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AI-DRIVEN BIOCLIMATIC DESIGN FOR SUSTAINABLE AVIATION INFRASTRUCTURE: TRANSLATING RESEARCH INTO DESIGN

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Abstract: Airports are increasingly becoming vulnerable to climate-related challenges, particularly rising temperatures, solar exposure, and changing environmental conditions that can affect infrastructure performance and long-term resilience. Despite growing interest in sustainable airport development, limited research has integrated AI-assisted conceptual generation with bioclimatic and performance-driven design approaches during the early stages of airport planning. This study proposes an AI-assisted and performance-driven computational framework for developing climate-responsive airport architecture, for Jewar International Airport, Noida, India, as a hypothetical study and aligning with Sustainable Development Goal 9 (SDG-9). The methodology combines generative AI tools (Midjourney, Adobe Firefly, and DALL·E) for conceptual form generation with Rhino/Grasshopper for parametric modeling, Ladybug for environmental analysis, Kangaroo for physics-based form finding, ZBrush for geometric refinement, and Twinmotion and Lumion for visualization. The design process incorporated biomorphic principles, fractal geometries, and climate-responsive strategies to explore alternative airport configurations. The findings demonstrate that AI-assisted concept generation, when integrated with parametric design tools, can support the development of environmentally informed and climate-responsive airport concepts. However, the objective of the study was not to provide quantitative validation of thermal performance, energy consumption, carbon reduction, or operational efficiency. Therefore, the proposed framework should be interpreted as an exploratory design methodology that may support future sustainable airport development rather than a validated environmental optimization model. Future research may incorporate comparative baseline models and quantitative environmental performance assessments to further evaluate the effectiveness of the proposed approach.

Keywords: Keywords: Climate-responsive design, biomorphic design, airport architecture, sustainability, energy efficiency, AI-assisted designs

1. Introduction

Airports are complex spatial environments that are large energy-consuming zones and contributors to high carbon emissions (Ashford et al., 2011; Graham, 2023). With the rising climate concerns, we need to explore countermeasures to design aviation infrastructure in such a way that it facilitates a reduction in energy consumption (Intergovernmental Panel on Climate Change, 2021). This paper examines how architects can incorporate nature-inspired concepts alongside AI to create an airport that is environmentally beneficial and aesthetically pleasing. Airports need to be designed keeping in mind the climate and environmental parameters of the region (Sobin & Olgyay, 1963). This paper aims to determine how to make airports more environmentally friendly by employing climate-responsive architecture and biomorphic design to reduce their environmental impact and improve the overall airport experience. Airports, which are very much at the core of the world's transport infrastructures, also serve as a stage for economic growth, cultural exchange, and tech development. But in the past few decades, climate change has become a significant challenge to airport operations, infrastructure resilience, and long-term sustainability. The greatest concern has been the increase in average and extreme temperatures. High ambient temperatures have a considerable impact on the performance of runways, the efficiency of aircraft take offs, the lifespan of materials used in the industry, and the comfort as well as safety of the passengers (Zhang, 2019). Heatwaves, specifically, lead to the softening of the runway and higher requirements for cooling, further leading to operational delays. The reliance of conventional airport designs on mechanical systems is becoming inefficient and unsustainable in the face of these changing conditions (Santamouris, 2016).

This paper highlights the ways biomorphic designs, shape-shifting architecture, and artificial intelligence can work together to build airport infrastructure that actually responds to the climate, reinforcing climatic resilience while maintaining its operational efficiency as well as enhancing its ambient and visual-spatial experience. The idea is simple: take inspiration from nature and combine it with advanced technological systems (Benyus, 1997; Oxman, 2017). With this approach, this research lays out a framework for designing airports that adapt to their surroundings, run more smoothly, and make things better for people passing through. This study focuses on Sustainable Development Goal 9 (SDG-9), which emphasizes the necessity of resilient infrastructure, sustainable industrialization, and innovation. By exploring a hypothetical airport design project, this paper discusses how we can develop architectural strategies that effectively develop climatic resilience and environmental responsiveness while ensuring both functionality and aesthetic appeal. Despite increasing research on sustainable infrastructure, limited studies have integrated AI-assisted nature-based design approaches with climate-responsive and performance-driven workflows for airport architecture. Existing approaches predominantly focus on energy efficiency or environmental performance independently, while the potential of combining AI-assisted conceptual generation with bioclimatic design strategies remains underexplored. Therefore, this study investigates the following research question: How can AI-assisted nature-inspired design, integrated with parametric and environmental analysis tools, contribute to the development of climate-responsive and resilient airport architecture? The study proposes an AI-assisted and performance-driven framework that combines generative AI concepts, parametric modeling, environmental analysis, and physics-based form finding. The framework was applied to a site located at Jewar International Airport, Noida, Uttar Pradesh, India, which is characterized by a composite climate with high summer temperatures, monsoon rainfall, and seasonal climatic variability. Within this study, resilience refers to the ability of the design to adapt to changing environmental conditions, adaptive systems refer to flexible and responsive design strategies, sustainability refers to minimizing environmental impacts through passive design approaches, environmental benefits refer to improved climate responsiveness and reduced solar exposure, and aesthetics refer to biomorphic and nature-inspired formal qualities. The findings demonstrate that integrating AI-assisted conceptual generation with performance-driven analysis can support context-responsive airport design while contributing to the objectives of Sustainable Development Goal 9 (SDG-9).

2. Literature Review

Contemporary airport planning is increasingly shaped by the need to respond to climate-related risks, particularly rising average and extreme temperatures, which significantly affect infrastructure performance, passenger comfort, and operational continuity (Citaristi, 2022). Climate-responsive airport design has therefore emerged as a critical research domain, emphasizing passive environmental strategies, resilience-based planning, and sustainable infrastructure aligned with global frameworks such as the United Nations Sustainable Development Goals, particularly SDG-9 (United Nations, 2015). Within this context, bioclimatic architecture and resilient infrastructure planning have been recognized as essential approaches for mitigating thermal stress while improving long-term adaptability (Olgyay et al., 2016; Vale, 2013).

Recent scholars have increasingly explored biomorphic architecture as a generative design methodology in the architecture discipline, where principles derived from natural systems inform form, structure, and environmental performance (Benyus, 1997; Pawlyn, 2025). Fractal geometry, introduced by Benoit Mandelbrot, has been widely adopted in architecture due to its hierarchical organization, self-similarity, and scalability, which can support efficient spatial planning and environmental integration (Mandelbrot, 1982). Similarly, the Fibonacci sequence has been employed in architectural design to establish balanced spatial relationships and proportions observed in natural growth systems (Livio, 2008). Studies by Richard Taylor have further demonstrated that fractal characteristics found in natural environments may positively influence human perception and visual comfort (Taylor et al., 2014). Within this research, these concepts were not used solely as aesthetic inspirations but as design generators to develop biomorphic roof structures, circulation systems, and climate-responsive envelopes that could be integrated with the assistance of AI tools and parametric design softwares to generate a bio-inspired, climate responsive infrastructure. GINA-based methodologies were incorporated to support adaptive form exploration and the translation of nature-inspired principles into architectural geometries suitable for airport applications. Together, these approaches provide a theoretical foundation for integrating environmental responsiveness, spatial organization, and biomorphic design principles in airport architecture. Biomorphic and fractal geometries, in particular, have demonstrated their potential in optimizing shading, ventilation, and thermal regulation while enhancing experiential and spatial qualities (Abboushi et al., 2019). This, when combined with another architectural advancement of the 21st century called 'adaptive and shape-shifting architecture', leads to the development of highly functional and aesthetically appealing transformable architectural forms that are enormously capable and reliable in terms of climatic resilience planning and functionality, as could be witnessed at prominent places such as Al-Masjid an-Nabawi (Prophet's Mosque), where 'Piazza Shading Umbrellas' are installed in Medina, Saudi Arabia, to counter the scorching heat of the desert (Ahmad et al., 2021). These 250 giant umbrellas use a kinetic PTFE membrane system by SL-Rasch that unfolds during the day to provide shade and reduce temperatures by up to 7.7°C. They retract into slim pillars at night to release heat, essentially "breathing" with the environment while also doubling as drainage systems during rare rainfall. Similarly, another such example is the 'Folding Theatre Wall' in Beijing by Origin Architect, which transforms a closed industrial space into an open-air theatre (Frearson, 2014). The massive operable wall lifts to adapt to changing climate conditions, enabling natural ventilation and flexible indoor-outdoor use. The massive operable wall lifts to adapt to changing climate conditions, enabling natural ventilation and flexible indoor-outdoor use. Therefore, it is very recent that shape-shifting architecture has gained relevance as a responsive design paradigm capable of adjusting to dynamic climatic conditions through transformable envelopes, kinetic systems, and performance-driven morphologies (Fox, 2016; Schumacher, 2011).

Previous studies on sustainable airport architecture have primarily focused on improving energy efficiency, reducing carbon emissions, and optimizing operational performance through environmental simulations and passive design strategies. However, relatively few studies have integrated AI-assisted bioclimatic design and performance-driven computational workflows. Existing research often treats environmental analysis and architectural form development as separate processes, limiting opportunities for developing climate-responsive and adaptable airport infrastructure. In this study, AI-assisted design refers to the use of generative AI tools to expand early-stage design exploration, while environmental performance is evaluated through climate-responsive parameters such as solar exposure, shading effectiveness, and site adaptation. Biomorphic architecture refers to design approaches inspired by natural systems and organic geometries, whereas shape-shifting architecture refers to adaptable forms capable of responding to functional or environmental requirements. Together, these approaches support climatic resilience by improving the capacity of airport infrastructure to respond to local environmental conditions while maintaining operational functionality and passenger comfort. Advancements in computational and AI-assisted design have further expanded the horizons of climate-responsive architecture, particularly through parametric modelling, generative algorithms, and simulation-based optimization. Tools such as Rhino–Grasshopper, Ladybug, and Kangaroo have been widely used to integrate environmental analysis directly into early-stage form generation, enabling designers to evaluate solar exposure, thermal behavior, and airflow as part of an iterative design process (Kolarevic & Malkawi, 2004; Terzidis, 2016). Emerging studies also highlight the role of AI augmentation in improving architectural performance and supporting innovative infrastructure solutions through data-driven design exploration (Burry, 2011).

Despite growing research in biomorphic and climate-responsive design, their application in aviation infrastructure remains relatively underexplored, particularly in relation to integrating adaptive forms, spatial planning, and climatic simulation within a unified design framework. Existing literature often addresses sustainability in airport engineering and operations, while limited studies investigate airports as climate-adaptive architectural systems. This study is grounded in SDG-9, which promotes resilient infrastructure, sustainable industrialization, and innovation. The proposed airport design framework integrates AI-assisted conceptual generation, parametric modeling, and performance-driven environmental analysis to develop climate-responsive and adaptable architectural solutions. In this study, climate resilience refers to the ability of the built environment to adapt to changing environmental conditions while maintaining operational performance. Cost-effective adaptive technologies refer to digital tools and design strategies that improve environmental performance while minimizing resource consumption and operational costs. Bioclimatic design and climate-responsive architecture describe design approaches that respond to local climatic conditions such as solar radiation, temperature variations, prevailing winds, and seasonal rainfall. Biomorphic architecture refers to architectural forms inspired by natural systems and organic geometries, whereas shape-shifting architecture refers to adaptable or dynamic forms capable of responding to functional or environmental requirements. Within this framework, AI tools (Midjourney, Adobe Firefly, and DALL·E) were employed for conceptual form generation and refinement, while Rhino/Grasshopper, Ladybug, and Kangaroo were used for parametric development, environmental analysis, and physics-based form finding. Together, these methodologies establish an integrated human–AI collaborative workflow that supports resilient, energy-conscious, and climate-responsive airport design.

3. Materials and Methods

The proposed methodology combines AI-assisted concept generation, parametric modeling, and performance-driven environmental evaluation within a human–AI collaborative workflow. The theoretical basis of the framework is derived from bioclimatic design principles, climate-responsive architecture, and Sustainable Development Goal 9 (SDG-9), which emphasize resilient, innovative, and sustainable infrastructure development. The design process consisted of three stages: (1) AI-assisted generation of conceptual alternatives using Midjourney, Adobe Firefly, and DALL·E; (2) reconstruction and parametric development of selected concepts in Rhino 3D and Grasshopper; and (3) environmental and performance evaluation using Ladybug and Kangaroo. The primary design variables included building orientation, solar exposure, shading configuration, geometric form, and spatial adaptability. Validation criteria included environmental responsiveness, climate adaptation, passive design performance, and the feasibility of implementation within the local context of Jewar International Airport, Noida. ZBrush was employed for geometric refinement, while Twinmotion and Lumion were used for visualization and communication of the final design proposals.

The research further adopts a six-step, performance-driven, systematic architectural design approach that integrates AI-assisted form generation with bioclimatic and climate-responsive form-finding principles to develop a biomorphic, shape-shifting airport typology. The methodological framework is structured as a six-stage iterative workflow (Figure 1), aligning with contemporary parametric and simulation-based design paradigms in which architectural form is not predetermined but emerges from environmental data and multi-criteria optimisation.

The process begins with (1) Problem Identification, wherein the research establishes the need for climate-resilient airport infrastructure capable of responding dynamically to increasing environmental variability, including thermal stress, wind patterns, and energy consumption. This is followed by (2) Site Analysis, involving the acquisition and mapping of climatic datasets (solar radiation, wind vectors, humidity, and temperature gradients) consistent with performance-oriented design approaches that embed microclimatic conditions into early-stage architectural decision-making. In (3) Concept Development, biomorphic principles derived from natural adaptive systems are translated into architectural design, leveraging biomimicry to define responsive spatial strategies and morphogenetic rules that enhance environmental integration and resilience.

The research adopts this six-step, performance-driven, systematic architectural design approach that integrates AI-based generative design with bioclimatic and climate-responsive form-finding principles to develop a biomorphic, shape-shifting airport typology. The methodological framework is structured as a six-stage iterative workflow (Figure 1), aligning with contemporary parametric and simulation-based design paradigms in which architectural form is not predetermined but emerges from environmental data and multi-criteria optimisation.

Subsequently, (4) Form Development employs AI-assisted generative design techniques, such as AI generated concepts and parametric modelling, to produce multiple iterations of airport form configurations. These forms are informed by performance objectives, including aerodynamic efficiency, daylight optimization, and thermal regulation, reflecting the capacity of generative systems to explore complex design spaces and generate adaptive morphologies. The methodology advances into (5) Simulation and Optimization, where each iteration undergoes rigorous environmental evaluation using the simulation tool Ladybug, in this case. This stage integrates AI-assisted optimization loops, enabling continuous refinement of form based on performance feedback, a process that significantly improves energy efficiency and climate responsiveness in contemporary building design.

Finally, (6) Design Finalization synthesizes the optimized outputs into a cohesive architectural proposal, wherein the selected biomorphic form demonstrates enhanced climate resilience through reduced energy loads, improved environmental comfort, and adaptive spatial performance. The proposed workflow integrates generative artificial intelligence, parametric modeling, performance analysis, and visualization tools within a human–AI collaborative design framework. Generative AI platforms, including Midjourney, Adobe Firefly, and DALL·E, were employed during the early design stages to generate and refine conceptual morphological alternatives from text-based prompts and visual references. Selected AI-generated concepts were subsequently reconstructed and parameterized in Rhino 3D using Grasshopper to enable geometric control and iterative development. Ladybug was utilized to evaluate environmental responsiveness, while Kangaroo was employed for physics-based form finding under predefined constraints. ZBrush was used for digital sculpting and surface refinement, and Twinmotion and Lumion were used for visualization and photorealistic rendering. In this workflow, AI served as a design augmentation tool for ideation and exploration, whereas parametric and simulation-based tools were used for technical development and performance evaluation. No custom machine-learning models or training datasets were developed in this study. The resulting design embodies a shape-shifting architectural paradigm, where form is not static but evolves as a responsive system aligned with environmental forces. Overall, this methodology positions the airport as a dynamic, parametric and performance-driven ecological infrastructure, integrating AI, biomorphic logic, and climatic simulation into a unified research-driven design process aimed at achieving long-term sustainability and resilience.

4. Form Development and Spatial Planning

4.1. Concept Development

The concept design for the airport was developed through a biomorphic architectural approach, drawing inspiration from adaptive natural systems and shape-shifting geometries to generate a responsive and climate-resilient built form. The design concept integrates fractal patterns as a modern art form with adaptive architecture to create an airport form capable of responding to environmental fluctuations, particularly solar heat gain, prevailing winds, and changing climatic conditions. Through shape-shifting architectural strategies, the building envelope and roof morphology were conceived as dynamic, fluid forms that emulate organic structures, enabling passive environmental regulation while establishing a strong architectural identity (Figure 2).

In the form development stage, these biomorphic geometries were refined using parametric softwares and performance-driven design methods to optimize shading, enhance natural

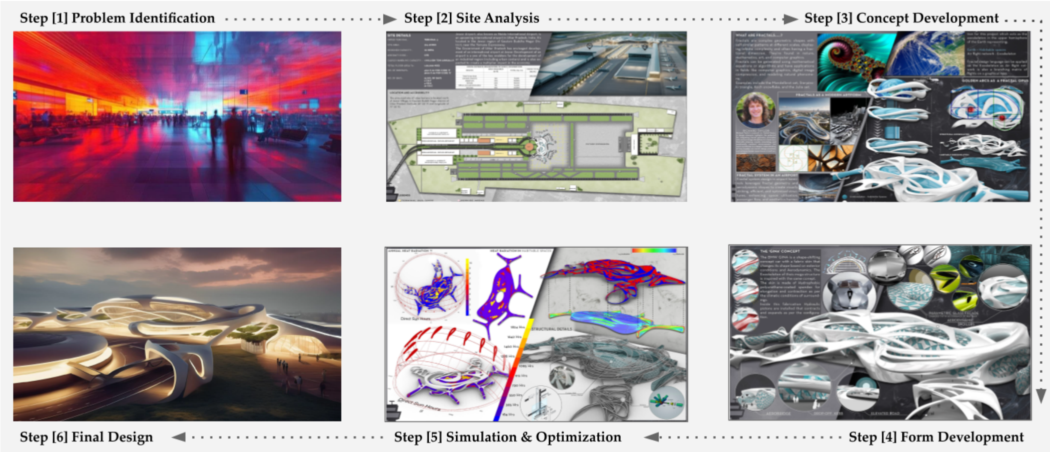

Figure 1: Simulation-based Biomorphic airport design workflow

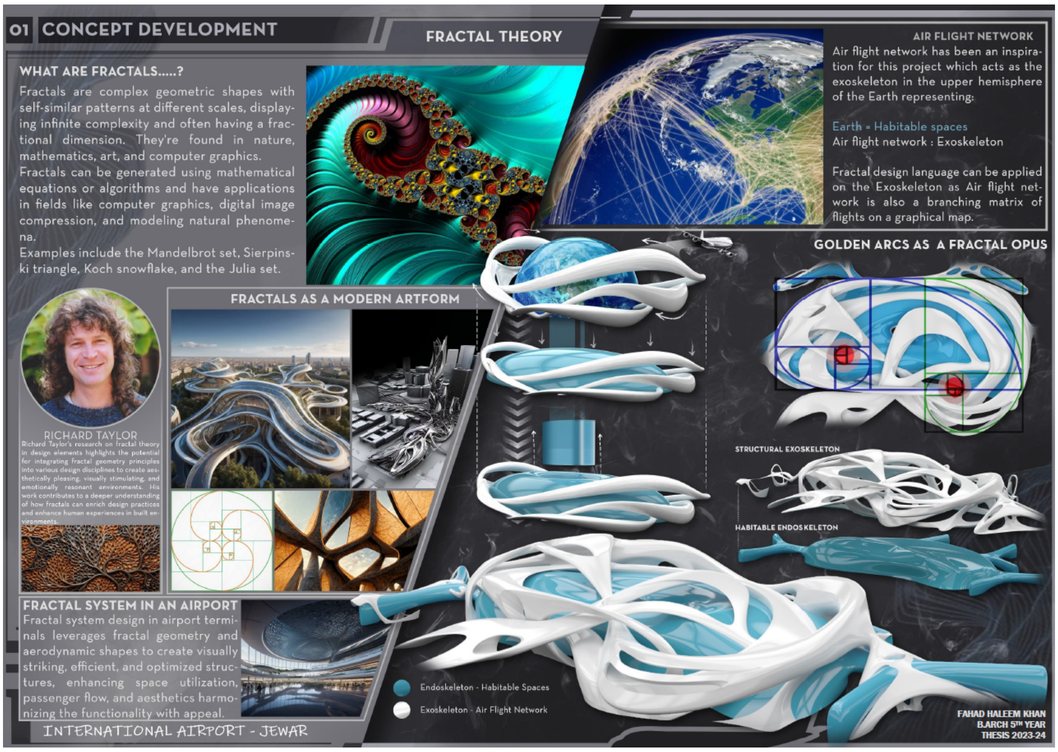

Figure 2: This illustration shows detailed conceptual planning for biomorphic form development, combining fractal geometry with an air-flight network as its exoskeleton. Source: Authors' Work

ventilation, and reduce heat impact through self-shading surfaces, and climate-responsive façade articulation. The resulting form was not only expressive but also functional as a bioclimatic mediator, reinforcing climatic resilience through enhanced environmental responsiveness. Spatial planning was guided by both operational efficiency and environmental responsiveness, organizing passenger circulation, terminal functions, and transitional spaces in a manner that supports comfort, adaptability, and passive cooling. Buffer zones, shaded concourses, and naturally ventilated public spaces were strategically integrated within the spatial framework to strengthen microclimatic performance while supporting the dynamic requirements of airport operations. Together, the concept design, form development, and spatial planning establish a resilient airport prototype where biomorphic and shape-shifting architecture operate as both formal and environmental strategies. Fractal geometry, the Fibonacci sequence, and GINA-inspired principles were selected as they represent well-established nature-inspired design approaches that support hierarchical organization, spatial efficiency, and biomorphic form generation. Fractal geometries provide self-similar patterns that can facilitate scalable spatial organization, while

Fibonacci-based proportions contribute to balanced spatial relationships observed in natural systems. These principles were employed as design generators rather than purely aesthetic references. Their application was limited to architectural components that can benefit from environmental adaptation, including roof canopies, façade systems, shading devices, circulation spaces, and landscape integration. Critical operational spaces such as runways, aircraft taxiways, boarding gates, and air traffic control infrastructure retained conventional geometries to comply with functional and operational requirements. The objective was to integrate nature-inspired forms where environmental responsiveness and passenger experience could be improved without compromising airport operations.

4.2. Site Context and Climatic Considerations

The proposed design was developed for a site located at Jewar International Airport, Noida, Uttar Pradesh, India. The site was a proposed site by the government for an International Airport and was selected due to its strategic significance as a rapidly developing international aviation hub and its challenging climatic conditions, which provide an appropriate context for evaluating computational and AI-assisted design methodologies. The region is characterized by a composite climate, experiencing extremely hot summers (often exceeding 40°C), a monsoon season with significant rainfall, cool winters, and high annual solar exposure. These climatic factors influenced key design decisions, including building orientation, shading strategies, solar exposure control, and form development. Site-responsive performance evaluations were conducted using Ladybug environmental analysis, while Kangaroo simulations were employed to investigate physics-based form-finding strategies under predefined constraints. Weather data (EPW) corresponding to the Noida/Jewar region were imported into Ladybug to evaluate solar radiation, sun-path behavior, and environmental responsiveness under local climatic conditions. The proposed workflow demonstrates how AI-assisted conceptual generation, parametric modeling, and performance-driven simulations can be integrated to develop feasible architectural solutions that respond to local environmental conditions and operational requirements associated with airport infrastructure.

4.3. Spatial Planning

The development of detailed floor plans, structural systems, and material specifications was guided by an integrated approach combining operational functionality, climatic responsiveness, and structural efficiency. The floor plans were organized through spatial zoning, ensuring efficient passenger circulation, clear segregation of functional programs, and seamless integration of terminal operations, public amenities, and service infrastructure. Spatial layouts were developed to optimize wayfinding, adaptability, and environmental comfort, while incorporating passive design strategies such as shaded transitional spaces, naturally ventilated zones, and thermally buffered areas.

The structural system evolved in response to the biomorphic and shape-shifting architectural form, utilizing long-span, lightweight, and adaptive structural solutions capable of supporting complex geometries while maintaining flexibility and resilience. Structural articulation was conceived to complement the dynamic envelope performance, integrating considerations of load distribution, environmental forces, and future adaptability. The resulting design approach establishes a cohesive relationship between form, structure, and performance, ensuring that the airport infrastructure remains adaptable, resource-efficient, and resilient under evolving climatic and operational requirements. The figure 3 illustrates the integrated spatial planning strategy and floor plate zoning logic of the main airport terminal, developed through a mathematically informed concept based on Fibonacci fractal order to achieve hierarchical organization, spatial efficiency, and environmental responsiveness. The planning approach is moved from conventional linear terminal layouts by adopting a non-linear, biomorphic spatial configuration, where circulation, programmatic distribution, and volumetric articulation are derived from recursive geometric principles observed in natural growth patterns.

At the macro scale, the terminal layout is structured using the Fibonacci sequence $(1, 1, 2, 3, 5, 8, \dots)$ as a generative framework to define proportional relationships between major functional zones, including departures, arrivals, security processing, retail concourses, and boarding gates. This proportional logic ensures a gradual expansion of spatial volumes, enabling the efficient distribution of passenger flow while minimizing congestion points. The fractal-based zoning further introduces a self-similar hierarchy, where each spatial cluster, ranging from primary halls to secondary waiting lounges, reflects scaled iterations of the overall organizational geometry, thereby enhancing spatial legibility and intuitive wayfinding. While at the micro scale, floor plate zoning is articulated through nested fractal modules, where circulation corridors, service cores, and transitional spaces are embedded within progressively scaled geometric subdivisions. This results in a multi-scalar spatial network that accommodates fluctuating passenger densities while maintaining operational clarity. The zoning strategy also integrates adaptive flexibility, allowing certain modules to expand or contract in response to real-time functional demands, aligning with the broader concept of shape-shifting architecture.

From an environmental performance perspective, the Fibonacci-driven geometry contributes to optimized daylight penetration, natural ventilation pathways, and thermal zoning. The spiraling and radiating spatial configurations facilitate controlled solar exposure and enhance cross-ventilation by aligning openings and voids with prevailing wind directions. Additionally, the fractal organization enables the strategic placement of semi-conditioned buffer zones, which act as

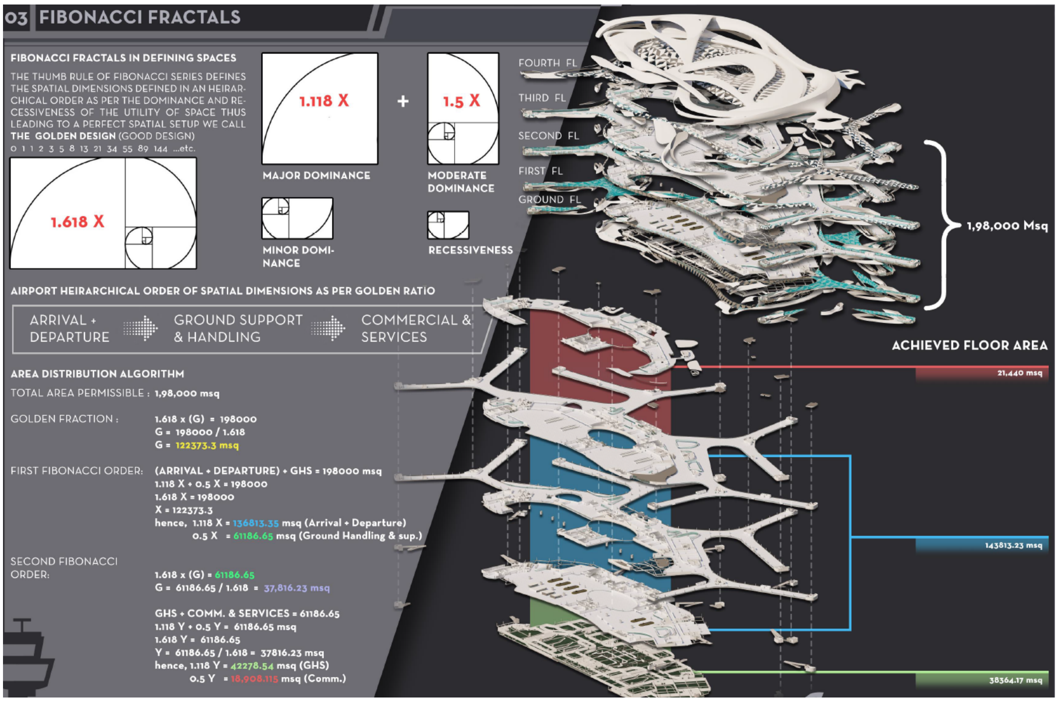

Figure 3: The figure exhibits Spatial Planning and Floor Plate Zoning of the main airport building, along with Fibonacci fractal order concept in spatial dimensions. Source: Authors' Work

transitional climatic layers, enhancing shading effectiveness across the building envelope. Furthermore, the spatial planning incorporates programmatic stratification across vertical levels, where each floor plate corresponds to distinct operational functions while maintaining visual and spatial continuity through atria and interconnected voids. These voids, also governed by fractal scaling, serve as environmental moderators and orientation anchors, reinforcing both climatic performance and user experience.

This approach exhibits how the application of the Fibonacci fractal concept in spatial planning transcends formal aesthetics, functioning as a computational and performative tool that contributes to circulation efficiency, spatial adaptability, and environmental resilience. The resulting airport terminal emerges as a coherent, self-organizing system in which mathematical order, biomorphic inspiration, and functional zoning converge to produce a highly adaptive and climate-responsive architectural infrastructure.

Additionally, material selection within the proposed airport design (as discussed in figure 4) was guided by a multi-criteria performance framework that prioritized sustainability, thermal efficiency, durability, and climate responsiveness. The specification process emphasized the integration of low-carbon and recycled materials, such as supplementary cementitious concrete, engineered timber composites, and high-recycled-content steel, to minimize embodied carbon while maintaining structural integrity. The building envelope was developed as a high-performance facade system, incorporating double-skin assemblies, spectrally selective glazing, and advanced insulation layers to regulate heat transfer and optimize indoor environmental quality. In parallel, solar-responsive skins, including kinetic shading devices and parametrically optimized louvres, were employed to dynamically modulate solar gain, glare, and daylight penetration based on diurnal and seasonal variations. Material choices were further calibrated to climatic conditions, ensuring resistance to thermal stress, dust accumulation, and long-term weathering, while also leveraging regionally sourced materials to reduce transportation impacts and support contextual integration.

Collectively, the alignment of materiality with spatial planning enabled the translation of conceptual biomorphic and climate-responsive strategies into a technically robust and operationally viable architectural solution. The coordinated approach ensured that material systems were not applied superficially but functioned as active environmental mediators, contributing to passive cooling, energy efficiency, and occupant comfort. Structural components were synchronized with the facade and envelope systems to contribute to thermal bridging, air tightness, and load distribution under dynamic environmental conditions. This integrative methodology reinforces an airport's capacity for long-term resilience, supporting energy-conscious design decisions while accommodating future adaptability. Ultimately, the convergence of planning, structure, and material specification established a holistic design ecosystem, where material decisions substantively supported the overarching objective of delivering a climate-responsive, sustainable airport infrastructure.

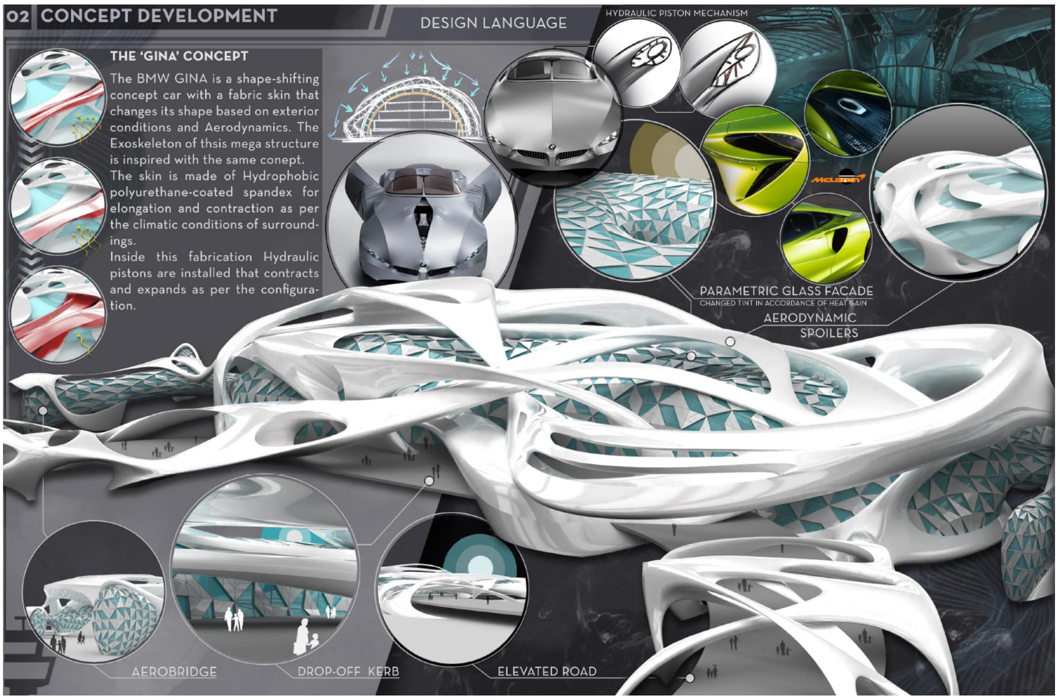

Figure 4: The figure illustrates the final derived from post-concept development, along with details of the aerobridge, drop-off zone, road elevation, and parametric glass facades. Source: Authors' Work

Similarly, the elevations and sections of the airport (see Figure 5 and 6) were developed to articulate the biomorphic and shape-shifting architectural language while maintaining strong environmental responsiveness, structural efficiency, and functional integration. The elevations express the fluidity and organic character of the design through adaptive facade systems, responsive skins, and self-shading envelope configurations derived from biomorphic design principles, which were incorporated to minimize solar heat gain, regulate daylight penetration, and enhance the building's climatic performance.

Variations in facade articulation, layered screening elements, and aerodynamic surface modulation contribute not only to the visual identity of the terminal but also function as passive environmental control mechanisms responding to sun paths, wind patterns, and thermal loads. The sectional development further illustrates the spatial and environmental concept of the design, revealing the integration of dynamic roof morphologies with terminal circulation, structural systems, and passive cooling strategies.

Through the sections, spatial layering is demonstrated via atria, shaded transitional zones, thermal buffer spaces, and vertically connected public concourses that support natural ventilation, stack effect cooling, and optimized daylight distribution. The relationship between the biomorphic roof geometry and long-span structural systems is also expressed in section, showing how the architectural form supports large, unobstructed terminal spaces while accommodating environmental control and operational requirements. Together, the elevations and sections communicate the synthesis of form, structure, and climatic resilience, reinforcing the airport as a coherent adaptive system where architectural expression and environmental responsiveness are intrinsically linked.

4.4. Design for Climatic Resilience

Following the development of the airport design, its climatic resilience and thermal performance were evaluated using environmental simulation software to examine the potential influence of biomorphic form and shape-shifting architectural strategies. Performance simulations and heatmap analyses were conducted under annual climatic conditions to assess solar exposure, heat radiation, and surface temperature distribution throughout the year.

The resulting heatmaps (Figure 7) provided a visual and quantitative representation of how the biomorphic geometry, self-shading envelope, and adaptive form may contribute to reducing thermal stress across the building and its surrounding microclimate. The simulation outcomes suggest that the integration of organic form modulation, and shape-shifting architectural elements has the potential to reduce heat accumulation, lower solar heat gain, and enhance thermal comfort relative to more conventional airport design approaches. These findings indicate that biomorphic and adaptive design strategies may support climatic resilience and highlight the value of environmentally informed form generation in reducing heat impacts while contributing to more sustainable and resilient airport infrastructure.

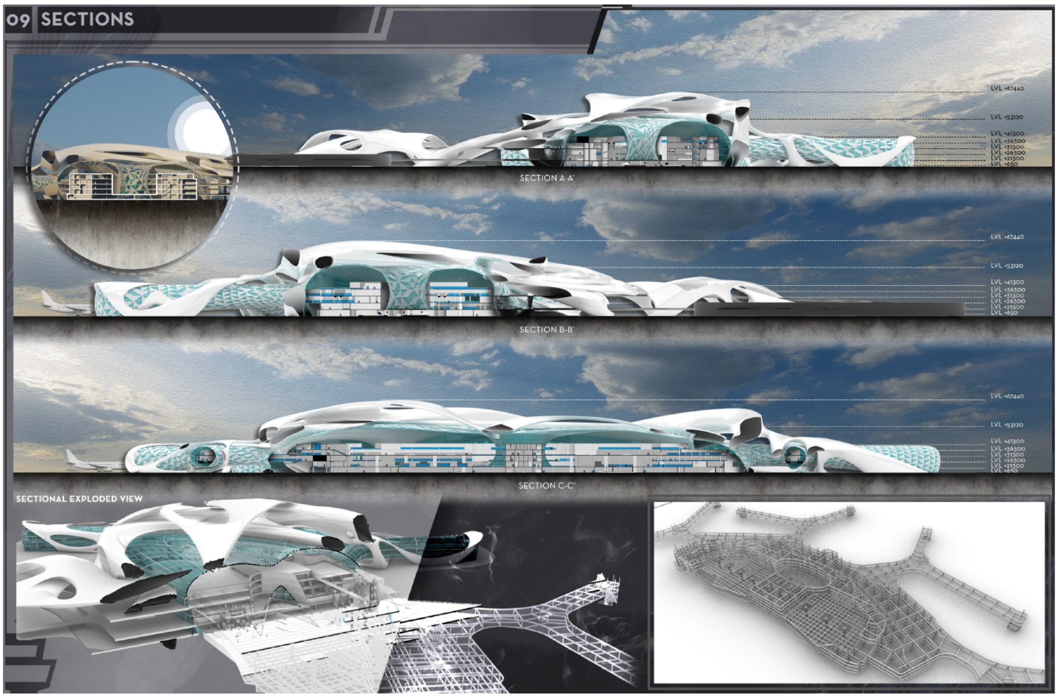

Figure 5: Detailed sections and structural design details. Source: Authors' Work

Figure 6: Elevations of the Building-Block from all perspectives (Front, Rear, Right, and Left). Source: Authors' Work

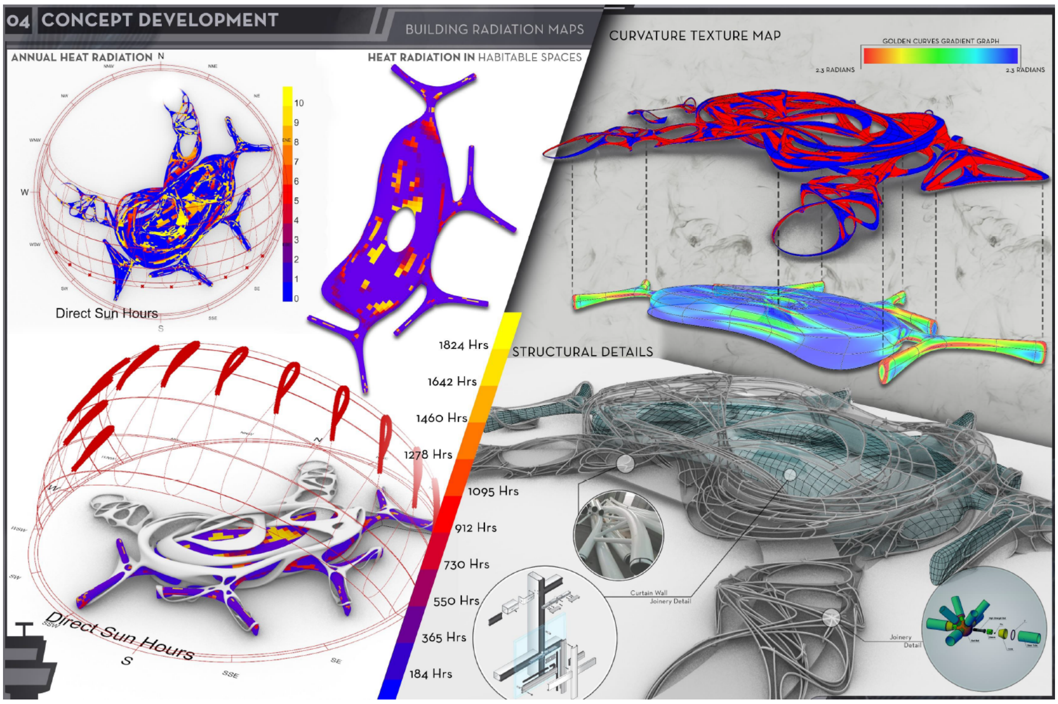

Figure 7: Heat Maps and Radiation Map generated through Ladybug Simulation. Source: Authors' Analysis

5. Conclusions

This study proposes a framework for exploring climate-responsive airport architecture by integrating biomorphic design principles, adaptive architectural strategies, and generative AI tools. Using Jewar International Airport, Noida, India, as a case study, the workflow combined AI-assisted conceptual generation with parametric modeling, environmental analysis, and physics-based form finding to investigate nature-inspired design alternatives that respond to site-specific climatic conditions. The findings demonstrate the potential of integrating AI-assisted design approaches with computational tools to support the development of climate-responsive and environmentally informed airport concepts. However, this study does not claim quantified improvements in thermal efficiency, energy consumption, carbon reduction, or operational performance, as these parameters were not directly measured or comparatively validated within the scope of this research. Therefore, the proposed framework should be interpreted as an exploratory design methodology rather than a validated environmental optimization model.

The study contributes to Sustainable Development Goal 9 (SDG-9) by illustrating how AI-assisted conceptual generation, biomorphic principles, and climate-responsive design strategies may support innovative approaches to infrastructure development. Furthermore, the proposed workflow demonstrates a human–AI collaborative process that can assist designers in integrating environmental considerations during the early stages of airport planning. The implementation of such methodologies may require interdisciplinary collaboration, technical expertise, and additional resources, particularly when integrating multiple digital platforms within a unified design process. Consequently, practical implementation should be accompanied by detailed environmental assessments, engineering evaluations, and operational analyses specific to the project context. However, this study also has several limitations that must be acknowledged. First, the study primarily focused on conceptual design development and qualitative environmental assessment rather than quantitative performance validation. Second, comparative analyses with conventional airport typologies were not conducted. Third, metrics such as thermal comfort, land surface temperature reduction, annual energy consumption, and long-term operational efficiency were not evaluated. These aspects represent important opportunities for future research.

Future studies should incorporate comparative baseline models, detailed environmental simulations, and quantitative assessments of thermal comfort, solar exposure, energy consumption, and carbon reduction to validate the effectiveness of the proposed approach. In addition, future research may explore the integration of renewable energy systems, smart materials, and cost-effective adaptive technologies to further strengthen climate-responsive airport design. Such investigations could contribute to the development of evidence-based planning frameworks that support sustainable and resilient infrastructure development in response to evolving environmental challenges.

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Conflicts of Interest

The authors declare no conflict of interest.

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