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Cooling Strategies for Urban Courtyard Blocks: A Comprehensive Analysis and Research Gap Assessment

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ABSTRACT

Urban courtyards are essential for counteracting the negative impacts of increasing temperatures and creating more enjoyable outdoor spaces in cities. To understand how to enhance cooling within urban courtyard blocks, this research analyzes a range of studies from different locations and years and has many potential benefits for sustainable living and aligns with several Sustainable Development Goals (SDGs) like Energy Efficiency (SDG 7 - Affordable and Clean Energy), Sustainable Cities and Communities (SDG 11 - Sustainable Cities and Communities) and Good Health - Well-being (SDG 3 - Good Health and Well-being). The outcomes from this paper will possibly help in reducing effects of climate change by making a positive contribution to sustainable development. To understand the direction of research interest in the past decade, this analysis first identifies prominent authors, journals, and publication trends. It then explores the various parameters, algorithms, and software tools that researchers have utilized to improve cooling in urban microenvironments. Various algorithms including genetic algorithms, deep learning algorithms, etc. were used in the research proposed by various researchers, most of them aimed at enhancing thermal comfort and energy efficiency. This review further studies the outcomes and predicted parameters achieved from these optimization strategies, providing insights into their efficiency and possible real-world applications. These results and outcomes presented by various researchers are discussed thoroughly in the current study which helps in easy implementation on the real word applications. Despite the fact that several studies have produced promising results, the accuracy and results vary greatly in the literature and hence the present work not only reviews previous research but also identifies limitations and scope for interdisciplinary collaboration.

1. INTRODUCTION

1.1 Background

Cities around the world are grappling with an issue, the increase in temperatures. This problem is mainly influenced by two interconnected factors; climate variations and urbanization. Climate change, which involves the buildup of greenhouse gasses in the atmosphere, has resulted in a consistent global temperature rise. At the time rapid urbanization has led to cities expanding rapidly increasing the heat experienced within regions. The "urban heat island effect" is at the core of this issue. It refers to the condition in which cities have higher temperatures than the surrounding countryside. This is due to factors such as the high density of buildings, roads, and construction, all of which absorb and contain heat within them. Consequently, urban regions often become heat traps causing discomfort for residents and various negative health impacts [1]. Against this backdrop of increasing temperatures and the urban heat island effect, urban planners and researchers have recognized that urban courtyard blocks may be the possible solution. These enclosed or partially enclosed spaces within city landscapes offer an opportunity for optimizing cooling strategies. By designing and planning these courtyard blocks they can function as microclimates that counteract the effects of the heat island phenomenon [2]. This ultimately enhances comfort for both residents and visitors.

1.2 Research objectives

The purpose of this paper is to discuss the current body of knowledge on the topic of cooling rate optimization in buildings with courtyards in urban areas. It will provide a special emphasis on recent trends in the research and explore various parameters, algorithms, and tools being applied. The study will address several critical research gaps:

- Limited Validation and Scope: Understanding of validation in the real world cases. If the model is only applicable in a virtual environment and scope is limited then what measures could be taken in that regard.

- Complexity and Computational Limitations: Reviewing and analyzing how current optimization methods may have computational problems, and suggest ways to address them.
- Insufficient Consideration of Additional Factors: Stressing the importance of including factors that are often disregarded, including human activities and regional climate fluctuations, in the modeling process.
- Exclusion of Essential Variables and Data Limitations: Discussing about variables that are commonly left unspecified, such as microclimates, and how data scarcity can affect the results of a study.

1.3 Study of published review

The field of courtyard design has very few published reviews, as shown in Table 1, which outlines the goals, methods, and findings of existing studies. This lack of research highlights the importance of the current review, which takes a fresh approach by using advanced tools like Machine Learning (ML) and Deep Learning (DL) to fill in the gaps and provide practical, data-driven solutions for sustainable courtyard design. By addressing these gaps, it opens up new possibilities for creating more energy-efficient and resilient urban spaces.

Table 1. Study of published review

Ref No.	[3]	[4]	Our Study
Objective	Examines passive design criteria for courtyards to enhance energy efficiency and thermal comfort in various climates	Reviews the impact of courtyard geometry and orientation on microclimate performance across diverse climatic zones	Focuses on using algorithms, numerical modeling techniques, and data-driven insights to make informed decisions about urban courtyard design
Design Parameters	Highlights traditional optimization techniques and their influence on airflow, solar radiation, and thermal comfort in courtyards	Focuses on traditional optimization techniques like courtyard design, shading, vegetation, and orientation for climatic adaptation	Introduces ML/DL and optimization algorithms
Geographic Coverage	Highlights studies from the Middle East, Mediterranean, and tropical climates, mapping results to global regions for broader applicability	Includes region-specific examples from Nigeria, China, and other areas to illustrate passive design strategies in residential and institutional courtyards	Examines global studies but emphasizes applicability in hot-arid zones and urban settings
Unique Contribution	Emphasizes combining aspect ratios and orientations with climatic conditions to maximize energy efficiency and thermal comfort	Proposes checklists for courtyard optimization, addressing vegetation, water features, and wall materials to improve microclimates	Explores research gaps, interdisciplinary collaboration opportunities, and the role of ML/DL in optimizing courtyard cooling
Future Direction	Recommends specific design strategies for energy-efficient courtyards, applicable in residential, institutional, and urban planning contexts	Targets architects and urban planners for integrating passive strategies into new and retrofitted courtyard buildings	Offers actionable insights for urban planners, architects, and policymakers, integrating advanced computational techniques to support sustainable urban design

1.4 Significance of study

In this work, the large area of urban courtyard blocks is chosen as the research object and the layout is optimized. By comprehensively analyzing existing research in the field of cooling optimization within urban courtyard blocks, this study plays an important role in the following ways:

- Guiding Urban Planners and Designers: When it comes to the ways in which tomorrow's cities will look like, urban planners and designers are held accountable for. They deal with coming up with urban building forms that are not only practical, but are also capable of handling a changing climate. These highlights are important to this research as they better inform their actions to design a climate resilient urban environment. These practitioners are able to make informed decisions regarding the design, layout and features of closed urban roofs from the synthesis of existing knowledge. These guidelines assist to decrease the impact of urban heat island and enhance the quality of life of inhabitants of such cities.
- Advancing Strategies for Thermal Comfort and Energy Efficiency: It is very important to make cities cool and energy efficient. In this research various publications were studied to filter the ones that were most relevant to courtyard optimization. This can help researchers and architects to create constructions in a way that consumes less energy and is better for the environment. Additionally, this research may help the professionals to draw the right balance between comfort and sustainable practices.
- Identifying Research Gaps and Fostering Collaboration: The effects of urban heat are numerous and multifaceted hence this study very deliberately defines where more work needs to be done. These areas are the further exploration and opportunities for new ideas. If such identified research gaps could be viewed in a more collaborative manner, it would become easier to solve problems involving heat and efficiency in relation to cities [5].
- Contributing to Cooler, More Sustainable Urban Environments: It is very important to propose evidence-based studies on critical issues where the cities face adverse effects of climate change every day. These strategies should be proposed in a way that urban environments are not only cooler but also comfortable [6]. We in this research focus on such strategies. The basic correlation of the previous description is explained in Figure 1.

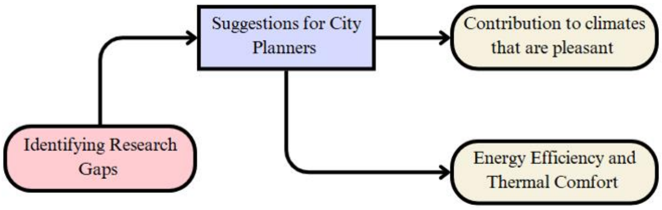

Figure 1. Significance of study

Management of courtyards enables town designers to create integrated environment strategies that enhance physical ventilation and natural light thereby cutting down electrified luminosity, heating, and cooling. This leads to more efficient use of energy and generally creates better quality urban environments.

2. RESEARCH STRATEGY

2.1 Source and methods

Our research is focused on qualitative and quantitative analysis of the topic of "Courtyard Optimization". In quantitative analysis, we collect information from research papers, review papers, etc., and then apply various algorithms to find trends and patterns in literature. Here we use various analysis techniques such as citation network graphs, co-author relationships, and keyword analysis to gain specific knowledge in the related field. Under qualitative analysis, we evaluate the history of publications and also provide brief information on emerging research areas. All this information can be accessed by people from popular repositories called "Scopus" and "Web of Science".

By exploring the quantitative aspects of academic publications, bibliometric analysis helps to understand the dynamics of scholarly communication, facilitating informed decisions in academia and beyond. It plays an important role in assessing the productivity and effectiveness of researchers, identifying collaborative networks, tracking the development of research fields over time, and guiding research strategies across disciplines.

2.2 Data selection and extraction

The approach employed to acquire data from the Scopus and Web of Science databases is showcased in the tabular representation provided. It is important to emphasize the significance of employing fitting and essential keywords during the quest for information. These specific keywords were meticulously selected subsequent to a comprehensive review of earlier surveys pertaining to courtyard optimization. The principal keyword that served as the crux of the search was "Courtyard optimization." Additionally, during the process of reviewing abstracts, two supplementary keywords, namely "Cooling Rates" and "Hot-Arid zones," were uncovered. Notably, in the context of queries executed within the realm of research articles, "Courtyard" stands as the exclusive keyword utilized.

The details can be found in the table below. The search outcomes provide information collected until the year 2024. As illustrated in Figure 2, the relevant research articles procured from the database inquiries are shown. It's important to note that the scope of this study is limited to scholarly journals, conference proceedings, and critical review publications.

Only 10 documents remained after filtering. These 10 documents were chosen in accordance with the highest relativity with the fundamental keyword i.e. "Courtyard Optimization" Metadata covering the article title, publication year, and source, number of citations, author's name, author's keywords, cited references, organization, and country is extracted for the retrieved research publications. Table 2 shows the primary terms employed in the search strategy.

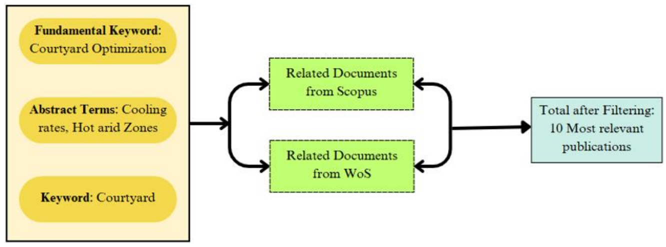

Figure 2. Search strategy

Table 2. List of keywords used

Fundamental Keyword	Courtyard Optimization
Primary Keyword using "AND"	Deep Learning Algorithms
Secondary Keyword using "OR"	Genetic Algorithms
Author Keyword using "OR"	Cooling Rates, Hot Arid Zones

2.3 Data analysis and procedure

When data is conveyed through graphical representations, it enhances comprehensibility and facilitates in-depth analysis. Moreover, it plays a pivotal role in drawing conclusions, making informed decisions, and even predicting future trends, with other applications This examination employs a diverse set of data visualization tools, including Python, Excel, and Power BI. The analysis carried out in this paper is structured into two principal categories, namely quantitative and qualitative assessments.

Within the domain of quantitative analysis, the following investigations are conducted:

- Examination of documents categorized by year
- Citation based analysis

3. QUANTITATIVE ANALYSIS

3.1 Analysis of documents by year

The study of yard optimization began to gain prominence in 2009-2010. Since then, many researchers have been actively publishing numerous papers on this topic. We can see this trend visually through a bar graph showing how many papers are published from 2010 to 2023 per year.

Figure 3 below shows relatively continuous growth over the years, thus proving that more researchers are increasingly interested in working in the field of courtyard optimization. The research literature on courtyard optimization has grown more after the year 2020 because of more concern in sustainable design, energy efficiency, and IAQ improvement. These features largely relate to urbanization and climate change demands that call for new building designs that incorporate light and air and green areas. Similarly, innovative ideas connected with new digital tools in architecture and new technologies in the shape of AI facilitate more creative and more optimal courtyard planning in modern architecture.

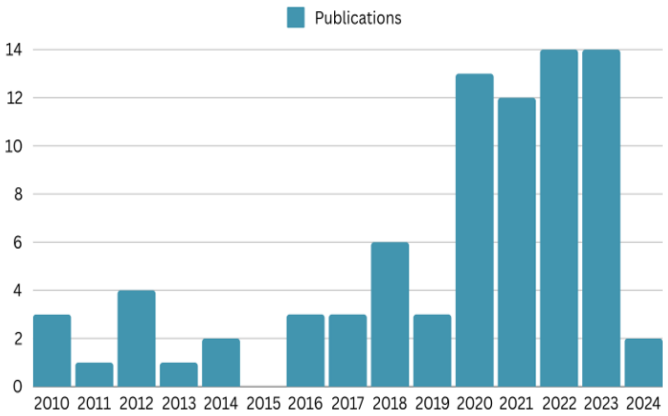

Figure 3. Publication trends over the years

3.2 Citation based analysis

Figure 4 here shows visually the number of times research papers are referred to by others has been going up consistently as the years pass. This increase in citations is closely connected to how many papers are being written on the same subject. To put it simply, when more researchers write and share papers about a specific topic, it naturally grabs the interest of other experts. These experts then mention and use those papers in their own studies.

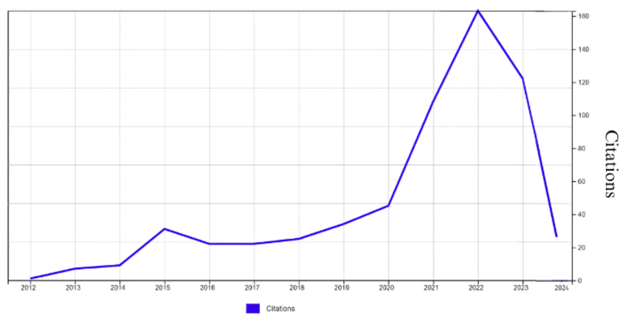

Figure 4. Citation trend over years

The tabular data presented in Table 3 provides a comprehensive overview of the 5 most frequently cited research papers within the specified field, accompanied by the respective publication years. These papers have garnered substantial recognition, with their influence reverberating throughout the academic community. It is to be noted that these papers are amongst the top category only when the keyword is “Courtyard Optimization”. Addition of primary and secondary keywords will change the top cited papers.

The citation shows that these particular papers have played a major role in shaping the discourse in the field of study. Additionally, including years of publication contextualizes the temporal development of these key works, allowing for an understanding of how their influence has endured and evolved over time. Figure 5 below shows the collective comparison of publication and citations over a specific period. With technological breakthroughs in the field of sustainability, study into energy usage and heat transfer has increased significantly. This increase in research trend also results in references to other researchers' work, and therefore citations have gradually increased.

Table 3. Popular papers in context of research

References and Years	Authors	Total Citations
[7]	Katzgraber et al.	110
[8]	Zhu et al.	48
[9]	Yasa and Ok	41
[10]	Natanian et al.	29
[11]	Xue et al.	22

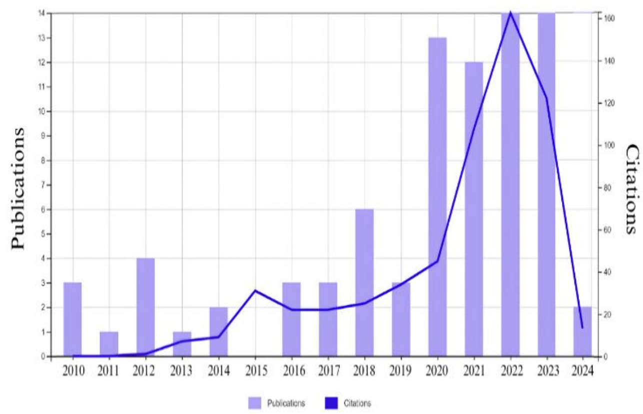

Figure 5. Citation and publication trends over the years

4. QUALITATIVE ANALYSIS

4.1 History of courtyards

Courtyards are known functional living spaces that existed in human constructions for many years; their use can be traced back to Mesopotamia and Rome to the Islamic period. They were especially relevant in the hot climate zones as they provided an opportunity to manage heat and actions, and maintain a collective serenity. Originally, the inception of a courtyard involved the practice of functionalism while at the same time being an architectural design element that has been used over the years; today’s concept of a courtyard optimization aims at refining features of a courtyard that were signifying benefits in the past through methods that are modern though based on history principles where comfort, technology, sustainability and the use of the right material in construction are given paramount importance and hence qualitative analysis is also essential. Many studies have been focused on the history of courtyards [12, 13]. Optimizing courtyards for various purposes, including cooling and enhancing outdoor comfort, has a rich history rooted in architectural and urban design principles. The evolution of courtyard optimization can be understood through key milestones and developments over time [14]. This is stated briefly in Figure 6.

Courtyard optimization includes several key concepts and innovations. First, microclimate control is central to courtyard design, leveraging elements such as shading, vegetation, and water features to influence local environmental conditions [15]. Second, courtyards act as natural ventilation systems, effectively channeling airflow through buildings to enhance indoor air quality. Privacy is another important aspect, providing enclosed, private spaces within urban settings for outdoor living and recreation. Following Figure 7, depicts the traditional courtyards from various countries and their variations in design. Shape and form affect cooling in courtyards by the promotion of cross ventilation where spaces are opened to allow the air to move and cool the surfaces. Water sprinkling, or plants in the courtyard can also help cool the air by evaporation and shading based on the area. As to the size, form, and orientation of the courtyard, they also play a role in the chilling effect or the amount of sunlight able to penetrate the building.

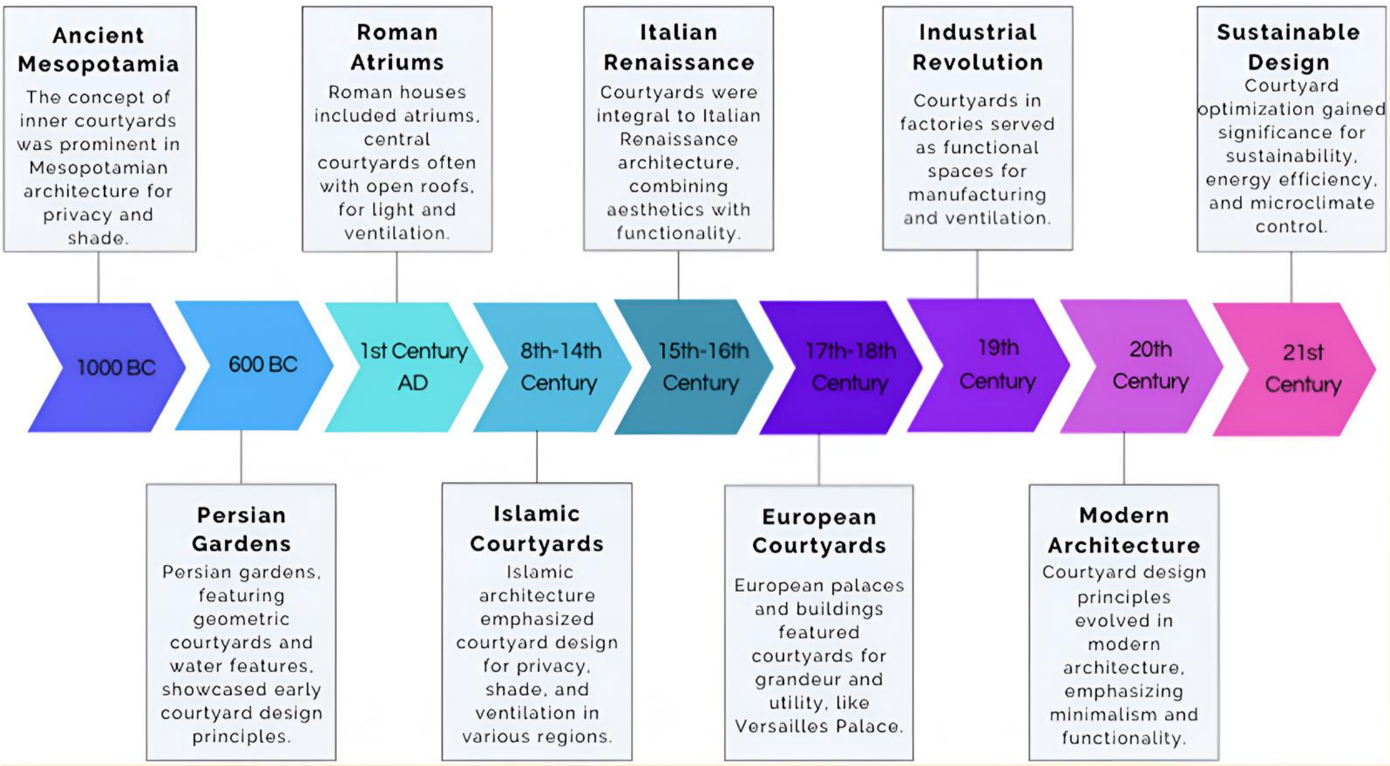

Figure 6. Evolution of courtyard optimization

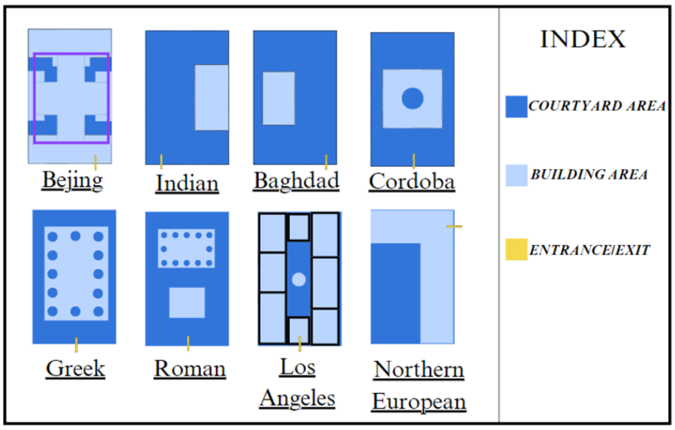

Figure 7. Variation of courtyard designs

Modern field development emphasizes sustainability by combining passive design with energy-efficient design elements, reducing environmental impact. In addition, energy-efficient arenas focus on reducing energy consumption by choosing smart designs. Finally, achieving thermal comfort is a modern goal, and there are aspects of the field such as temperature and humidity that are carefully monitored to ensure the health of the occupant [16]. The thermal comfort and microclimatic conditions of a modern society depends on the design of urban courtyard blocks. If the courtyard design is neglected, this may result in higher building temperatures, increased energy consumption and reduced human comfort. Considering this, researchers have made important contributions over past years to overcome a variety of challenges faced due to irregular courtyard design [17]. Our review of literature offers a detailed analysis on the studies by various researchers. We here focus mainly on the type of algorithm used by researchers, numerical modeling techniques and more, to make right decisions related to urban courtyards. The urban heat island effect is the foremost challenge that has been faced by the modern blocks, where the urban societies experience higher temperatures compared to their rural counterparts. Urban courtyards if optimized effectively can help in eliminating this issue of "heat island effect". With the help of this research, we can say that the researchers have discovered a few ways to manage the rising temperatures and increase energy efficiency.

4.2 Traditional approach for optimization

Generally, genetic algorithms, a type of optimization algorithm, is used extensively in this field. This is because these algorithms are inspired by the principles of natural selection. These algorithms, through iterative processes, help in identifying optimal configurations that can maximize cooling and minimize energy consumption within these urban blocks to eliminate the heat island effect [18]. Additionally, research is being carried out in the field of HVAC systems as well for optimization and efficiency energy savings [11, 12]. In order to achieve this, a very basic workflow is displayed in Figure 8, which involves dataset collection (height, orientation, directions etc.) and goes up to real life implications for sustainability.

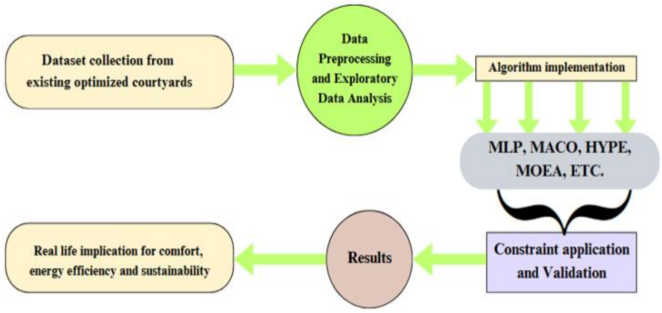

Figure 8. Basic workflow

Additionally, Numerical modeling is also used as a tool for optimizing urban courtyards. The researchers also used computational simulations to simulate heat flow, wind movement and temperature distribution in these open spaces [19]. By creating virtual mathematical modelling, one can experiment with different design parameters and evaluate their impact on various aspects of heat transfer in various applications [20]. These models allow for accurate forecasts and quantitative evaluations, enabling designers and urban planners to make informed decisions about courtyard layout, shading elements and material choices.

Computationally, one begins their processes by identifying the problem and collecting relevant datasets. The next step is choosing appropriate design parameters and variables. The mathematical model is then created for a systematic algorithm selection and implementation. Further in this procedure simulations are carried out for effective constraint handling. If further optimization converges, we visualize our results and validate them and the model is ready for real-life implementation [21]. A streamlined flow to the basic approach to courtyard optimization is represented in Figure 9.

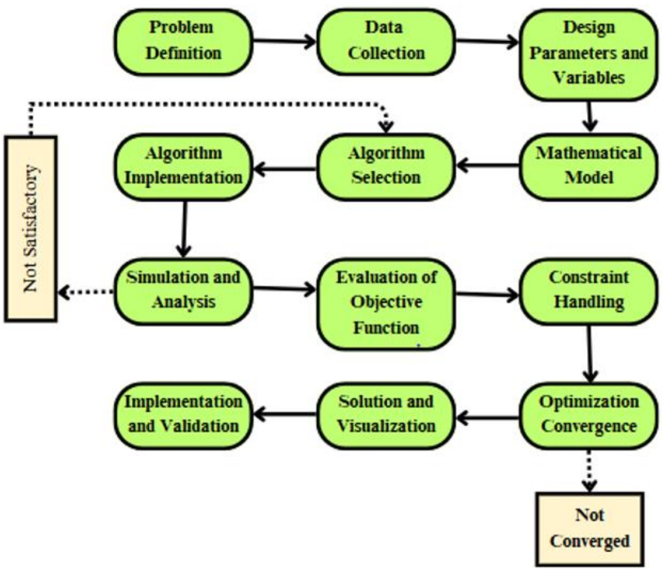

Figure 9. General methodology for optimization

Furthermore, the records-pushed technique has been utilized in a new era of city courtyard optimization. By collecting and reading actual-time environmental facts, inclusive of temperature, humidity, and solar radiation, researchers have gained insights into the overall performance of present courtyards. Machine studying algorithms were employed to pick out patterns and correlations in this information, supporting to uncover the powerful techniques for boosting microclimate conditions and thermal comfort. This records-driven method allows for adaptive design solutions that respond dynamically to converting city situations.

4.3 Key concepts and the need for Machine Learning (ML) and Deep Learning (DL) algorithms

Before exploring the literature on city courtyard cooling, it is essential to understand the basic key concepts as shown in Figure 10 and highlight the role of advanced methods, such as ML and DL algorithms, in optimizing urban courtyard designs.

● Thermal Comfort:

Thermal comfort is an important aspect of urban courtyard design, as it reflects an individual's state of satisfaction or dissatisfaction with their surrounding thermal environment. Key contributing factors include temperature, humidity, and wind speed, as well as their interrelations. Ensuring thermal comfort is very important for the well-being and productivity of the urban residents. Most of the time, the traditional approach fails to model the spatial and temporal variability of these influencing factors. ML and DL algorithms process huge amounts of past and present environmental circumstances which form more accurate forecasts and optimizations. These models help in the design by enhancing the ability of the system to make adjustments in response to changes in the prevailing conditions so that thermal comfort is easily sustained, and by extension, so is the quality of urban courtyards [22].

● Sustainable Design:

Urban courtyard sustainable design is attempting to balance human needs with natural resource conservation, reducing resource consumption rates, minimizing environmental footprints, and improving quality of life. When it comes to sustainable design, it requires the least amount of energy, emissions, and resource use costs. However, the standard simulation tools are not designed for the kind of complicated, multi-objective optimization (MOO) in the initial use cases required for these objectives. To achieve this, ML and DL models are capable of handling such multi-variable scenarios that together constitute the aforementioned data pillars (e.g., building geometry, material properties, energy usage, etc.) to not only aggregate the data from different sources, but also provide feedback near real-time. Such an ability serves to inform sustainable design choices, resulting in environmentally achievable, economically feasible, and socially enhancing urban courtyards [22].

● Energy Efficiency:

Energy-efficient design is a fundamental principle for the urban courtyard approach, and it seeks to minimize energy consumption without damage to its purpose or comfort. Traditional approaches are often inaccurate predictors of how design modifications impact energy performance. The procedure must encompass efficient layout design, construction material choice, and spatial organization if a decrease in energy requirements is to be achieved in a dense urban context. When driving energy efficiency through modeling, ML and DL can mimic and predict various courtyard configurations utilizing a diverse dataset of attributes-i.e., building orientations, insulation characteristics, and external states. This data-driven strategy supports energy-efficient urban courtyards that mitigate the urban heat island effect, the building-related energy use, and sustainability objectives [22]. Energy saving using AIML results not only in sustainability but also may result in heat management [23, 24].

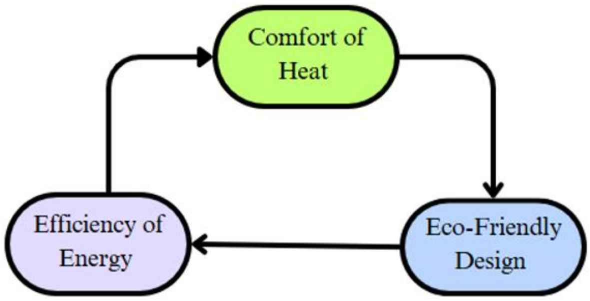

Figure 10. Interconnectivity of key concepts

4.4 Review of selected studies

Out of the 34 studies, 10 most relevant papers were shortlisted. The 10 screened papers were about courtyard optimization in urban blocks and hot arid zones only. The research papers under the scope of this review focus on the implementation of different optimization methods to enhance the thermal comfort levels for outdoor spaces, mainly urban courtyards, across diverse climatic regions. The optimization approaches employed across these enquiries include a selection of genetic algorithm, multi-objective evolutionary algorithm (MOE) and artificial neural network (ANNs) techniques [19, 25]. In addition, these searches are based on a range of data sources including actual measurements, simulation-based observations as well as historical records. Results from these studies demonstrate the applicability of optimization approaches for increasing thermal comfort within urban courtyards. However, these questions expose a series of challenges and constraints in the actual/processual enactment of such strategies. These challenges include:

- The need for accurate and detailed datasets.
- The need to consider a wide range of factors, such as climate, building geometry, and vegetation.
- The constant need to develop good optimization algorithms that can solve complex problems.

Meng-Ren et al. [26] in the study use Grasshopper for the purpose of optimizing the space structure of aerial courtyards in super high-rise buildings. Super high rise buildings are detrimental to the overall coordination of the functional subsystems of the building. Incorporation of aerial courtyards will improve the surroundings of each floor and make the surroundings more dynamic. If several courtyard-centered clusters are constructed on each higher floor, the general organization of the space can be enhanced. In their paper, space syntax theory is applied to systematically study the strategies on connecting aerial courtyard of super high-rises. It implements a space syntax model developed using Grasshopper to study and enhance courtyard patterns within various kinds of spatial configurations while providing enhanced design solutions based on its results. Ibrahim et al. [27] implemented a study that builds on Ladybug simulation tools to investigate the impact of shape, arrangement of three different blocks of cities scattered, linear, and courtyard on environment and out-door comfort and energy consumption established in Cairo Egypt, their study involves 3430 different designs with different parameters. The analyses reveal a high correlation between design parameters and thermal comfort and energy consumption (R^2 = 0.84). The most dominant variable is urban density which affects comfort and energy use significantly (R^2 = 0.7 and 0.95). Their study shows that, for the purpose of natural ventilation, compact, medium density urban layouts work best when their orientation is about 45°. Wortmann and Natanian [28] tried to determine the ratio with which one has to construct more densely on an urban site and for how much area one has to provide sufficient sunlight in the hot and dry climate of Tel Aviv. They use multi-objective optimization (MOO) to study this trade-off, testing seven MOO algorithms on two design types: courtyard and high-rise. The main objectives on which the maximum points are to be awarded include Floor Area Ratio and a fresh emerging index known as Context Exposure Index that has been derived from the Israeli green buildings standards. The high-rise design is found to be superior to the conventional design and three powerful and reliable MOO algorithms examined in this study include HypE, SPEA2, and RBFMOpt. Ibrahim et al. [29] focus on optimizing the design of courtyard blocks for the hot, dry climate of Cairo, Egypt. Using simulations in Rhino 3D with Grasshopper and Ladybug tools, the study looks at factors like building height, orientation, and spacing. Three types of courtyard blocks were tested: square and two elongated shapes (1.5 and 2.5 times the width of the inner courtyard). The best designs had the smallest spacing between buildings. For the square type, a 45° orientation worked best, while for the elongated types, 135° was preferred. The optimized designs reduced cooling loads by up to 31.7% and lowered the Universal Thermal Climate Index (UTCI) by up to 1.6℃, compared to a reference case. Additionally, the designs increased the percentage of exposed surfaces by 4%, which could help reduce heating needs in winter.

Tabadkani et al. [30] their research, seek to understand comfort levels of indoor environment and energy consumption and cost implications of residential building courtyards. In the course of the research design variations and simulations with Grasshopper, Ladybug, Honeybee tools, the options such as courtyard shape, window size, building material, and location are investigated. A Machine Learning approach is used to forecast the effects of such factors on thermal comfort and energy budgets. The findings of the study indicate that weather, and design settings (such as temperature ranges) significantly affect perceived comfort and costs. In warm climates such as Singapore, the concept of having a courtyard may not work so well. The study indicates that the thermal comfort and utility cost predictions offered by deep learning models are accurate. Toris-Guitron et al. [31] examine the impacts of the courtyards on housing internally established temperature of conventional houses in hot and humid regions. They discover that rather than having a cooling effect from the sun, residences with courtyards actually introduce more heat when these courtyards are extensive and broad. Location is also very crucial especially the orientation of the courtyard since east-west orientation causes minimal heat build up. Similarly, the study indicates that regulation of window apertures can lead to a decrease of indoor temperature by 1 degree C at night.

Li et al. [32] indicated that multi-storied buildings have to manage the interrelated factors of capacity and solar rights during urban redevelopment. In order to design better buildings with more area, less shading and more solar radiation their study has employed automatic workflow and optimization. There were three building expansion methods whereby: Horizontal, Vertical, and a mixed test. Using the mixed method of construction yielded the best results because floor space was raised by 70%. The vertical method reduced the solar shading to the least extent while the horizontal was appropriate where height limitations existed. This approach may benefit reasoning for capacity and solar needs in urban renewal. Yu et al. [33] focused on the influences of building design in energy and daylight in old Beijing's courtyard houses.

It suggests an efficient approach towards quick building performance evaluation through ML. Their research employed genetic algorithm to collect the building data after which they fine-tuned it with LightGBM model with high accuracy. The purpose is to develop a rapid assessment tool useful for building performance determination and equally time-saving during the design process in urban regeneration to minimize reversals. Dhanraj et al. [19] use multi-objective DL algorithms to increase cooling rates in urban courtyard blocks in hot desert regions. They apply the Radial Basis Function Network (RBFN), Multi-Layer Perceptron (MLP) Regressor, and Recurrent Neural Network - Long Short-Term Memory (RNN-LSTM) algorithms in the study. The research shows that the RBFN model had the highest accuracy of all models achieving the lowest Mean Squared Error (MSE) of 0.0016 and an RMSE of 0.0395 for predicting cooling loads; they reduced cooling loads and increased thermal comfort and energy economy by optimizing courtyard designs for better harsh climate resilience. Optimization variables include building height, courtyard orientation, and surrounding geometric elements that improve the cooling ability of an urban courtyard block. Xu et al. [34] employ Multi-Objective Optimization, and Machine Learning in modifying village courtyard design. Calculations prove that flexing spatial and architectural variables can enhance energy recovery by 32.3%, winter thermal comfort by 8.3% and summer thermal comfort by 3.8%. During the data-driven phase, courtyard performance is forecasted with 83% accuracy and an F1 of 0.81. The validation also demonstrates that the performance score increases from the initial design value of 59.12 to 85.62. It helps in improving the design time and also aids in better planning of the villages.

Table 4. Summary of the reviewed paper and authors' research focus area

Ref. and Year	Dataset Source	Algorithms Used/Methodologies	Outcomes	Thermal Comfort	Energy Efficiency	Sustainable Design/ Environment Improvement
[26] 2021	High-rise building aerial courtyards	Grasshopper	Enhanced space structure optimization R^2 for Sample V improved from 0.8721 to 0.9492 after optimization.			✔
[27] 2021	Bath, Egypt	Ladybug simulation tools	Design choices impact thermal comfort and energy use (R^2= 0.84), with density having the biggest effect (R^2 = 0.7, 0.95).	✔	✔	
[28] 2021	Tel Aviv, Israel	HypE, SPEA, RBFMOpt, NSGA-II, MOEAD, NSPSO, MACO	High-rise buildings perform better, with HypE, SPEA2, and RBFMOpt as the top optimization algorithms.			✔
[29] 2022	Bath, Egypt	HypE, MOE, SPEA-2	Optimized courtyard block designs in Cairo reduced cooling loads by up to 31.7%, lowered UTCI by 1.6°C, and increased exposed surfaces by 4%, improving both summer and winter thermal performance.	✔		
[30] 2022	[30]	Deep Learning Methodologies	Courtyard design affects comfort, energy use, and costs, with deep learning offering accurate predictions.	✔		
[31] 2022	Colima, Mexico	Simulation software based research	Courtyards increase heat gain, with larger ones raising temperatures, while controlling window openings overnight (23:00–11:00) can lower indoor temperature by 1.1°C, improving comfort.	✔		
[32] 2022	Nanjing, China	Multi-objective Genetic Algorithm	The research found that a mixed building expansion method maximized floor area while minimizing solar shading, offering an optimal solution for urban renewal.			✔
[33] 2023	Beijing, China	LightGBM algorithm	Predicted energy consumption, daylighting, and thermal comfort 90% (Re) 80% (F1)	✔	✔	
[34] 2024	Shandong Province, China	XGBoost algorithm	Results show a 32.3% increase in energy efficiency, 8.3% higher winter comfort, 3.8% higher summer comfort, 83% prediction accuracy, an F1 score of 0.81, and a performance score improvement from 59.12 to 85.62	✔	✔	
[35] 2024	Rural regions of China	Neural Network model, Multiobjective optimisation	The model's performance validation shows R^2 = 0.988 and MSE = 0.0148, indicating high accuracy in predicting building performance.	✔	✔	
[22] 2023	University of Bath (hot arid zones)	RBFN, MLP Regressor, RNN-LSTM	RBFN model improved cooling efficiency, forecasting cooling rates for sustainable urban planning	✔	✔	✔

Sun et al. [35] applied a neural network model together with a MOO method to optimize energy consumption, cost, and thermal comfort for rural homes located in the cold regions of China. Using parametric modeling and ML allowed the team to better predict a number of design parameters on building performance. Their study was able to achieve an MSE of 0.0148 and an R^2 of 0.988. Their research would be practical in providing insights into building energy-efficient and sustainable housing solutions in rural areas, improving living conditions while bringing down the cost to an environmentally-friendly minimum. The research highlights the potential of these methods for informed decision-making in building design, although further refinements are needed for broader applicability across different climatic zones. The error metric in real life indicates that the model's predictions closely match actual data, leaving very little unexplained error.

Table 4 gives a generalized summary of the review made on 10 most relevant papers on courtyard optimization and also gives a brief insight into how the authors from relevant studies may be focusing on three important factors of Thermal Comfort, Energy Efficiency and Sustainable Design additionally the next paragraph represents the full forms of prominent algorithms used in the research.

The most prominent research in many fields frequently uses a variety of algorithms to accomplish its objectives. Some of these key algorithms include ANN, which simulate human neural processes for ML tasks, Environmental Meteorology and Microclimate (ENVI-met), a tool for studying environmental conditions and Hypervolume Estimation (HypE), Multi-objective Ant Colony Optimization (MACO), MOEA, Multi-Objective Evolutionary Algorithm based on Decomposition (MOEAD). They have also used Multi-Layer Perceptron (MLP), Non-dominated Sorting Genetic Algorithm II (NSGA-II), Non-dominated Sorting Particle Swarm Optimization (NSPSO), Radial Basis Function-based Multi-objective Optimization (RBFMOpt) and Strength Pareto Evolutionary Algorithm 2 (SPEA-2).

5. DISCUSSIONS

5.1 Important findings

Optimized Microclimatic Conditions: Most researchers could improve the microclimate to some extent effectively and thus, were successful in upgrading outdoor comfort. Among the several parameters tried were controlling temperature, humidity, and radiation.

Effective Algorithm Selection: Among the algorithms that have been applied, genetic algorithms, heuristic algorithms, and MOE algorithms were the most successful for optimizing various aspects of courtyards. These include layout and design variables, building heights, and orientation and these helped in the production of more efficient and comfortable courtyard spaces.

High Correlation in Thermal Predictions: These studies focused on predicting thermal comfort inside the courtyard which achieved high correlation coefficients (often 90% or more). This indicates a strong association between chosen parameters and thermal comfort of courtyard users, proving the need for effective courtyard optimization methods.

Consideration of Environmental Factors: Several research studies have examined environmental factors like solar access and urban density, aiming to optimize metrics such as FAR and minimize CEI to boost energy efficiency and sustainability [20].

Limitations in Scope and Validation: Many of these studies, however, face notable limitations including small sample sizes, restricted geographical focus, and a lack of thorough validation or comparative analysis. These limitations indicate that there is room for a lot more research and investigation into backyard adaptations that are more detailed and in depth.

User-Friendly Design Tools: Numerous studies have highlighted the importance and need of creating accessible interfaces for ML models, which would allow architects and planners to assess performance metrics without requiring deep technical knowledge.

Scalability of Findings: The methods introduced in these researches were flexible, thus making it easy for them to be adapted into the constructions of different types of buildings as well as different regions across the globe as long as proper local data is considered.

Integration with Policy and Regulation: These researches provide valuable findings that can mold the local urban planning policies by acting as the guidelines for sustainable urban planning that boosts energy efficiency and improves thermal comfort.

5.2 Future suggestions, challenges and drawbacks

From the studies reviewed, researchers have mentioned a few drawbacks, some suggestions and challenges. Following are a few suggestions and drawbacks in no particular order.

A major limitation is the narrow range of climatic factors that is taken into consideration in the study. Many works are devoted to a small number of environments, for example, midlatitude urban areas, so the results of the research would not likely be similar at other climatically different places receiving different amounts of direct sunlight and heat. Subsequent studies should employ a wider climatic span so that one could see how introduced insolation-scrud-building designs work in tropical or high latitude climates in the case of the studied European context.

Another strategic problem relates to assumptions made in models of building systems and energy use. A lot of research on the layout, especially the courtyard layout presents the building envelope coupled with mechanical systems of improbable efficiency in terms of Heating and Cooling. This assumption may cause an overestimation of the amount of potential energy that could be saved by use of these designs. Moreover, the fact that people control or open windows or use the HVAC system is commonly disregarded, but these aspects also contribute to energy consumption and indoor environment significantly. Future research should take into consideration these real-world parameters so as to offer more usable evaluations on courtyard strategies.

Some studies also fail to consider some elements like; lighting energy as well as vegetation. Courtyards can have a great impact on daylight and natural light and its distribution but unfortunately, this aspect is not well incorporated in the simulation. Similarly, although it is recognized that vegetation influences the comfort level of outdoors and shading, the factor is often not incorporated into the design numeration models. Further studies should also assess the impact of variations in vegetation, trees, and green systems on thermal comfort and energy use of courtyard blocks.

Last, the reliance on simple building models, and the suppression of detailed architectural components continue to be concerns in these analyses. One will notice that such concepts as self-shading effects, or the relative window-to-wall ratios, and material properties of the construction, are disregarded; however, they play a significant role in performance of the insulated constructions. However, most of the analyzed research ignores the effects of alterations in the volume of the constructed envelope by extensions or alterations in the exterior environment thermal comfort and microclimatic characteristics. Additional architectural specificity should be introduced to the models, as well as the concerns about building form and density in context of high-density developing areas to give the audience the broader perspective on the courtyard design strategies.

6. CONCLUSIONS

To act upon various challenges like climate change and urbanization, it is necessary to have a detailed review of strategies that optimize urban courtyards. During the survey, it was found that urban heat island effect is the major challenge that the courtyards face. In this research, we studied numerous articles that have been published in past years in reputed journals. The result after reviewing the papers displayed that authors used methodologies like genetic algorithms, numerical modeling, etc. to enhance the cooling conditions within courtyards. The outcomes of these studies resulted in comfort, efficiency and sustainability as they displayed good accuracy suggesting the potential to have optimized urban courtyards.

These include the want for generalization throughout one-of-a-kind weather zones, greater substantial validation of findings, interdisciplinary collaboration, consideration of practical conduct, and a focal point on lengthy-term performance and scalability. Additionally, the integration of renewable power resources, public engagement, and advanced technology can similarly decorate the effectiveness and sustainability of adaptive outside designs. Since there is constant growth in urbanization and warmer climates, the insights in this study may help the architects, designers and researchers for better future planning. The manual efforts to create urban environments that aren't best functionally and aesthetically pleasing are additionally resilient, power-efficient, and environmentally responsible. If the urban courtyards are optimized, we can reduce the heat generated in urban infrastructures contributing to sustainable surroundings. The future scope lies in expanding the DL models to predict not only cooling rates but also thermal comfort and energy efficiency in diverse climate conditions beyond hot arid zones. It also opens opportunities for developing user-friendly tools for urban planners and architects to optimize building designs for sustainability. Real-world implementation and validation of these models could further strengthen their application, while collaborations with policy-makers could help establish energy-efficient urban design regulations. This research supports global sustainability goals and promotes greener, more resilient urban environments amid climate change challenges.

REFERENCES

[1] Giridharan, R., Ganesan, S., Lau, S.S.Y. (2004). Daytime urban heat island effect in high-rise and high-density residential developments in Hong Kong. Energy and Buildings, 36(6): 525-534. https://doi.org/10.1016/j.enbuild.2003.12.016

[2] Sasaki, Y., Tanaka, T. (2021). Analysis of factors affecting residents' evaluation of enclosed landscapes in urban areas including natural landscapes. Journal of the City Planning Institute of Japan, 56(3): 1069-1076. https://doi.org/10.11361/journalcpij.56.1069

[3] Zhu, J.Y., Feng, J.J., Lu, J.F., Chen, Y., Li, W.L., Lian, P.J., Zhao, X. (2023). A review of the influence of courtyard geometry and orientation on microclimate. Building and Environment, 236: 110269. https://doi.org/10.1016/j.buildenv.2023.110269

[4] Markus, B. (2016). A review on courtyard design criteria in different climatic zones. African Research Review, 10(5): 181-192. https://doi.org/10.4314/afrrev.v10i5.13

[5] Santamouris M. (2020). Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. Energy and Buildings, 207: 109482. https://doi.org/10.1016/j.enbuild.2019.109482

[6] Salimi, M., Al-Ghamdi, S.G. (2020). Climate change impacts on critical urban infrastructure and urban resiliency strategies for the Middle East. Sustainable Cities and Society, 54: 101948. https://doi.org/10.1016/j.scs.2019.101948

[7] Katzgraber, H.G., Hamze, F., Andrist, R.S. (2014). Glassy chimeras could be blind to quantum speedup: Designing better benchmarks for quantum annealing machines. Physical Review X, 4(2): 021008. https://doi.org/10.1103/PhysRevX.4.021008

[8] Zhu, L., Wang, B.H., Sun, Y. (2020). Multi-objective optimization for energy consumption, daylighting and thermal comfort performance of rural tourism buildings in north China. Building and Environment, 176: 106841. https://doi.org/10.1016/j.buildenv.2020.106841

[9] Yaşa, E., Ok, V. (2014). Evaluation of the effects of courtyard building shapes on solar heat gains and energy efficiency according to different climatic regions. Energy and Buildings, 73: 192-199. https://doi.org/10.1016/j.enbuild.2013.12.042

[10] Natanian, J., Kastner, P., Dogan, T., Auer, T. (2020). From energy performative to livable Mediterranean cities: An annual outdoor thermal comfort and energy balance cross-climatic typological study. Energy and Buildings, 224: 110283. https://doi.org/10.1016/j.enbuild.2020.110283

[11] Soflaei, F., Shokouhian, M., Tabadkani, A., Moslehi, H., Berardi, U. (2020). A simulation-based model for courtyard housing design based on adaptive thermal comfort. Journal of Building Engineering, 31: 101335. https://doi.org/10.1016/j.jobe.2020.101335

[12] A variety of approaches are being developed to minimize urban heat island effect. (2015). Physics Today. https://doi.org/10.1063/pt.5.028952

[13] Al Natour, I., Hashmi, M.S.J. (1993). A mathematical model and computer aided design for the temperature distribution in an open hydraulic system. International Journal of Numerical Methods for Heat & Fluid Flow, 3(5): 411-427. https://doi.org/10.1108/eb017539

[14] Rezaei Larijani, M., Zolghadri, M.R. (2021). Design and implementation of an ADC-based real-time simulator along with an optimal selection of the switch model parameters. Electrical Engineering, 103(5): 2315-2325. https://doi.org/10.1007/s00202-021-01237-1

[15] Maheshwari, S., Dubey, D.S., Gulia, V., Solke, N. (2023). Comparative analysis of optimization algorithms for energy consumption minimization in HVAC Systems. In

Proceedings of the 5th International Conference on Information Management & Machine Intelligence, Jaipur, India, pp. 1-10. https://doi.org/10.1145/3647444.3652475
[16] Shevendrakumar, D.D., Maheshwari, S., Shaikh, H. (2023). Analyzing machine learning algorithms applied to HVAC systems for sustainability and efficiency. International Journal of Intelligent Systems and Applications in Engineering, 12(1): 70-79. https://ijisae.org/index.php/IJISAE/article/view/3677.
[17] Li, Q. (2018). History of the vintage courtyards in the old city of Lhasa. In The Evolution and Preservation of the Old City of Lhasa. Springer, Singapore, pp. 139-181. https://doi.org/10.1007/978-981-10-6735-8_6
[18] Nelson, R. (2014). The courtyard inside and out: A brief history of an architectural ambiguity. Enquiry the ARCC Journal for Architectural Research, 11(1): 10. https://doi.org/10.17831/enq:arcc.v11i1.206
[19] Mirzabeigi, S., Razkenari, M. (2022). Design optimization of urban typologies: A framework for evaluating building energy performance and outdoor thermal comfort. Sustainable Cities and Society, 76: 103515. https://doi.org/10.1016/j.scs.2021.103515
[20] Han, J., Li, X.Y., Li, B.Y., Yang, W., Yin, W., Peng, Y., Feng, T. (2023). Research on the influence of courtyard space layout on building microclimate and its optimal design. Energy and Buildings, 289: 113035. https://doi.org/10.1016/j.enbuild.2023.113035
[21] Xie, K., Lee, M., Khalid, R., Zakka, V.G. (2023). The impact of personal environmental control on the performance of thermal systems: Building energy consumption, occupant thermal comfort, and productivity. Energy and Buildings, 298: 113552. https://doi.org/10.1016/j.enbuild.2023.113552
[22] Dhanraj, D., Vora, D., Naik, P. (2023). A multiobjective deep learning solution for optimizing cooling rates of urban courtyard blocks in hot arid zones. International Journal of Sustainable Development and Planning, 18(10): 3051-3059. https://doi.org/10.18280/ijsdp.181008
[23] Kannan, R., Roy, M.S., Pathuri, S.H. (2020). Artificial intelligence based air conditioner energy saving using a novel preference map. IEEE Access, 8: 206622-206637. https://doi.org/10.1109/ACCESS.2020.3037970
[24] Liu, Y.K., Zhang, D.X., Gooi, H.B. (2020). Optimization strategy based on deep reinforcement learning for home energy management. CSEE Journal of Power and Energy Systems, 6(3): 572-582. https://doi.org/10.17775/CSEEJPES.2019.02890
[25] Xue, F., Gou, Z., Lau, S.S.Y. (2016). Human factors in green office building design: The impact of workplace green features on health perceptions in high-rise high-density Asian cities. Sustainability, 8(11): 1095. https://doi.org/10.3390/su8111095
[26] Meng-Ren, D., Yang, C., Hao-Xu, G. (2021). A study of aerial courtyard of super high-rise building based on optimisation of space structure. Applied Mathematics and Nonlinear Sciences, 6(2): 65-78. https://doi.org/10.2478/amns.2021.1.00037
[27] Ibrahim, Y., Kershaw, T., Shepherd, P., Coley, D. (2021). On the optimisation of urban form design, energy consumption and outdoor thermal comfort using a parametric workflow in a hot arid zone. Energies, 14(13): 4026. https://doi.org/10.3390/en14134026
[28] Wortmann, T., Natanian, J. (2021). Optimizing solar access and density in Tel Aviv: Benchmarking multi-objective optimization algorithms. Journal of Physics: Conference Series, 2042(1): 012066. https://doi.org/10.1088/1742-6596/2042/1/012066
[29] Ibrahim, Y., Kershaw, T., Shepherd, P., Elkady, H. (2022). Multi-objective optimisation of urban courtyard blocks in hot arid zones. Solar Energy, 240: 104-120. https://doi.org/10.1016/j.solener.2022.05.024
[30] Tabadkani, A., Aghasizadeh, S., Banihashemi, S., Hajirasouli, A. (2022). Courtyard design impact on indoor thermal comfort and utility costs for residential households: Comparative analysis and deep-learning predictive model. Frontiers of Architectural Research, 11(5): 963-980. https://doi.org/10.1016/j.foar.2022.02.006
[31] Toris-Guitron, M.G., Esparza-López, C.J., Luna-León, A., Pozo, C.E.D. (2022). Evaluation of the thermal performance of traditional courtyard houses in a warm humid climate: Colima, Mexico. Heritage Science, 10(1): 187. https://doi.org/10.1186/s40494-022-00820-4
[32] Li, J.J., Wang, Y.X., Xia, Y., Song, Y.C., Xie, H.H. (2022). Optimization of urban block form by adding new volumes for capacity improvement and solar performance using a multi-objective genetic algorithm: A case study of Nanjing. Buildings, 12(10): 1710. https://doi.org/10.3390/buildings12101710
[33] Yu, T.Q., Zhan, X.Q., Tian, Z.C., Wang, D.R. (2023). A machine learning-based approach to evaluate the spatial performance of courtyards—A case study of Beijing's old town. Buildings, 13(7): 1850. https://doi.org/10.3390/buildings13071850
[34] Xu, Z., Huang, X., Zheng, X., Deng, J.Y., Sun, B. (2024). A performance and data-driven method for optimization of traditional courtyards. Sustainability, 16(13): 5779. https://doi.org/10.3390/su16135779
[35] Sun, M.H., Xue, Y.B., Wang, L. (2024). Research on optimized design of rural housing in cold regions based on parametrization and machine learning. Sustainability, 16(2): 667. https://doi.org/10.3390/su16020667