	-	-	13	
Other	Akyüz et al. (2021a)	✓		-	-	-	4
	Kim et al. (2020)	✓		-	-	-	
	B. Li et al. (2017)		✓	-	-	-	
	Ahn and Cho (2015)		✓	-	-	-	

Note. '-' = No report; HVAC = Heating, ventilation, and air conditioning; LC = Lighting control of Energy Use Intensity (EUI) in accurately predicting and optimizing energy performance. For instance, Ahn and Cho (2015) conducted a study on United States airports. They demonstrated that EUI optimization could lead to significant cost reductions, with estimated annual electricity savings exceeding $472,000 based on California electricity rates.

Generally, energy efficiency estimates for ATBs cover several aspects, including environmental conditions, passenger occupancy conditions, energy end-use load, and operating costs. Furthermore, an in-depth analysis of the relevant indicator parameters was conducted to understand better and assess their energy-saving potential. Table 4 consolidates the main parameters identified in the reviewed papers for evaluating energy efficiency and shows that air temperatures, passenger distribution, and cooling load were the most frequently assessed parameters in the 34 reviewed energy-related papers, occurring 20, seven, and 14 times, respectively. In addition, the energy analysis mainly focused on the cooling load. Most studies focused on the cooling demands of ATBs; hence, reducing overcooling and energy waste risk during the cooling season is a paramount concern in ATB research.

ATBs typically have an area of several hundred thousand square meters and are larger than general public buildings. Therefore, researchers usually apply simulation model methods to address energy issues. The energy simulation is a mathematical analysis of the physical properties of its elements (Delzendeh et al., 2017). In recent years, two categories of model methods have been widely applied in building load prediction: physical-based and data-driven approaches (B. Chen et al., 2024). Appendix presents an in-depth analysis

Table 4
Overview of main parameters evaluated for the energy savings indicators in airport terminal buildings

References	**Main parameters evaluated**																	
	Environment condition								**Passenger behavior**				**Energy consumption**					
	Air temperature	Surface temperature	Relative humidity	Air velocity	Air infiltration	Wind environment	Solar radiation	Illumination level	Passenger distribution	Passenger numbers	Walking speeding	Dwelling time	Cooling load	Heating load	Electricity load	Total energy demand	Coefficient of performance	Energy use intensity
B. Chen et al. (2024)													✓					
Xu et al. (2024)	✓	✓	✓										✓					
Z. Li et al. (2023)									✓									
Lin et al. (2023)	✓		✓	✓			✓						✓					
Tang et al. (2023)	✓		✓															
Z. Chen et al., 2023	✓								✓							✓		

Table 4 *(continue)*

References	**Main parameters evaluated**																	
	Environment condition								**Passenger behavior**				**Energy consumption**					
	Air temperature	Surface temperature	Relative humidity	Air velocity	Air infiltration	Wind environment	Solar radiation	Illumination level	Passenger distribution	Passenger numbers	Walking speeding	Dwelling time	Cooling load	Heating load	Electricity load	Total energy demand	Coefficient of performance	Energy use intensity
Gu, Xie, Huang, and Liu (2022)									✓				✓	✓				
Gu, Xie, Huang, Ma, et al. (2022)	✓		✓										✓					
da Costa et al. (2022)	✓																✓	
Yıldız et al. (2022)																✓		
Xianliang et al. (2021)																✓		
Akyüz et al. (2021a)	✓									✓						✓		
Yıldız et al. (2021)	✓					✓								✓		✓		
Liu, Liu, et al. (2021)	✓				✓									✓				
Liu, Zhang, et al. (2021)	✓		✓	✓											✓			
Lin et al. (2021)	✓		✓											✓				
Faizah et al. (2021)								✓							✓			
Kim et al. (2020)	✓												✓					✓
Liu et al. (2019)									✓				✓					
Sinha et al. (2019)									✓		✓	✓	✓					
Miao et al. (2018)													✓	✓				
Malik (2017)	✓		✓													✓		
Zhang et al. (2017)													✓		✓			
B. Li et al. (2017)																✓		
Ahn and Cho (2015)	✓															✓		
Falvo et al. (2015)	✓															✓		
H. Huang et al. (2014)	✓												✓					
Wang (2014)																✓		
Sun et al. (2013)													✓			✓		
Gowreesunker and Tassou (2013)	✓			✓									✓					
Perdamaian et al. (2013)	✓								✓						✓	✓		
Dai et al. (2012)	✓		✓										✓					
Lau et al. (2011)	✓								✓						✓	✓		

Note. Parameters under evaluation must be mentioned at least twice in the selected papers of the selected papers based on the model method, in which the data-driven approach accounted for 55% and the physical-based approach accounted for 45% (Table 5 and Figure 7). Despite the analysis suggesting less use of the data-driven approach in optimizing ATB rates, it has outperformed the physical-based method regarding energy optimization over the past 5 years, primarily owing to the limitations of the latter. In addition, data-driven approaches have shown greater applicability, computational efficiency, and proficiency in managing nonlinearities (Ala'raj et al., 2022).

Table 5
Summary of energy consumption prediction methods in reviewed studies: Approaches, algorithms, and simulation software

References	Method	Technique/Algorithm	Softerware
B. Chen et al. (2024)	Data-driven method	SSA-CNN-Transformer model	-
Xu et al. (2024)	Physical-based method	Least squares method	-
Lin et al. (2023)	Data-driven method	Clustering analysis (K-means) Uncertainty analysis Bayesian calibration	EnergyPlus DeST
Z. Li et al. (2023)	Data-driven method	PSO	TRNSYS
Z. Chen et al. (2023)	Data-driven method	YOLOv5s algorithm	CAD
Tang et al. (2023)	Data-driven method	U-NSGA-III	Python
da Costa et al. (2022)	Data-driven method	MBE; Cv (RMSE)	AnyLogic IES
Gu, Xie, Huang, and Liu (2022)	Physical-based method	MBE Cv (RMSE)	AnyLogic IES
Gu, Xie, Huang, Ma, et al. (2022)	Physical-based method	Recommissioning	-
Yıldız et al. (2022)	Physical-based method	-	DesignBuilder EnergyPlus
Akyüz et al. (2021a)	Data-driven method	Regression functions	SimaPro
Xianliang et al. (2021)	Data-driven method	Regression functions	Origin
Faizah et al. (2021)	Data-driven method	Energy performance indicators	DesignBuilder EnergyPlus
Liu, Liu, et al. (2021)	Data-driven method	Fuzzy logic	-
Lin et al. (2021)	Data-driven method	Energy performance indicators	-
Liu, Zhang, et al. (2021)	Data-driven method	Monte Carlo method K-means	EnergyPlus Matlab
Yildiz et al. (2021)	Physical-based method	Regression functions	Matlab
Kim et al. (2020)	Data-driven method	Regression functions	EnergyPlus
Sinha et al. (2019)	Data-driven method	Characteristics of the occupancy	AnyLogic OpenStudio EnergyPlus
Liu et al. (2019)	Data-driven method	Characteristics of the occupancy	AnyLogic;
Miao et al. (2018)	Physical-based method	MBE CVRMSE	Trane Trace 700 GLHEPro 5.0

Table 5 *(continue)*

References	Method	Technique/Algorithm	Softerware
Malik (2017)	Data-driven method	Statistical analysis	-
B. Li et al. (2017)	Data-driven method	Sequential Quadratic Programming	Matlab 1stOpt DeST
Zhang et al. (2017)	Physical-based method	Statistical analysis	-
Falvo et al. (2015)	Data-driven method	Regression functions	EnergyPlus
Ahn and Cho (2015)	Physical-based method	Dynamic energy modelling	EnergyPlus Design Builder
Wang (2014)	Data-driven method	ANN	TRNSYS
H. Huang et al. (2014)	Data-driven method	Intelligent control	-
Gowreesunker and Tassou (2013)	Physical-based method		TRNSYS FLUENT
Perdamaian et al. (2013)	Physical-based method	Thermodynamics Principles of matrix algebra	
Sun et al. (2013)	Physical-based method		TRNSYS
Dai et al. (2012)	Physical-based method	Linear regression	-
Lau et al. (2011)	Physical-based method		IES
Meng et al. (2009)	Physical-based method	Thermodynamic principles	DeST PHOENICS

Note. '-' = No report; SSA = Singular Spectrum Analysis; ANN = Artificial neural network; DeST = Designer's Simulation Toolkit; PSO = Particle swarm optimization; TRNSYS = Transient System Simulation Tool; CAD = Computer-aided Design Software; U-NSGA-III = Unified Non-dominated Sorting Genetic algorithm; MBE = Mean bias error; Cv (RMSE) = Coefficient of Variation of root mean square error; IES = Integrated Environmental Solutions Software; SimaPro = Sustainable Product Design and Life Cycle Assessment Software; FLUENT = Fluid Dynamics Software; GLHE = Ground Loop Heat Exchanger Software; PHOENICS = Parabolic Hyperbolic or Elliptic Numerical Integration Code Series

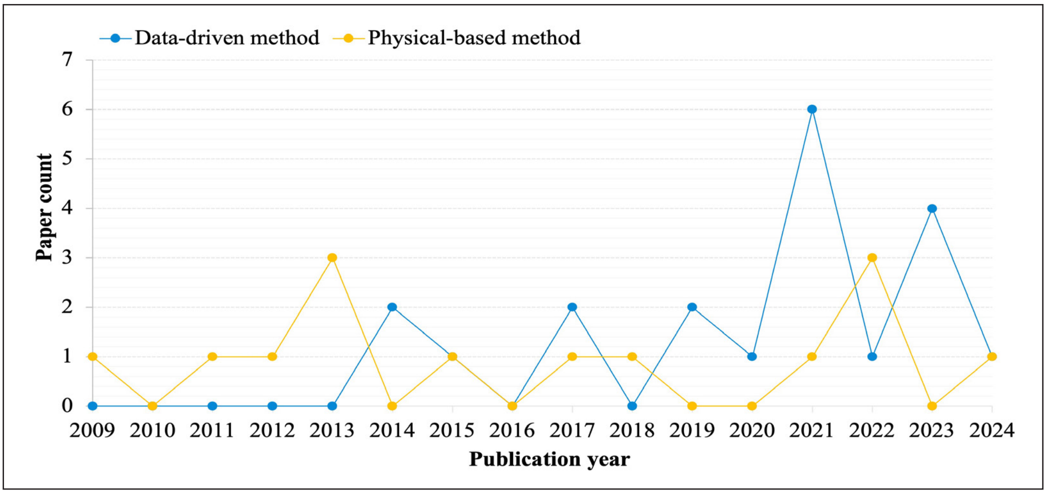

Figure 7. Trends in energy prediction methods for airport terminal buildings (2009-2024): Data-driven vs. physics-based approaches

After analyzing 34 energy-related papers, 18 different types of energy simulation software were identified. As shown in Table 5 and Figure 8, EnergyPlus was primarily used for energy analyses of ATBs, particularly regarding energy issues related to air-conditioning systems (e.g., Kim et al., 2020; Lin et al., 2021, 2023; Sinha et al., 2019; Yıldız et al., 2021, 2022). Although EnergyPlus is a console-based software (Mendes et al., 2024), it also ensures some interoperability with other tools such as DesignBuilder (e.g., Falvo et al., 2015; Yıldız et al., 2021, 2022). In addition, energy analyses of ATBs often used Transient System Simulation Tool (TRNSYS) (e.g., Gowreesunker & Tassou, 2013; H. Huang et al., 2014; Sun et al., 2013; Z. Li et al., 2023) and Anylogicl (e.g., Gu, Xie, Huang, and Liu, 2022; Gu, Xie, Huang, Ma, et al., 2022; Liu et al., 2019; Sinha et al., 2019), and Anylogicl was usually combined with IES-VE to explore passenger distribution and energy consumption relationships (e.g., Gu, Xie, Huang & Liu, 2022; Gu, Xie, Huang, Ma et al., 2022).

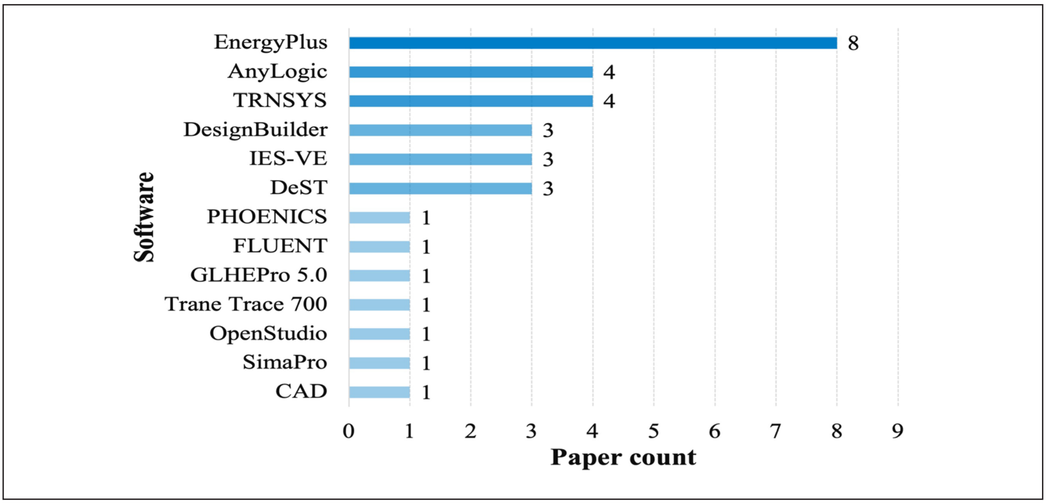

Figure 8. Software usage frequency in the energy simulation of airport terminal buildings (2009–2024): Darker shades indicate higher frequency

Note. TRNSYS = Transient System Simulation Tool; IES-VE = Integrated Environmental Solution-Virtual Environment Software; DeST = Designer's Simulation Toolkit; PHOENICS = Parabolic Hyperbolic or Elliptic Numerical Integration Code Series; FLUENT = Fluid Dynamics Software; GLHE = Ground Loop Heat Exchanger Software; SimaPro = Sustainable Product Design and Life Cycle Assessment Software; CAD = Computer-aided Design Software

Energy Performance Optimization Approach in Terms of Occupant Comfort

The occupant comfort is a key point in architectural design, especially in public buildings. ATB stands out as a complex public transportation facility, characterized by strict service requirements, high passenger densities, and substantial passenger traffic volume (Liu et al., 2018). Consequently, occupant comfort plays a crucial role in determining the degree of passenger satisfaction and energy demand in ATB. Therefore, improving occupant comfort has become a popular research topic in recent years, and 16 (25%) of the selected papers addressed the topic of occupant comfort (refer to Appendix). Comfort commonly includes thermal, acoustic, visual, and indoor air quality (Ala'raj et al., 2022; Shafei et al., 2020). According to Table 6, thermal comfort has been the most widely considered factor in ATB comfort research, particularly in the summer, accounting for 22% (14 documents). In contrast, acoustic, visual, and indoor air quality received significantly less attention, accounting for 6%.

Within the set of reviewed comfort-related papers, environmental factors and subjective sensations dominated the evaluation of comfort performance indicators in ATBs, closely followed by physiological conditions (Table 7). Regarding environmental conditions, air temperature, relative humidity, and air velocity dominated the main parameter evaluations, with almost all relevant papers mentioning the air temperature parameter and recommending

Table 6

Categorization of reviewed studies on occupant comfort: Analysis by comfort type and season

References	**Occupant comfort**									
	Studied season					**Comfort type**				
	Spring	**Summer**	**Autumn**	**Winter**	**Not report**	**Thermal**	**Acoustic**	**Visual**	**Indoor air quality**	**Other**
L. Yang et al. (2024)		✓				✓				
Y. Yang et al. (2024)		✓				✓				
X. Li and Zhao (2023)					✓		✓			
Jia et al. (2022a)		✓				✓				
Jia et al. (2022b)		✓				✓				
Jia et al. (2022)		✓				✓				
Hu et al. (2022)		✓				✓				
Jia et al. (2021)		✓		✓		✓				
Akyüz et al. (2021b)		✓				✓				
Dong et al. (2021)		✓				✓				
Lin et al. (2019)		✓				✓				
Pasaribu et al. (2019)					✓					✓
Kotopouleas and Nikolopoulou (2018)		✓		✓		✓		✓		
Weng et al. (2017)				✓		✓				
Jiying (2015)		✓				✓				
Kotopouleas and Nikolopoulou (2016)		✓		✓		✓				

Note. Other means that personal factors and preferences, indoor physical conditions, external weather conditions, and so on, affect the comfort of occupants

Table 7

Overview of comfort performance indicators in studies on airport terminal buildings: Categorization based on environmental, subjective, and physical conditions

References	Environment condition							Subjective condition					Physical condition			
	Air temperature	**Relative humidity**	**Air velocity**	**Air infiltration**	**Wind environment**	**Lighting**	**Carbon dioxide concentration**	**Thermal sensation vote**	**Thermal performance vote**	**Thermal comfort vote**	**Thermal acceptance**	**Sound sensation vote**	**Skin Temperature**	**Metabolic rate**	**Walking speed**	**Dwelling time**
L. Yang et al. (2024)	✓	✓			✓			✓		✓		✓				
Y. Yang et al. (2024)	✓															
X. Li and Zhao (2023)												✓				
Jia et al. (2022a)	✓	✓	✓					✓	✓	✓	✓		✓	✓	✓	
Jia et al. (2022b)	✓		✓					✓	✓	✓			✓	✓		
Jia et al. (2022)	✓	✓	✓					✓	✓	✓			✓			
Hu et al. (2022)	✓	✓			✓			✓								
Jia et al. (2021)	✓	✓	✓					✓	✓	✓	✓			✓		
Akyüz et al. (2021b)	✓	✓					✓									
Dong et al. (2021)	✓		✓													
Lin et al. (2019)	✓	✓	✓				✓									
Pasaribu et al. (2019)																✓
Kotopouleas and Nikolopoulou (2018)	✓	✓				✓	✓									
Weng et al. (2017)	✓	✓														
Jiying (2015)	✓		✓													
Kotopouleas and Nikolopoulou (2016)	✓	✓					✓	✓	✓							

an indoor set temperature between 24 and 26°C. Additionally, as earlier mentioned, thermal comfort is one of the main focuses; thus, subjective parameters, such as thermal sensation, performance, and comfort, play an important role in evaluating comfort conditions. In ATB, the physiological parameters, such as skin temperature and metabolic rate, are not the primary parameters evaluated, owing to individual differences among passengers; hence, they have not been frequently mentioned.

Figure 9 outlines the standards that the reviewed comfort-related papers frequently apply for the evaluation of the comfort performance of ATBs. As shown in Figure 9, the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) 55 standard, established by the ASHRAE, has emerged as a primary reference in the thermal comfort criteria for ATB. ASHRAE recommends a temperature range of 23–26°C, with

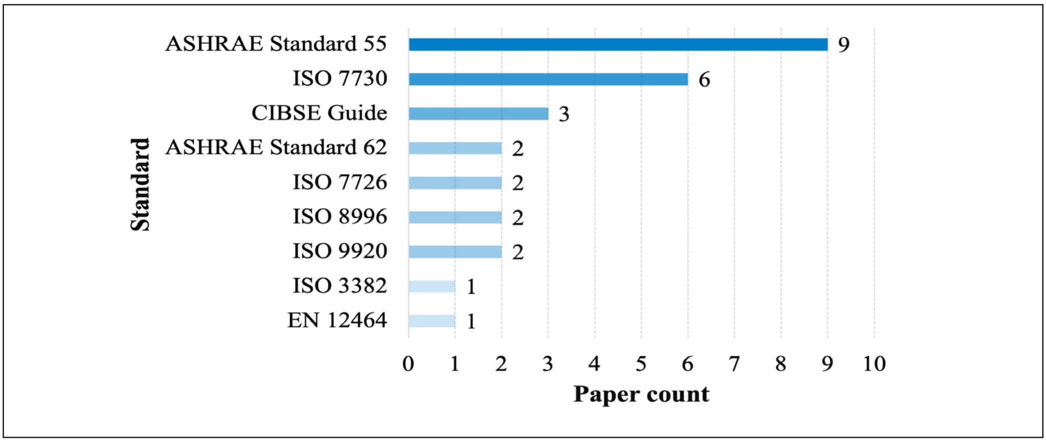

Figure 9. Overview of reference standards adopted in airport terminal buildings thermal comfort studies: Darker shades represent adoption frequency
Note. ASHRAE = American Society of Heating, Refrigerating, and Air-conditioning Engineers; ISO = International Organization for Standardization; CIBSE = Chartered Institution of Building Services Engineers; EN = European Standard

relative humidity values of 30–40% in winter and 40–55% in summer, achieving an 80% comfort acceptability rate (de Dear & Brager, 2002). Previous studies have illustrated the application of this standard (e.g., Akyüz et al., 2021b; Dong et al., 2021; Hu et al., 2022; Jia et al., 2021, 2022, 2022a, 2022b; Kotopouleas & Nikolopoulou, 2016, 2018). In addition, the International Organization for Standardization (ISO) 7730 standard has been widely applied to thermal comfort assessment, with a primary focus on occupant perceptions of the environment (e.g., Akyüz et al., 2021b; Hu et al., 2022; Jia et al., 2021, 2022, 2022a, 2022b). The Chartered Institution of Building Services Engineers (CIBSE) produces CIBSE Guide publications, notably the CIBSE Guide A, another notable authoritative reference standard when evaluating comfort performance.

Energy Performance Optimization Approach in Terms of Energy Savings and Occupant Comfort

Given the nonlinear relationship between energy demand and comfort, 21% (13 documents) of the reviewed papers focused on reducing energy efficiency without jeopardizing occupant comfort, ensuring a suitable trade-off between energy efficiency and comfort performance (Appendix). Therefore, a multi-objective optimization strategy is employed to maximize human comfort, Dual-dimension Strategy (DDS), while minimizing energy consumption. Table 8 demonstrates the application of this strategy, with 19% (12 documents) of the reviewed papers adopting it, attaining energy savings for ATBs between 10 and 40%, while maintaining occupant comfort. Regarding comfort performance, it is noteworthy that almost all the relevant studies address thermal comfort.

Table 8

Categorization of reviewed studies on energy savings and comfort improvement in airport terminal buildings: Optimization strategies and methods

References	Method	Max HVAC system savings (%)	Max total energy savings (%)	Comfort factor	Optimization strategy	Optimization algorithm
Ma et al. (2024)	Data-driven method	10	-	Thermal	OBMPC	GA
Ma et al. (2023)	Data-driven method	13	-	Thermal	OBMPC	GA
Yue et al. (2023)	Data-driven method	34.3	-	Thermal	MPC	BAB
Esmaeilzadeh et al. (2023)	Data-driven method	28	-	Thermal	MPC	GA
Yan et al. (2022)	Data-driven method	44	-	Thermal	SBC	SLSQP
Abdallah et al. (2021)	Data-driven method		24.5	Thermal	MOT	-
Y. Huang et al. (2021)	Physical-based method	-	-	Thermal Acoustic Sound	MOT	OLS
Shafei et al. (2020)	Data-driven method	26.5	13	Thermal	FLC	FA
Shafei et al. (2019)	Data-driven method	-	25	Thermal	DDS	FA
Mary Reena et al. (2018)	Data-driven method	27	-	Thermal	RBC	ANN
H. Huang et al. (2015)	Data-driven method	-	41	Thermal	HMPC	ANN
Danjuma Mambo et al. (2012)	Data-driven method	-	-	Comfort	FLC	FA
Balaras et al. (2003)	Physical-based method	-	40	Thermal	-	-

Note. '-' = No report; OBMPC = Occupant-based model predictive control; GA = Genetic algorithm; MPC = Model predictive control; BAB = Branch and bound; SBC = Scenario-based control; SLSQP = Sequential least squares programming algorithm; MOT = Mathematical optimization technique; OLS = Ordinary Least Squares Algorithm; FLC = Fuzzy logic control; FA = Fuzzy algorithm; DDS = Dual-dimension Strategy; RBC = Rule-based control; ANN = Artificial neural network; HMPC = Hybrid model predictive control

Furthermore, this topic primarily utilizes the data-driven approach, accounting for around 16% (10 documents) of relevant papers on energy and comfort studies, owing to its effectiveness at handling nonlinear relationships. Data-driven approaches typically incorporate various strategies and algorithms to model, control, or optimize energy consumption systems, with model predictive control (MPC) being the most employed approach on ATB energy optimization in the last 5 years (Table 8). Specifically, MPC is a widely recognized approach for managing constrained control based on feedback control and numerical optimization principles (Yaramasu & Wu, 2016). From Table 8, five (8%) of the selected papers (i.e., Esmaeilzadeh et al., 2023; H. Huang et al., 2015; Ma et al., 2023, 2024; Yue et al., 2023) applied MPC-based control approaches combined with different optimization algorithms and achieved energy savings without compromising occupant comfort conditions. Generally, an optimization algorithm aims to minimize or maximize mathematical objective functions to identify the best possible solution or the most efficient way to solve a problem from available alternatives (Ala'raj et al., 2022). Esmaeilzadeh et al. (2023) and Ma et al. (2023, 2024) employed a genetic algorithm (GA) to achieve 10, 13, and 23% energy savings, respectively. Yue et al. (2023) applied the branch and bound (BAB) algorithm, resulting in energy savings of 34.3%. H. Huang et al. (2015) integrated the artificial neural network (ANN) algorithm, achieving up to 41% energy savings. A comprehensive analysis of the algorithms revealed that the primary approach in this field is a combination of MPC-based strategies and GA (Figure 10). However, this method showed a lower maximum energy savings percentage compared with others. GA, an evolutionary algorithm, has gained widespread use in building energy optimization due to its exceptional accuracy, high sensitivity to parameter variations, and rapid execution speed. Therefore, future research could continue to leverage this advantage along with an MPC-based approach to address the multi-objective optimization challenges of ATBs.

Furthermore, ATB optimization frequently employs the fuzzy logic control strategy, in addition to MPC. Despite the potential ability of this strategy to solve complex control problems, its use in optimizing ATB energy consumption has decreased over the past five years. Besides, researchers have also addressed nonlinear problems in ATB optimization with the ANN-based algorithm, particularly when large amounts of data are involved, but this application is still rarely used today. Considering the previously mentioned information, we found that Swarm Intelligence methods, including particle swarm optimization, ant colony optimization, and grey wolf optimization, have not been applied for ATB energy optimization. This represents a potential direction for future research.

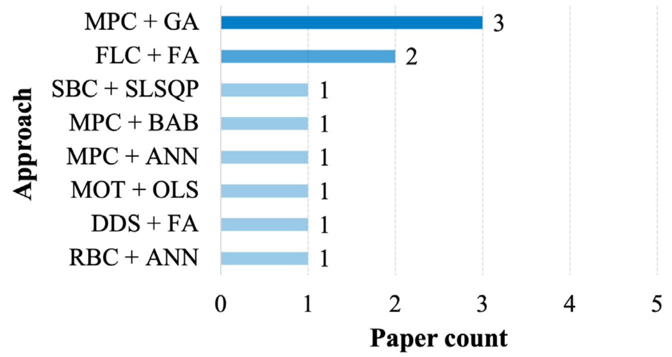

Figure 10. Overview of strategy and algorithm combinations for simultaneous energy optimization and occupant comfort improvement in airport terminal buildings: Darker shades indicate higher adoption frequency

Note. MPC = Model predictive control; GA = Genetic algorithm; FLC = Fuzzy logic control; FA = Fuzzy algorithm; SBC = Scenario-based control; SLSQP = Sequential least squares programming algorithm; BAB = Branch and bound; ANN = Artificial neural network; MOT = Mathematical optimization technique; OLS = Ordinary Least Squares Algorithm; DDS = Dual-dimension strategy; RBC = Rule-based control

DISCUSSION

This study conducts a systematic review of 63 research papers on energy efficiency and occupant comfort in ATBs. Among them, 34 studies specifically examine energy optimization in ATBs, with reported energy savings ranging widely, reaching a maximum of 57% in a single study when occupant comfort is not considered. Additionally, 16 studies explore various aspects of occupant comfort in ATB environments. Furthermore, 13 studies examine energy optimization while preserving occupant comfort, indicating a maximum energy savings of 41%. Notably, the reported minimum and maximum values reflect the global range of findings across the reviewed studies, indicating that energy savings rates are influenced by experimental setups, climatic conditions, and building characteristics, making direct comparisons somewhat limited.

Compared to single-objective energy optimization, multi-objective optimization of both energy consumption and occupant comfort yields a relatively lower energy savings rate (41% vs. 57%). Nevertheless, it ensures occupant comfort while achieving energy savings in ATBs, a factor particularly crucial for buildings with prolonged occupancy, such as airport terminals. This discrepancy can be attributed to the fundamental trade-off between energy efficiency and occupant comfort, as enhanced thermal comfort often requires higher HVAC energy consumption due to increased ventilation rates, stricter temperature controls, and more dynamic system adjustments.

In contrast to data-driven methods, which demonstrate high adaptability in multi-objective optimization, physics-based modeling methods face significant computational and implementation challenges. Among the reviewed studies, 16 papers (25%) employed physics-based modeling methods. However, their application in multi-objective optimization remains limited. Among these 16 studies, physics-based modeling has been predominantly applied to energy consumption minimization, with only two studies attempting to optimize both energy performance and occupant comfort due to the high computational complexity associated with multi-objective simulations.

Physics-based approaches require highly accurate input parameters to ensure reliable simulations. However, compared to conventional buildings, ATBs pose significant challenges in data acquisition. The vast spatial scale limits the feasibility of high-resolution sensor deployment, leading to coarse-grained environmental data. Moreover, dynamic occupant behavior, such as fluctuating passenger density, varying metabolic rates, and diverse clothing insulation levels, introduces uncertainties in thermal comfort modeling. Additionally, ATBs integrate multiple energy systems, including HVAC, lighting, and renewable energy sources, which increases the complexity of energy flow modeling. These factors collectively contribute to parametric uncertainties, potentially leading to deviations between simulated and actual energy performance.

In addition, software limitations further restrict the application of physics-based modeling in optimization. Among the reviewed studies, DesignBuilder is the most used software for physics-based energy simulations, providing a user-friendly graphical interface while integrating EnergyPlus into dynamic thermal modeling. However, it lacks built-in multi-objective optimization capabilities, requiring researchers to integrate external optimization algorithms such as NSGA-II or Python-based solvers, which increase implementation complexity. These factors collectively hinder the feasibility of physics-based methods in optimizing both energy consumption and occupant comfort for ATBs. In contrast, data-driven methods, while highly dependent on data accuracy, have demonstrated high adaptability in optimizing both energy performance and occupant comfort. Given their effectiveness in handling complex multi-objective problems, this approach has shown promising potential in ATB and other large-scale building applications.

Future Research Directions

The primary focus of this review was energy efficiency and comfort performance of ATB. This was achieved by analysing the research methods, evaluated parameters, and energy savings capacity. For future research, recommend the following strategies:

- Most studies highlight that indoor lighting systems have a relatively higher energy demand and that these systems can indirectly help other systems, particularly HVAC systems, reduce cooling loads, and improve indoor thermal comfort. It is worth noting that none of the reviewed studies examined the energy demand and comfort performance of ATB from an indoor lighting conditions perspective. Therefore, future research directions should focus on addressing lighting as a crucial research point for improving energy efficiency and comfort level.
- Because of the design features of ATBs, the facade frequently uses larger-sized glass materials, which usually trigger interior over-illumination during the day, resulting in energy waste and visual discomfort. Therefore, the ATB window-to-wall ratio is worth considering for further research.
- Nowadays, research on ATB energy issues primarily focuses on enhancing energy efficiency while simultaneously improving occupant comfort. However, this topic has only gained wide attention in the last 5 years, which has led to limitations in research methods. Future research could delve into the application of swarm intelligence techniques, specifically Gray Wolf Optimize, given the limited usage of this method in ATB, as suggested by previous findings.
- Currently, research on ATB energy issues primarily focuses on enhancing energy efficiency while improving occupant comfort. However, as this field has gained attention only in the past five years, research methodologies still face limitations, particularly in data availability, model scalability, and evaluation consistency.

Physics-based models offer high interpretability but are computationally intensive, while data-driven approaches are adaptable yet reliant on extensive, high-quality datasets. Future research could explore hybrid modelling approaches that integrate machine learning with physics-based simulations, leveraging both computational efficiency and interpretability. For example, machine learning could assist in parameter tuning and anomaly detection, while physics-based models refine energy flow and occupant behaviour simulations.

- Future research should focus on enhancing data acquisition and real-time monitoring technologies to address the challenges of optimizing energy performance and occupant comfort in ATBs. Given the complexity of ATBs, including their large spatial scale, dynamic occupant behaviour, and multi-system interactions, ensuring the availability of high-resolution, real-time data remains a key challenge. Advancements in IoT-based sensor networks and digital twin technology could enable more precise environmental monitoring. At the same time, AI-driven analytics, such as deep learning and reinforcement learning, can enhance predictive modelling and adaptive control strategies. These developments will be essential in refining data-driven optimization approaches, ultimately improving both energy efficiency and occupant comfort in ATBs and other large-scale buildings.

CONCLUSION

Optimizing energy performance in buildings, especially in ATBs, requires a focus on reducing energy demand and enhancing occupant comfort levels. This study addresses the lack of a review paper focusing on ATB energy performance. Upon adopting a few inclusion and exclusion criteria, 63 research papers spanning 2003–2024 were analyzed and reviewed, with > 50% of the publications emerging within the last 5 years. Further details regarding the conclusions of this study are as follows.

- Bibliometric analysis: Among the reviewed papers, > 55% emerged within the last 5 years, signifying a marked increase in scholarly interest in the energy performance of ATBs; China had the highest number of authors contributing to the reviewed papers, and currently, in the research of ATB energy performance areas, research has mainly concentrated on cooling load and thermal comfort.
- Systematic review: Indoor cooling systems emerged as the predominant factor (68%), with a primary focus on enhancing energy efficiency and thermal comfort; while the evaluation of other systems, such as lighting and acoustic systems, was also aimed at improving the energy efficiency of ATBs, they represented a smaller proportion of the studies (11%).

Studies on the energy performance of ATBs predominantly employed data-driven approaches (49%) because these approaches are easier to compute and better suited for handling nonlinearities than physics-based approaches. Optimal intelligent controls (e.g., MPC) have been widely used in this context.

The parameters evaluated for energy performance indicators mainly focused on three aspects of ATBs: air temperature, passenger flow, and cooling load. According to the systematic review analysis and observed trends in ATB energy performance optimization, significant emphasis was placed on increasing energy efficiency while simultaneously providing thermal comfort based on passenger distribution during the cooling season.

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APPENDIX

List of papers included in the systematic review

	Year	Country	Doc type		Focus area		Method					Title	References
			Article	Conference	Energy	Comfort	Field test	Questionnaire	Experiment	Data-driven	Physical-based		
1	2024	China	✓		✓					✓		An advanced airport terminal cooling load forecasting model integrating SSA and CNN-Transformer	B. Chen et al. (2024)
2	2024	China	✓			✓	✓	✓				Effects of thermal-acoustic interaction on airport terminal's indoor thermal comfort: A case study in cold region of China	L. Yang et al. (2024)
3	2024	China	✓			✓	✓	✓				Extraction method of typical IEQ spatial distributions based on low-rank sparse representation and multi-step clustering	Y. Yang et al. (2024)
4	2024	China	✓		✓	✓				✓		Model predictive control for thermal comfort and energy optimization of an air handling unit system in airport terminals using occupant feedback	Ma et al. (2024)
5	2024	China	✓		✓						✓	Quantifying the energy flexibility potential of a centralized air-conditioning system: A field test study of hub airports	Xu et al. (2024)
6	2023	China	✓		✓					✓		Characterizing cooling load in multi-area airport terminal buildings: Clustering and uncertainty analysis for energy flexibility	Lin et al. (2023)
7	2023	China	✓		✓	✓				✓		Energy-oriented control retrofit for existing HVAC system adopting data-driven MPC – Methodology, implementation and field test	Yue et al. (2023)
8	2023	China	✓			✓	✓	✓				Evaluation of sound environment in departure lounges of a large hub airport	Z. Li et al. (2023)
9	2023	China		✓	✓	✓				✓		Model predictive control strategy of air conditioning system based on dynamic passenger flow: An airport terminal building case study	Ma et al. (2023)
10	2023	China	✓		✓					✓		Passenger spatiotemporal distribution prediction in airport terminals based on insect intelligent building architecture and its contribution to fresh air energy saving	Z. Li et al. (2023)
11	2023	China		✓	✓					✓		Research on intelligent light control system of terminal building based on human detection and path planning	Z. Chen et al. (2023)

12	2023	China	✓		✓					✓		Unlocking ventilation flexibility of large airport terminals through an optimal CO_2-based demand-controlled ventilation strategy	Tang et al. (2023)
13	2023	United States	✓		✓	✓				✓		How combination of control methods and renewable energies leads a large commercial building to a zero-emission zone – A case study in U.S.	Esmaeilzadeh et al. (2023)
14	2022	China	✓			✓			✓			A climate chamber study on subjective and physiological responses of airport passengers from walking to a sedentary status in summer	Jia et al. (2022)
15	2022	China	✓		✓						✓	A spatiotemporal passenger distribution model for airport terminal energy simulation	Gu, Xie, Huang, and Liu (2022)
16	2022	China	✓			✓			✓			Climate chamber study on thermal comfort of walking passengers at different moving speeds	Jia et al. (2022a)
17	2022	China	✓			✓			✓			Climate chamber study on thermal comfort of walking passengers with elevated ambient air velocity	Jia et al. (2022b)
18	2022	China	✓		✓						✓	Prediction of the spatiotemporal passenger distribution of a large airport terminal and its impact on energy simulation	Gu, Xie, Huang, Ma, et al. (2022)
19	2022	Brazil	✓		✓					✓		Recommissioning methodology for the evaluation of airport air conditioning systems	Costa et al. (2022)
20	2022	Turkey	✓		✓						✓	Reduction of energy consumption and CO_2 emissions of HVAC system in airport terminal buildings	Yıldız et al. (2022)
21	2022	China	✓		✓	✓				✓		Strategical district cooling system operation in hub airport terminals, a research focusing on COVID-19 pandemic impact	Yan et al. (2022)
22	2022	China		✓		✓	✓	✓				Study on human thermal comfort in asymmetric radiant heat environment in large space	Hu et al. (2022)
23	2021	Turkey	✓		✓						✓	An analysis on energy performance indicator and GWP at Airports; a case study	Akyüz et al. (2021a)
24	2021	China	✓		✓						✓	Analysis to energy consumption characteristics and influencing factors of terminal building based on airport operating data	Xianliang et al. (2021)
25	2021	Turkey	✓		✓					✓		Energy analysis of cold climate region airports: a case study for airport terminal in Erzurum, Turkey	Yıldız et al. (2021)
26	2021	China	✓			✓	✓	✓				Field investigation on thermal comfort of passengers in an airport terminal in the severe cold zone of China	Jia et al. (2021)
27	2021	Indonesia		✓	✓						✓	Fuzzy logic for lighting system in eco airport passenger waiting room	Faizah et al. (2021)

28	2021	Turkey	✓			✓	✓				Investigation of indoor air quality and thermal comfort condition in airport terminal buildings	Akyüz et al. (2021b)
29	2021	China	✓			✓				✓	Numerical study on coupled operation of stratified air distribution system and natural ventilation under multi-variable factors in large space buildings	Dong et al. (2021)
30	2021	China	✓		✓				✓		An investigation of the cooling performance of air-conditioning systems in seven Chinese hub airport terminals	Liu, Liu, et al. (2021)
31	2021	China	✓		✓				✓		Cooling load characteristic and uncertainty analysis of a hub airport terminal	Lin et al. (2021)
32	2021	Egypt	✓		✓	✓				✓	Energy audit and evaluation of indoor environment condition inside Assiut International Airport terminal building, Egypt	Abdallah et al. (2021)
33	2021	China	✓		✓				✓		Energy saving potential for space heating in Chinese airport terminals: The impact of air infiltration	Liu, Zhang, et al. (2021)
34	2021	China	✓		✓	✓	✓	✓			Research on indoor spaces and passenger satisfaction with terminal buildings in China	Y. Huang et al. (2021)
35	2020	South Korea	✓		✓				✓		Energy performance analysis of airport terminal buildings by use of architectural, operational information and benchmark metrics	Kim et al. (2020)
36	2020	Egypt	✓		✓	✓			✓		Fuzzy control scheme for energy efficiency and demand management in airports using 3D simulator	Shafei et al. (2020)
37	2019	Indonesia		✓		✓	✓				Active waiting: Potentials of waiting area at airport	Pasaribu et al. (2019)
38	2019	India		✓	✓				✓		An agent-based dynamic occupancy schedule model for prediction of HVAC energy demand in an airport terminal building	Sinha et al. (2019)
39	2019	Egypt		✓	✓	✓			✓		Improving energy efficiency in Egyptian airports: A case study of Sharm-Elshiekh Airport	Shafei et al. (2019)
40	2019	China		✓		✓	✓				Performance investigation of indoor thermal environment and air handling unit in a hub airport terminal	Lin et al. (2019)
41	2019	China	✓		✓				✓		Analysis of passenger flow and its influences on HVAC systems: An agent based simulation in a Chinese hub airport terminal	Liu et al. (2019)
42	2018	India	✓		✓	✓			✓		A flexible control strategy for energy and comfort aware HVAC in large buildings	Mary Reena et al. (2018)
43	2018	United Kingdom	✓			✓	✓	✓			Evaluation of comfort conditions in airport terminal buildings	Kotopouleas et al. (2018)

44	2018	United States		✓	✓						✓	Investigation and evaluation of a horizontally bored geothermal heat pump system used in the cold climate of the U.S.	Miao et al. (2018)
45	2017	India	✓		✓						✓	Assessment of energy consumption pattern and energy conservation potential at Indian airports	Malik (2017)
46	2017	China		✓		✓					✓	Field Measurement and Numerical Simulation of Air Infiltration from entrances in an Airport in Winter	Weng et al. (2017)
47	2017	China	✓		✓						✓	Operation strategy optimization of BCHP system with thermal energy storage: A case study for airport terminal in Qingdao, China	Zhang et al. (2017)
48	2017	China		✓	✓					✓		Research and analysis on energy consumption features of civil airports	B. Li et al. (2017)
49	2016	China		✓		✓					✓	A numerical study of the indoor thermal environment in an air-conditioned large space building	Jiying (2016)
50	2016	United Kingdom	✓			✓		✓				Thermal comfort conditions in airport terminals: Indoor or transition spaces?	Kotopouleas et al. (2016)
51	2015	Australia	✓		✓	✓				✓		A new model predictive control scheme for energy and cost savings in commercial buildings: An airport terminal building case study	H. Huang et al. (2015)
52	2015	United States		✓	✓						✓	Energy performance benchmark model for airport terminal buildings	Ahn et al. (2015)
53	2015	Italy		✓	✓					✓		Sustainable airports and NZEB: The real case of Rome International Airport	Falvo et al. (2015)
54	2014	Australia		✓	✓					✓		Model predictive control for energy-efficient buildings: An airport terminal building study	H. Huang et al. (2014)
55	2014	China		✓	✓					✓		The application of i-bus intelligent lighting control system in the terminal of Wuhan Tianhe International Airport	Wang (2014)
56	2013	United Kingdom		✓	✓						✓	A TRNSYS-fluent coupled simulation of the thermal environment of an airport terminal space with a mixing and displacement air conditioning system	Gowreesunker et al. (2013)
57	2013	Indonesia		✓	✓						✓	Scenarios to reduce electricity consumption and CO_2 emission at Terminal 3 Soekarno-Hatta International Airport	Laksana Gema Perdamaian et al. (2013)
58	2013	China	✓		✓						✓	Energy performance enhancement of Hong Kong International Airport through chilled water system integration and control optimization	Sun et al. (2013)
59	2012	United Kingdom		✓	✓	✓					✓	Fuzzy supervisory control strategies to minimise energy use of airport terminal buildings	Danjuma Mambo et al. (2012)

60	2012	China		✓	✓						✓	Test and energy consumption analysis of air-conditioning systems in terminal building of Guilin LiangJiang International Airport	Dai et al. (2012)
61	2011	Australia		✓	✓						✓	The application of a dynamic thermal model for the assessment of the energy efficiency of Adelaide airport terminal	Lau et al. (2011)
62	2009	China	✓		✓						✓	A case study of the thermal environment in the airport terminal building under natural ventilation	Meng et al. (2009)
63	2003	Greece	✓		✓	✓	✓				✓	Energy conservation potential, HVAC installations and operational issues in Hellenic airports	Balaras et al. (2003)

Note.

ANN	Artificial neural network
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ATB	Airport Terminal Building
BAB	Branch and bound
CAD	Computer-aided design
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient of Performance-based Control
DDS	Dual-dimension strategy
FA	Fuzzy algorithm
FLC	Fuzzy logic control
GA	Genetic algorithm
HMPC	Hybrid model predictive control
HVAC	Heating, ventilation, and air conditioning
IEQ	Indoor Environment Quality
IES	Integrated Environmental Solutions Software
ISO	International Organization for Standardization
MBE	Mean bias error
MOT	Mathematical optimization technique
MPC	Model predictive control
OBMPC	Occupant-based model predictive control
OLS	Ordinary Least Squares Algorithm
PSO	Particle swarm optimization
RBC	Rule-based control
PMSE	Root mean square error
SBC	Scenario-based control
SLSQP	Sequential least squares programming algorithm
SR	Systematic review
SSA	Singular Spectrum Analysis
TRNSYS	Transient System Simulation Tool
U.S.	United States