Tree-Inspired Structure in Architecture: Overview and Comparative Case Studies

Nevine G. Gado[1]

[1]Architectural Engineering Department, Faculty of Engineering, Modern academy for engineering and technology, Cairo, Egypt

*Corresponding author: First A. Author (nevine_gado@hotmail.com).

Abstract

This paper investigates the design and implementation of tree-inspired structural systems in architecture, a design approach that merges functionality, aesthetics, and a connection to nature. It emphasizes the harmonious interplay between structure and architecture, moving beyond purely structural dominance or disregard for limitations.

The core concept, the Tree-Shaped Structural System, draws inspiration from nature's efficiency and resilience. By mimicking branching systems and organic forms, these structures offer unique advantages. They can enhance natural light penetration, potentially reduce material usage, and foster a sense of place.

By examining and through the analysis of historical and contemporary case studies, including the Cambridge Central Mosque, Nine Bridges Golf Club Clubhouse, and Hulunbuir Hailar Airport, the research explores the structural, aesthetic, and functional attributes of these systems. Case studies were chosen for their innovative use of tree-inspired concepts and their representation of various building types.

This research aims to understand design principles, the structural performance, aesthetic implications, and functional characteristics of these systems in architecture. Employing a comparative analysis methodology, the study explores the relationship between tree-inspired design concepts and their impact on building performance.

Findings demonstrate the potential of tree-inspired structures to enhance natural lighting, optimize material use, and create visually appealing spaces. However, challenges related to structural complexity and integration with existing building infrastructure warrant further exploration. This research contributes to understanding the potential of tree-inspired architecture in creating sustainable and inspiring built environments.

Keywords

Tree inspired structures; Branching structures; Tree-like column; Nature-Inspired Design; Dendriform.

1. Introduction

The intricate forms and remarkable functionality of trees have long captivated human imagination. Their complex, fractal-like structures exhibit exceptional strength and efficiency, inspiring architects to emulate their form in building design. This paper aims to investigate the design principles, structural performance, and aesthetic implications of tree-inspired structural systems, often referred to as "dendriform" architecture.

Throughout examining history, humanity has been mesmerized by the intricate forms and remarkable functionality of trees. These complex, fractal-like shapes not only serve essential biological functions but also exhibit exceptional strength and efficiency. This inherent connection between form and structure has captivated architects for centuries, leading to the development of tree-inspired structure systems called " Tree-inspired (Dendriform)" architectural designs that emulate the branching patterns of trees [1]. The adoption of tree-like forms in buildings has evolved alongside advancements in technology and our understanding of engineering principles. This paper delves into this fascinating interplay through a two-part framework.

The first section provides a comprehensive introduction to Tree-inspired structure systems, exploring their branching concept, highlighting the key historical timeline. Further, introducing the structure idea, Benefits and Efficiency and different material properties that influence the design and application of tree-inspired structure systems.

The second part of the framework focuses on practical applications and potential limitations, by analyzing different contemporary international buildings that incorporate tree-inspired design principles. By the building general information, background, design, and structure concepts approach. Then highlighted how these projects integrate different functions, Aesthetics, materials used and the building sustainability impact within dendriform structures. Case studies, including the Cambridge Central Mosque, Nine Bridges Golf Club Clubhouse, and Hulunbuir Hailar Airport, seeks to understand the relationship between tree-inspired design concepts and their impact on building performance.

In conclusion, this research employed a comparative analysis methodology to investigate the design principles, structural performance, and aesthetic implications of tree-inspired structural systems. By examining case studies, the study identified key characteristics and challenges associated with the implementation of such systems. The findings contribute to a deeper understanding of the potential and limitations of tree-inspired architecture, providing valuable insights for future design and research endeavors.

2. Tree-inspired structures (Dendriform) Systems: Overview

The utilization of bionic patterns is a well-established method. Tree-inspired geometries, a subset of bionic forms, are commonly integrated into modular structures to optimize design for maximum strength and minimal weight. [2]. A rapidly increase in the usage of This innovative approach in both the 20th and 21st century offers numerous advantages in terms of flexibility, efficiency, and sustainability. [3]

Nowadays, tree systems with their ability to elegantly conquer large, open spaces while their branching mimics nature, offering exceptional flexibility and adaptability. This allows architects to push the boundaries of expansive structures as the key to this success lies in the system's efficient load distribution. The branching geometry naturally channels forces throughout the structure, eliminating the need for overly massive support beams, making it an ideal solution for vast, open areas, see Fig.1.

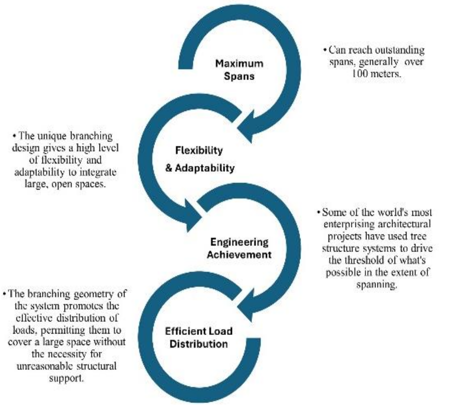

Figure 1. The Advantages of Tree-inspired (dendriform) Structures in Modern Architecture. Source Author

2.1 Tree-inspired Structure Systems: History

There is no denying the presence of tree-like structures throughout architectural history, but the true origins of dendriforms remain a contentious topic. Some point to the Prehistoric Era, the prehistoric cave paintings as evidence of an innate human fascination with branching forms. However, some argue that the early use of dendriform elements in architecture, like those seen in medieval arches and vaults, might not be a conscious emulation of trees. These structures could simply be a product of the available construction techniques at the time. The history of the structural system represented in sequence as shown in Fig 2: [4,5,6,7].

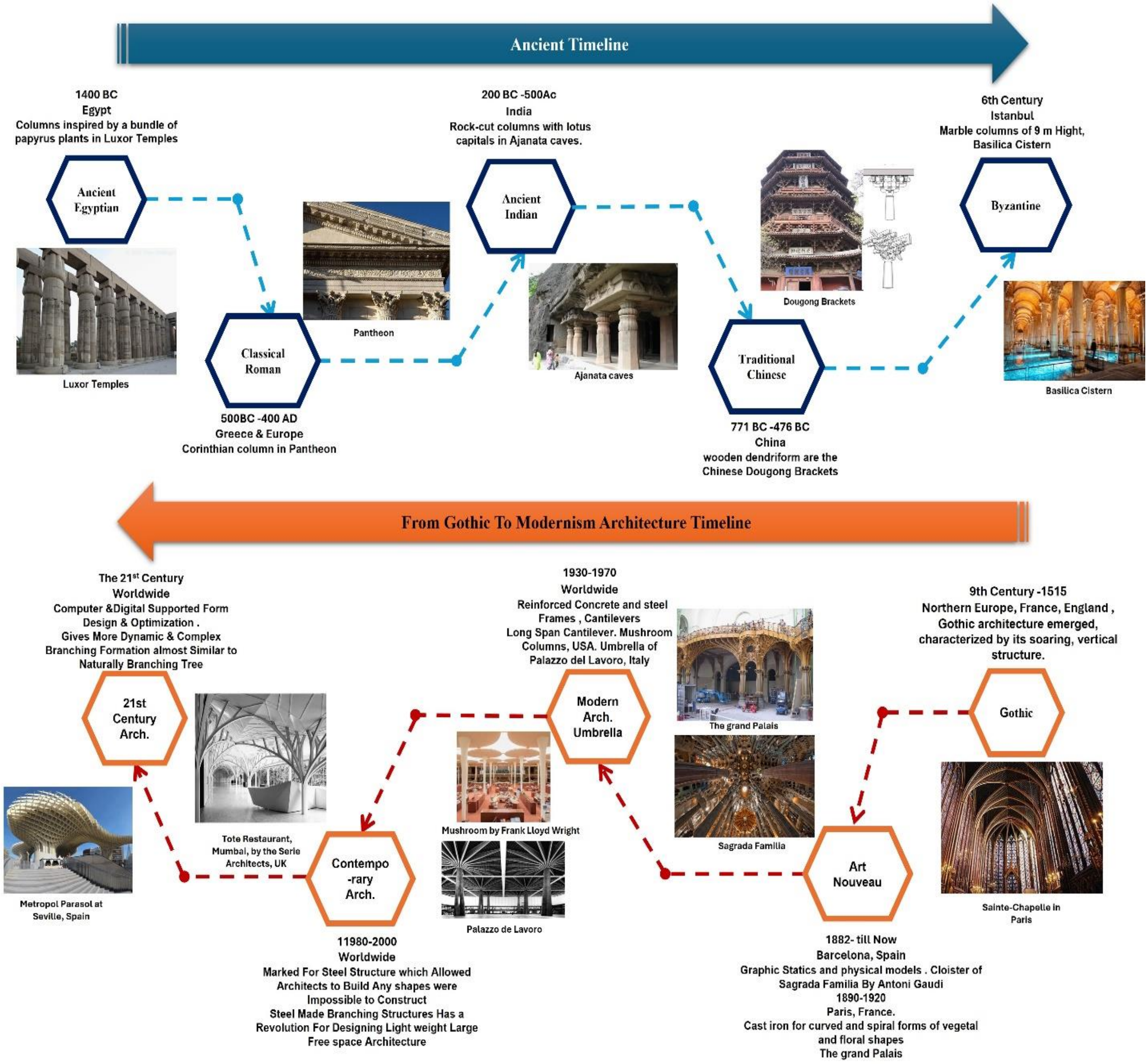

Figure 2. The Timeline for Tree – inspired Structure System. Source Author

2.2. Tree Structure Systems: Branching Concept

The template is used to format your where all margins, Tree structure systems, inspired by the natural world, utilize elements that mimic the branching structure of trees, Fig 3. These systems feature a central column, akin to a tree trunk, which rises from the ground and branches out towards the top to provide support for a larger area. This branching design offers a unique and efficient method for transferring loads and can be employed in various architectural applications. This biomimicry approach aims to create strong, aesthetically pleasing, and resource-efficient structures, which align with sustainable architecture principles.

Tree-like columns can be classified based on their position within the structure, Fig 4. The initial branches sprout directly from the main trunk, like shoots. These branches then give rise to secondary branches. The level of a branch. Similarly, the joints where branches originate from the main column are categorized based on their level (e.g., first-branching joint). Notably, the simplest form of a tree-like column has two branches sprouting from the main trunk. [8]

The structure efficiently transfers loads from a wide area down to a single column or point. Dividing the supports into smaller members creates an ideal load path system. This not only reduces the length of each member, minimizing the risk of buckling but also allows the structure to efficiently manage a large surface area.[9]

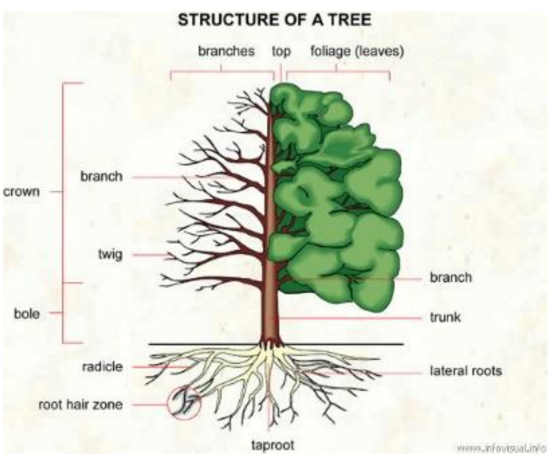

Figure 3. Tree plant Structure. Source: "Yang, Guangyu, and Pirjo Jaakkola. "Wood chemistry and isolation of extractives from wood." Literature study for BIOTULI project-saimaa university of applied sciences 10 (2011): 22 "

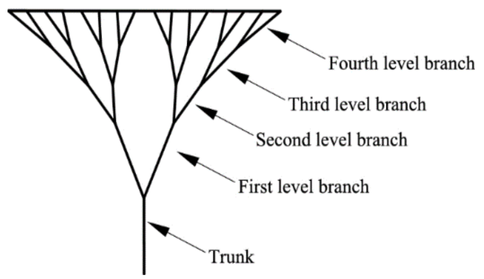

Figure 4 The Tree-inspired structure elements. . Source: "Khamees, Ali Abdulmohsin, and Khalid K. Shadhan. "Experimental study on structural behaviour of branching steel columns." In IOP Conference Series: Materials Science and Engineering, vol. 888, no. 1, p. 012044. IOP Publishing, 2020."

Computers have become invaluable tools for recreating the branching forms seen in natural trees. In addition, the IFS (Iterated Function System), and L-Systems offer another algorithmic approach.

Developed in 1968 by Hungarian biologist Aristid Lindenmayer, L-Systems are a type of algorithmic digital generator based on parallel rewriting systems, a form of formal grammar. This system excels at producing natural-looking fractals. L-Systems can effectively replicate the dynamic growth patterns of plants, Fig. 5a, allowing architects to translate these processes into architectural design.[10]

The Tote Restaurant in Mumbai, designed by Serie Architects and built in 2009, exemplifies the use of L-Systems for architectural form development, Fig. 5b. As a reflection of the surrounding green spaces, the architects envisioned a continuation of tree-like branching structures within the restaurant.[11]

Components and Classification: Fig. 6(a, b, c)

- Foundation: Anchors the structure to the ground [12]
- Primary Structure: The main vertical support, like a tree trunk
- Secondary Structure: The branching system that extends from the primary structure to support the widest area.

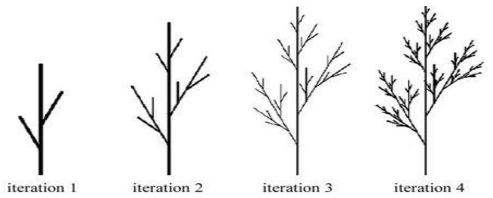

Figure 5 a Fractal generation (plant growth) using L-System Source: “Gawell, Ewelina. "Non-Euclidean geometry in the modeling of contemporary architectural forms." Journal Biuletyn of Polish Society for Geometry and Engineering Graphics 24 (2013): 35-43”.

Figure 5 b The Tote Restaurant, Mumbai, designed by the Serie Architects, UK. Source: “Gawell, Ewelina. "Non-Euclidean geometry in the modeling of contemporary architectural forms." Journal Biuletyn of Polish Society for Geometry and Engineering Graphics 24 (2013): 35-43”.

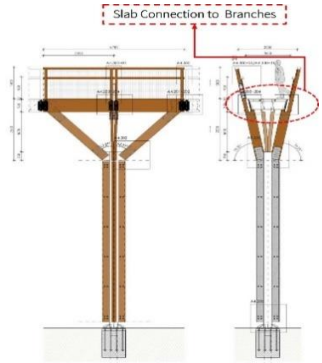

Figure 6 a Branching Connection for Timber trunk and foundation connections. . Source: “https://www.archdaily.com/946011/treetop-walk-carlos-castanheira?ad_medium=gallery”

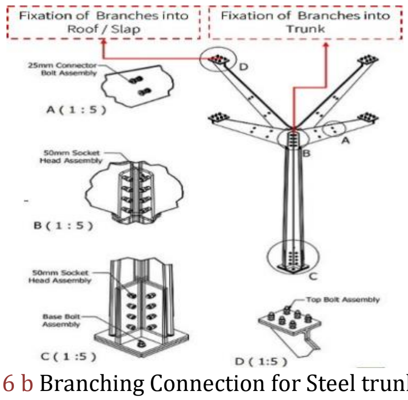

Figure 6 b Branching Connection for Steel trunk and foundation connections. Source: https://www.facit-homes.com/post/branching-out

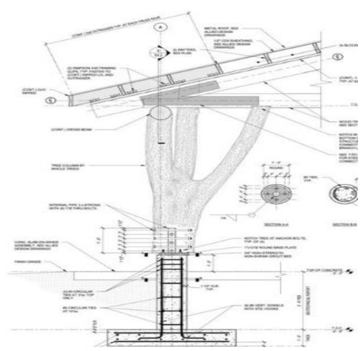

Figure 6 c Branching Connection for Concrete trunk and foundation connections. Source: https://wholetrees.com/portfolio-item/hitchcock-nature-center/

Benefits and Efficiency:

- Large Spans: The structure spreads out from one point to several branches, allowing it to support a large surface area.[13]
- Structural Efficiency: Loads are efficiently transferred from a larger surface to a single column or point, reducing the need for bulky support elements.
- Reduced Member Size: By dividing the structure into branches, the spans of roof members are reduced, enabling the use of smaller structural members.
- Shorter Buckling Length: The reduced member length minimizes the buckling length, improving stability.
- Ideal Load Path: The division of members creates an ideal system for distributing loads throughout the structure.

2.3 Tree Structure Systems: Used Material

The optimal material selection for your tree structure system hinges on several key factors. Understanding these factors and the properties of various materials is crucial for making informed decisions.

Some of such Key Considerations:

- Load Capacity: The structure must withstand anticipated loads. Steel excels in this area due to its high strength-to-weight ratio, making it ideal for large-scale projects with significant weight requirements.
- Durability: The structure needs to resist environmental factors and wear and tear. Precast concrete elements offer excellent fire resistance and durability [14].
- Elasticity: This refers to a material's ability to deform under load and then return to its original shape when the

load is removed. Timber has good elasticity, making it suitable for structures that experience dynamic loads (e.g., wind). However, excessive elasticity can lead to vibrations. Steel, on the other hand, has lower elasticity, making it stiffer and more suitable for structures requiring high stability. [15,16]

3 Tree- inspired structure case studies

For a comprehensive understanding of tree-inspired structures, case studies can be analyzed through several key criteria:

- First, the case study background should detail the project's purpose, location, and any specific design challenges.
- Next, the design concept should be explored, examining how the chosen tree species and its features inform the overall form and functionality.
- Structural analysis is then crucial, investigating how the tree-like form translates into efficient load bearing and stability. This analysis would delve into the chosen structural system, such as branching columns or tension members.
- Finally, element design, Functionality and material selection come into play. Here, the focus is on how individual components like beams, connections, and cladding are designed to achieve the desired aesthetics and structural performance, considering the use of sustainable or bio-inspired materials. By examining these criteria through case studies, we gain valuable insights into the potential and intricacies of tree-inspired architectural design.

3.1 Case 1: Cambridge Central Mosque to be "place of tranquility." [17,18,10,20]

Function:	Religious
Project Location	Cambridge, UK
Accomplished at	Sept. 2011 - April 2019
Building Area:	2340 sqm
Design Team:	Price & Myers (construction) Jacobs (planning), Blumer Lehman
Designers:	Marks Barfield Architects
Client:	The Cambridge Mosque Trust

The Cambridge Central Mosque, designed by Marks Barfield Architects, is the first eco-friendly mosque in Europe. The design draws inspiration from both Islamic and English architectural traditions, Fig.7. It incorporates sustainable design principles and local architectural features. The mosque replaced an older building that became too small for the congregation. The aim was to create a building that feels like a natural part of the British landscape while still maintaining a distinct Islamic identity.

Figure 7 Tree-like pillars form the structure of the Cambridge Central Mosque. Above: the design was based on the idea of a "calm oasis). Source: https://www.dezeen.com/2021/01/20/cambridge-central-mosque-marks-barfield-architects/

Design concept:

The design revolves around the idea of the central theme is a "calm oasis of contemplation" inspired by the Islamic concept of the garden of paradise. within a grove of trees. This is reflected in the use of tree-like pillars made from timber. These pillars join to form an interwoven octagonal canopy that supports the roof. The exterior walls are clad in brick and topped with a parapet, symbolizing the meeting of heaven and earth. Visitors enter through a series of spaces gardens, a cafe, an Islamic Garden, a covered walkway, and a vestibule designed to gradually transition them from the outside world to a more reflective state. The building incorporates elements from both Islamic and British architecture, such as geometric patterns, a qibla wall with a mihrab and minbar, and a castellated parapet.

Structure System Analysis

The structure is a unique combination of modern and traditional elements. The defining feature of the mosque is tree-inspired system made from sustainable spruce timber that supports the roof, while the surrounding walls are constructed from cross-laminated timber (CLT) clad in masonry tiles.

These "trees" are made from sustainably sourced spruce and are joined together to form an interwoven octagonal canopy. The design prioritizes natural light and ventilation through strategically placed roof lights and a building form that reduces energy consumption. This structure is both visually striking and symbolic of the natural world, provides structural support and carries symbolic weight. These "trees" represent growth, stability, and a connection to the divine, reinforcing the mosque's spiritual purpose, Fig. 8,9.

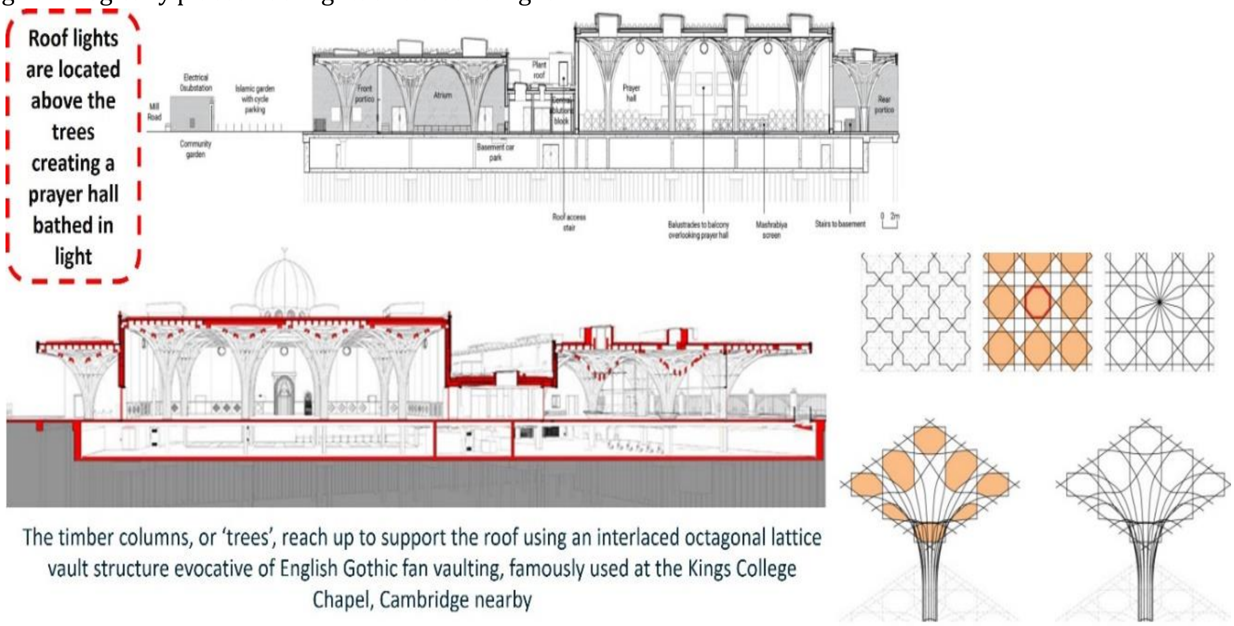

Figure 8 Tree-like pillars that join to form an interwoven, octagonal canopy that holds up its roof. Source: "https://www.dezeen.com/2021/01/20/cambridge-central-mosque-marks-barfield-architects."

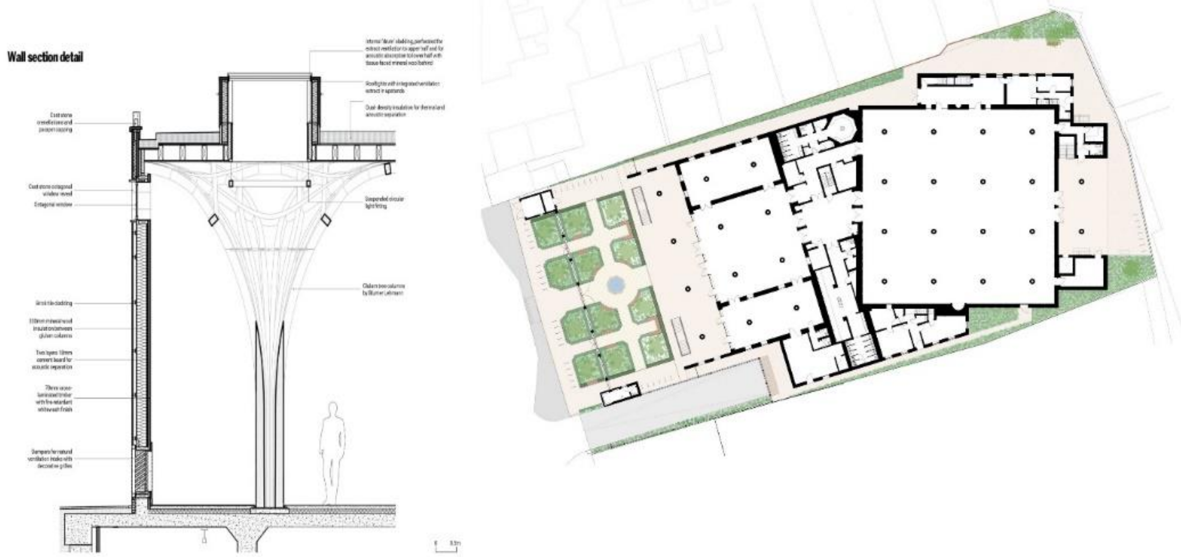

Figure 9 Wall section Details and Ground Floor plan. Source: "https://www.dezeen.com/2021/01/20/cambridge-central-mosque-marks-barfield-architects."

Element Design

A key design element is the tree-inspired system made from timber that contribute to its overall aesthetic and functionality: These design elements that Geometric patterns not only provide structural support but also create a sense of visual identity for the mosque. The geometric patterns incorporated throughout the building, represent a core principle of Islamic art, and symbolize a connection to the divine including the Kufic calligraphy on the brick facade, reflect Islamic artistic traditions, Fig. 10.

- Roof: Bi-directional single-layer reticulated shells (aluminum plates)
- Columns: Integrated with the roof and ceiling for a continuous space
- Curtain Wall: Shaped keels
- Roofing: TPO material

Functionality and Aesthetics:

The tree structure is not just symbolic; it is visually striking. The natural beauty of the timber complements the geometric patterns and calligraphy, creating a harmonious and inspiring space. The open canopy allows for ample natural light to filter through, further enhancing the feeling of tranquility.

Material Used:

- Timber: The primary building material due to its low carbon footprint and renewable nature, Fig12.
- Cross-laminated timber (CLT): Used for the structural walls surrounding the tree structure.
- Masonry tiles: Cladding the exterior walls, Fig.10.
- Glass roof lights: Maximize natural light throughout the building, reducing reliance on artificial lighting.

Sustainability Impacts:

- The design prioritizes environmental sustainability:
  - Natural lighting: Achieved through extensive use of roof lights, minimizing the need for artificial light.
  - Low-carbon materials: Timber construction and minimal use of energy-intensive materials, Fig.11,12.
  - Renewable energy: Solar panels contribute to the building's energy needs.
  - Water conservation: Rainwater harvesting for irrigation and toilet flushing.
- The potential for incorporating sustainable and local construction techniques exists.
- The use of natural light through extensive glass facades can reduce reliance on artificial lighting.

In conclusion, design demonstrates an innovative approach and the tree structure in the Cambridge Mosque design goes beyond mere functionality. It serves as a powerful aesthetic element, a symbol of faith and nature, and a key contributor to achieving the overall design concept of a peaceful and inspiring space for the community. The use of natural materials, sustainable practices, and symbolic elements creates a haven of tranquility for the Muslim community.

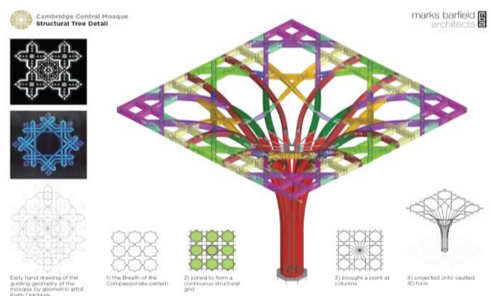

Figure 10. Structure Tree details. Source: https://www.architecture.com/awards-and-competitions-landing-page/awards/riba-regional-awards/riba-east-award-winners/2021/cambridge-central-mosque#

Figure 11. Marks Barfield Architects used cross-laminated timber as the main material. Source: https://www.dezeen.com/2021/01/20/cambridge-central-mosque-marks-barfield-architects:

Figure 12 Prayer Hall structure features digitally fabricated tree timber columns supporting the roof structure. Source: “https://www.dezeen.com/2021/01/20/cambridge-central-mosque-marks-barfield-architects.”

3.2. Case 2: Nine Bridges Golf Club Clubhouse. [21,22,23,24]

Function:	Sport center
Project Location	Yeoju-Gun, South Korea
Accomplished at:	2010
Building Area:	20977 sqm
Design Team:	Kyeong-Sik Yoon / KACI International + Shigeru Ban Architects
Designers:	Shigeru Ban Architects
Client:	City of Yeoju

Designed by Shigeru Ban Architects known for their innovative use of traditional materials., the Nine Bridges Golf Club Clubhouse in South Korea draws inspiration from the natural world serves a golf course with a main building, VIP facilities, and private suites, Fig. 13. Completed in 2010, the 16,000 sqm facility with an underground level and three floors above ground.

Figure 13 Haesley Nine Bridges Golf Clubhouse. Source: “https://shigerubanarchitects.com/works/cultural/haesley-nine-bridges-golf-clubhouse/”

Design concept:

Inspired by a traditional Korean summer pillow ("bamboo"), the design features a hexagonal grid that allows for natural light and ventilation. Glass curtain walls throughout the building, especially on the main facade, create a sense of openness and connection with the surrounding golf course. shell roof supported by tree-inspired structure system timber columns in the atrium. This creates a spacious and open atmosphere with natural light filtering through.

Structure System Analysis

The clubhouse utilizes a complex, independent timber structure. The roof and columns form a continuous unit, eliminating the need for separate beams and girders. The most prominent structural element is the hexagonal wooden grid roof structure. This structure is self-supporting and eliminates the need for separate beams and columns, Fig.14. The tree-like columns in the atrium are not the main load-bearing structure, Fig. 15. They are visually striking but function more as an aesthetic element complementing the overall design concept. Concrete columns at the basement level provide the primary support for the roof load. This innovative design required advanced digital modeling and prefabrication techniques.

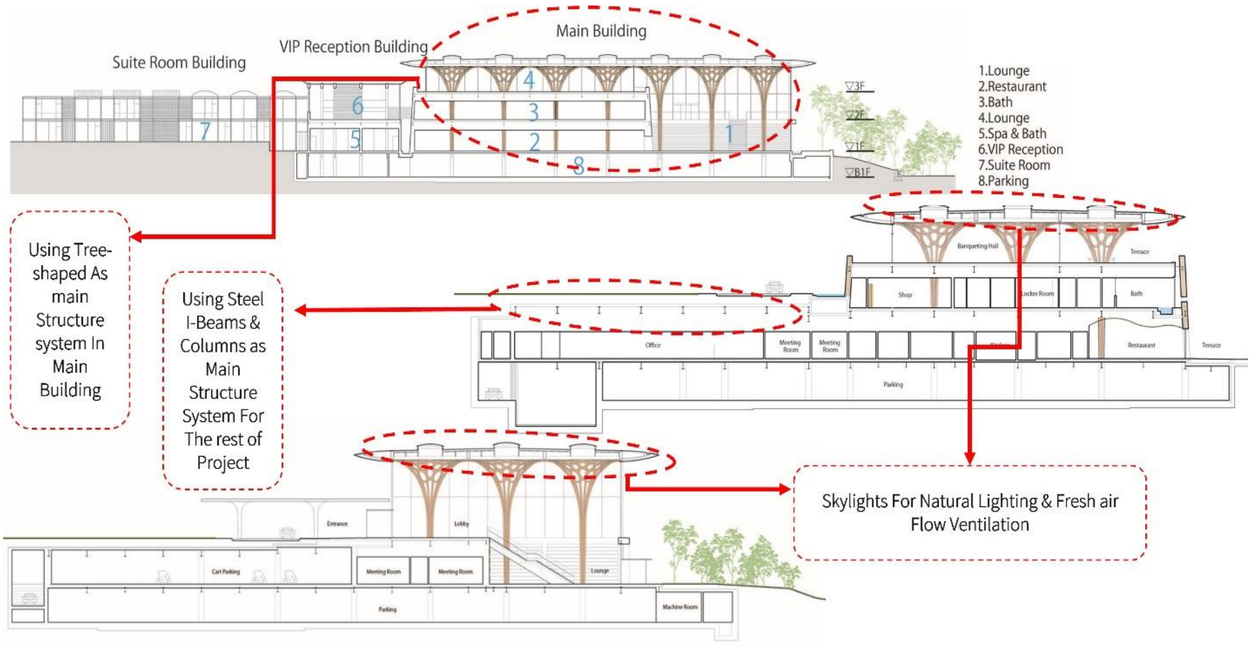

Figure 14 Tree-like pillars converge to form an octagonal, interwoven roof support. Source: “Shigeru Ban architects.”

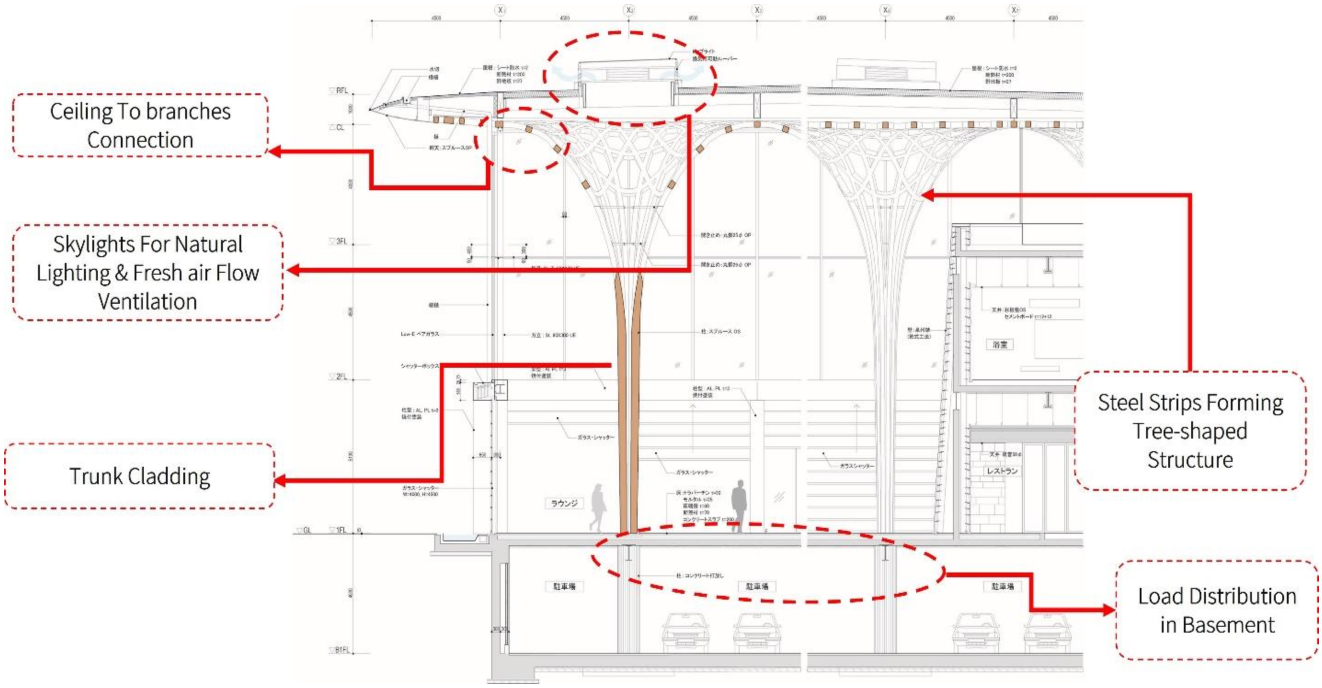

Figure 15 Sectional View of tree like columns. Source: “https://shigerubanarchitects.com/works/cultural/haesley-nine-bridges-golf-clubhouse.”

Element Design

Key design elements include:

- Hexagonal wooden grid roof structure
- Tree-like timber columns in the atrium
- Glass curtain walls with operable shutters
- A stone base made of locally sourced Korean rubble masonry.
- Composite steel deck with concrete for the Floor System

Functionality and Aesthetics:

The design prioritizes both functionality and aesthetics: The hexagonal grid roof is a self-supporting structure, eliminating the need for separate beams and columns, making it efficient and spacious. The extensive use of glass curtain walls provides panoramic views of the golf course and creates a sense of openness, Fig. 16.

- The exposed timber structure and tree-like columns create a visually striking interior space. The interplay of light and shadow through the glass walls further enhances the aesthetics.

Material Used:

- Timber plays a major role in the construction:
- Hexagonal wooden grid roof structure
- Tree-like columns in the atrium

Other materials include:

- Glass for the extensive curtain walls, Fig.17.
- Stone for the base of the building
- Composite steel deck for the floor construction

Sustainability Impact:

The design incorporates several sustainable elements:

- The use of natural light and potentially operable windows for ventilation could contribute to a more sustainable building operation.
- The use of timber promotes renewable building material.
- The innovative structure minimizes material usage through efficient design.

The Nine Bridges Golf Club Clubhouse utilizes natural materials, organic forms, and sustainable elements to create a visually striking and functional space that integrates seamlessly with the surrounding golf course environment.

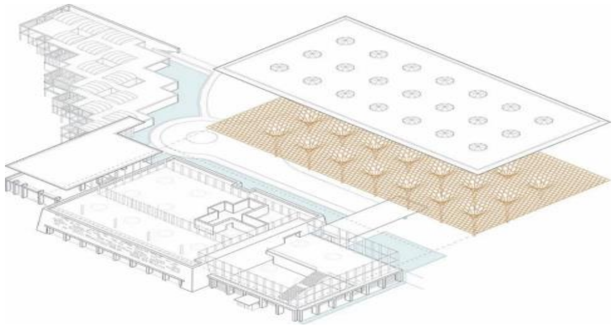

Figure 16. Tree Structure roof Axonometric. Source: https://www.archdaily.com/490241/nine-bridges-country-club-shigeru-ban-architects.

Figure 17 Openable Glass Shutters and Use of composite steel deck floor construction. Source: Kaci International + Shigeru Ban architects.

3.3. Case 3: Hulunbuir Hailar Airport A Tree-Inspired Terminal Expansion [25,26,27,28,29,30]

Function:	Sport center
Project Location:	Hailar District, Hulunbuir City, Inner Mongolia Autonomous Region
Accomplished at	June 2015 - March 2016
Building Area:	17,000 m2
Design Team:	U10 Studio, One Architecture Design Research Center
Designers:	Yu Haiwei, Yanyan, Zhefu, Lv Yan, Gao Chao, He Fan, Zhu Qipeng
Client:	Hulunbuir City Investment Co., Ltd.

Hulunbuir Hailar Airport, located in Inner Mongolia, China, Fig.18, is situated amidst stunning prairies and is known for its snowy winters. The existing T1 terminal's capacity was insufficient to handle the growing passenger volume due to the rise in prairie tourism. Therefore, an expansion project was initiated. This expansion faced the challenge of incorporating modern design with limited space for modifications.

Figure 18. Hulunbuir Hailar Airport Project view from northwest. Source: https://10atelier.cadg.com.cn/cn/project/detail/136

Design concept:

The design challenge was to create a modern terminal with a strong local identity despite predetermined building limitations. The architects achieved this by incorporating elements that evoke the Mongolian yurt a circular tent-like dwelling. and a unique structural system - V-shaped diagonal supports holding the roof on the second floor, Fig.19. This is achieved through the integration of columns, ceiling, and roof, eliminating the distinction between vertical and horizontal surfaces, and resulting in a continuous, flowing space. The gold and white color scheme further enhances the feeling of a bright and airy birch forest.

Structure System Analysis

The structure employs a modern approach with steel and glass elements, offering a sense of openness and lightness. However, there is a potential opportunity to incorporate sustainable practices and local construction techniques to better integrate the design with eco-friendly principles. An interesting feature is the double-height under-eave space created on the landslide. This is achieved through the varying heights of the south and north facades, Fig. 20.

The main structure is cleverly divided into two basic spans to simplify construction. The aluminum roof panels are categorized based on their curvature to minimize complexity and cost, while not a literal tree structure, the design utilizes V-shaped diagonal supports that branch out to hold the roof, creating a sense of openness. The integration of columns, ceiling, and roof eliminates clear demarcations, achieving a unified and continuous space.Fig.21,22.

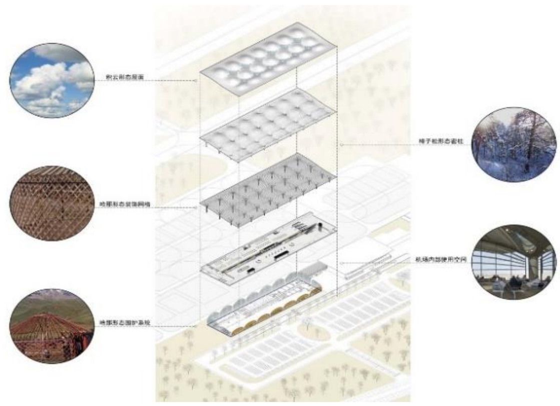

Figure 19. Sketch of Concept Generation analysis. Source: https://www.archdaily.com/918443/hulunbuir-hailar-airport-united-design-u10-atelier.

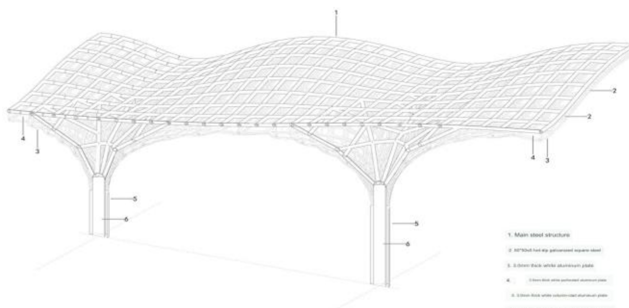

Figure 20. Nodes of flowering column made by aluminum plate. Source: https://www.archdaily.com/918443/hulunbuir-hailar-airport-united-design-u10-atelier.

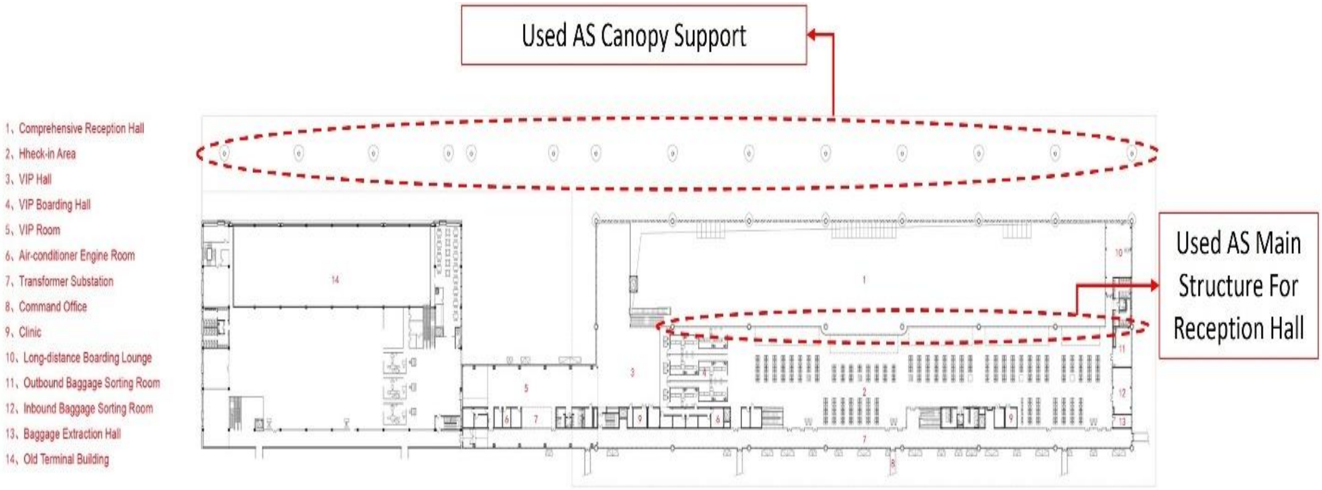

Figure 21 2nd Floor Plan. Source: https://www.archdaily.com/918443/hulunbuir-hailar-airport-united-design-u10-atelier.

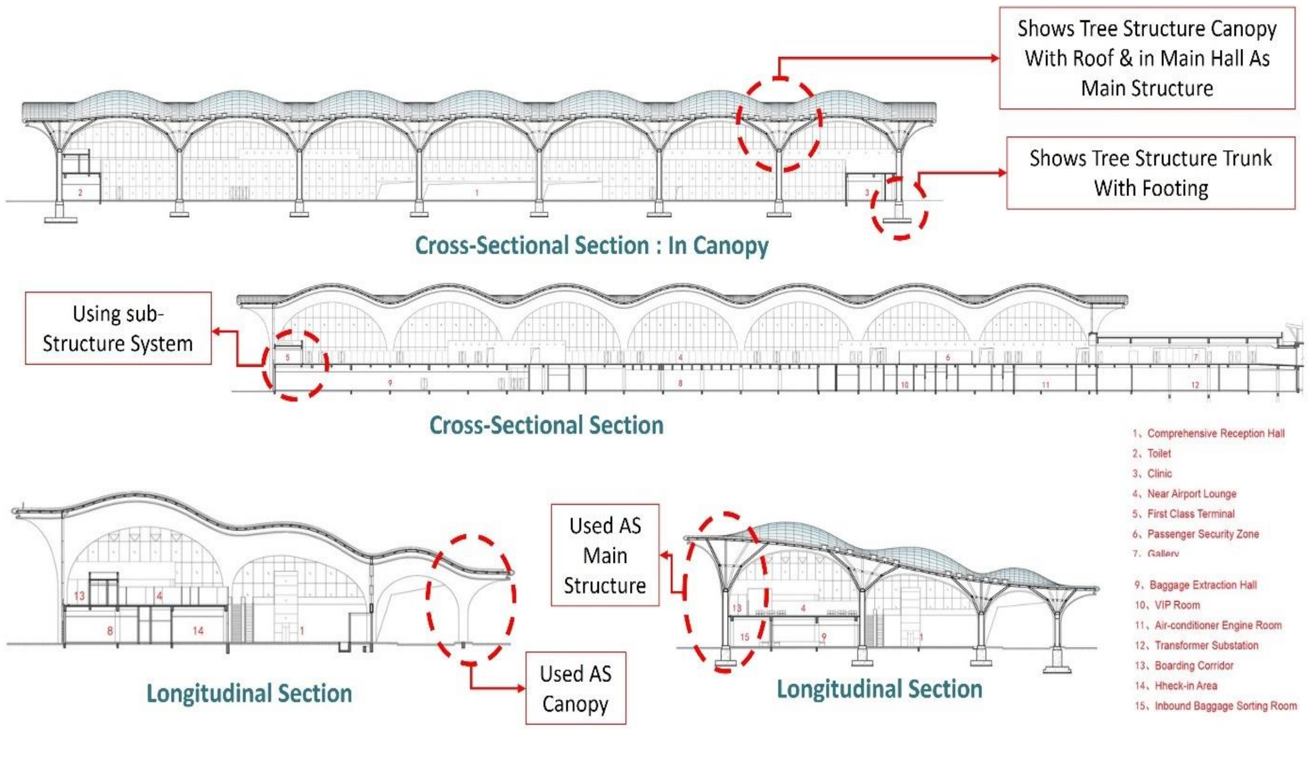

Figure 22. Cross- Section analysis & Canopy, a unified element. Source: https://www.archdaily.com/918443/hulunbuir-hailar-airport-united-design-u10-atelier.

Element Design

The V-shaped columns supporting the curved roof and the integrated structure eliminating the separation between vertical and horizontal elements are key design features, Fig 23,24.

The project also incorporates innovative elements like shaped keel curtain walls, TPO roofs, and double-curved aluminum flowering column nodes. A 1:1 mock-up was employed to ensure the desired construction effect.

Functionality and Aesthetics:

- The branching structure of the tree inspires design of the terminal layout, with "branches" representing different areas like check-in, security, and boarding gates, improves wayfinding by creating a more intuitive and organic flow for passengers. Moreover, it reduces the number of traditional support columns needed within the terminal. This creates more spacious and open spaces, as the modular construction techniques potentially speed up the building process and reduce costs.
- The very presence of a tree structure introduces a natural element into the airport, promoting a calming and stress-reducing environment for passengers. This aligns with the principles of biophilic design as the patterns inspired by the region's cultural heritage.

Figure 23 Model Production Source: https://www.archdaily.com/918443/hulunbuir-hailar-airport-united-design-u10-atelier

Material Used:

- Roof: Bi-directional single-layer reticulated shells (aluminum plates).
- Columns: Integrated with the roof and ceiling for a continuous space.
- Curtain Wall: Shaped keels.
- Roofing: TPO material.

Figure 24. Main Hall: Structure Connection with the Roof Aluminum panels & Level Slab

Sustainability Impact:

- The potential for incorporating sustainable and local construction techniques exists.
- The use of natural light through extensive glass facades can reduce reliance on artificial lighting.

Overall, the Hulunbuir Hailar Airport expansion corporation a tree structure concept into the design. While the focus on efficiency and openness is commendable, blends modern design with local cultural references. Offers a unique opportunity to enhance both functionality and aesthetics. By carefully addressing the challenges and considering the specific context of the region, this approach could create a truly remarkable airport experience for passengers.

4. Comparative analysis

This analysis examines the use of tree-inspired structures in contemporary architecture, comparing the key aspects for the case studies design concept, structures, including form and function, level of integration with the main building, materials used and sustainability impact, Table 1. By exploring these elements across such varied applications, we gain a high understanding of the versatility and potential of tree-inspired structures in architectural design.

Table 1. Comparative Analysis of Tree-Inspired Structural Systems for the discussed case studies: Source: Author

	Cambridge Mosque	Nine Bridges Golf Club Clubhouse	Hulunbuir Hailar Airport
Design Concept	Modern Islamic architecture with symbolic elements Combine structural functionality with symbolic meaning.	Organic architecture blending with golf course environment that Utilize a nature-inspired form for a visually striking and efficient roof structure.	Modern with local cultural references to enhance functionality, natural light, and evoke sense of place.
Tree Structure Analysis	Tree-like timber structure supporting the roof	Branching form in building envelope, not structural Using Hexagonal wooden grid roof structure	Branching structure inspired by a tree, the V-shaped diagonal supports for roof, not a complete tree structure
Canopy	Central tree structure forms canopy. Octagonal with interweaving branches.	No distinct canopy, branching form extends outwards.	Curved roof, no distinct canopy
Function	Structural support, spiritual connection structural support for the roof, eliminating need for additional ceiling elements.	Creates unique building envelope as roof Structural support, creates a visually striking and efficient space.	Supports roof, creates open interior Reduced column usage to get more open spaces.
Material	Solid timber is the primary material for the tree structure.	Timber is the primary material for the hexagonal grid roof structure.	Selection depends on wood or wood-like materials
Aesthetics	Harmonious and inspiring space with natural beauty and geometric patterns. Uplifting, spiritual atmosphere, natural light & geometric forms.	Visually striking and efficient design with exposed timber and a sense of openness. Natural & organic appearance.	Organic aesthetic with a potential connection to nature. Light, airy, spacious interior, flowing & modern.
Structure Integration	Fully integrated, forming the roof itself and creating a central light-filled space.	Seamless integration with Branching form integrated into facade & roof.	V-supports fully integrated.
Sustainability	Incorporate some sustainable elements as natural light, but not the focus.	Potentially high material selection for rainwater harvesting or natural ventilation.	Limited as it relies on conventional building materials and energy use.

5. Conclusion, findings, and recommendations:

This study has focused on the concept of tree-inspired structures in architecture. The review of literature and feedback gathered from providing a historical overview, highlighting their benefits and efficiency, and examining the influence of material properties on design provided a foundation for understanding these structures. Adding to the comparative analysis revealed the versatility of tree-inspired structures, highlighting their application in diverse settings. While not all structures were literal tree representations, they all employed branching systems or forms to achieve their functional and aesthetic goals. This study concludes the following points:

- Tree columns provide a highly efficient and effective structural solution for transferring substantial roof loads to a concentrated point on the ground. As such, they are well-suited for large public buildings including airports, sports facilities, railway stations, and shopping centers.
- Tree structures can offer improved wayfinding, natural light penetration, reduced column usage, and efficient structural support.
- These structures can carry symbolic weight, representing growth, stability, connection to nature, or a gateway to development.
- The level of integration with the main building varies. The Cambridge Mosque fully integrates the tree structure as the roof.
- Tree structures can create a visually striking and organic aesthetic, fostering a sense of place and connection to nature.
- Timber is a popular choice for its natural beauty and potential sustainability benefits, though fire safety and durability need to be addressed.
- When incorporating tree structures, careful the Design consideration should be given to material selection, fire

safety regulations, and maintenance requirements to ensure long-term performance and durability.

- Architects and engineers can explore innovative ways to integrate tree structures into different building types, pushing the boundaries of functionality, aesthetics, and sustainability.

By fostering a deeper understanding of tree-inspired structures and their potential benefits, this analysis encourages their continued exploration in architecture. Through thoughtful design and innovative approaches, these structures can contribute to creating not only functional but also inspiring and sustainable built environments.

References

[1] KAYA, Zeynep Gülcan, Murat ŞAHİN, and Ayça GÜLTEN. "Benchmarking Tree-Inspired-Fractal Branching Dendriform Structures from Bc to L-System Based Contemporary Structures." *Available at SSRN 4824646*.

[2] Aziz, Moheb Sabry. "Biomimicry as an approach for bio-inspired structure with the aid of computation." *Alexandria Engineering Journal* 55, no. 1 (2016): 707-714

[3] Benyus, Janine M. "Biomimicry: Innovation inspired by nature." Paperback – September 17, 2002

[4] Zhang, Hua, Jie Yan, Guoqiang Zhang, and Kaiya Zhou. "Phylogeography and demographic history of Chinese, Black-spotted frog populations (Pelophylax nigromaculata): evidence for independent refugia expansion and secondary contact." *BMC Evolutionary Biology* 8 (2008): 1-16.

[5] Perugini, Paolo, and Stefano Andreani. "Pier Luigi Nervi's columns: flow of lines and forces." *Journal of the International Association for Shell and Spatial Structures* 54, no. 2-3 (2013): 137-148.

[6] Rian, Iasef Md, and Mario Sassone. "Tree-inspired dendriforms and fractal-like branching structures in architecture: A brief historical overview." *Frontiers of Architectural Research* 3, no. 3 (2014): 298-323.

[7] Arslan Selçuk, Semra, Nur Banu Gülle, and Güneş Mutlu Avinç. "Tree-like structures in architecture: Revisiting Frei Otto's branching columns through parametric tools." *SAGE Open* 12, no. 3 (2022): 21582440221119479.

[8] Ancelin, Philippe, Benoît Courbaud, and Thierry Fourcaud. "Development of an individual tree-based mechanical model to predict wind damage within forest stands." *Forest ecology and management* 203, no. 1-3 (2004): 101-121.

[9] TR, Sreelakshmi, Aswin Dharmadas, and Rekha V Kumar. "Arboreal Architecture." *Rekha, Arboreal Architecture (June 22, 2023)* (2023).

[10] Gawell, Ewelina. "Non-Euclidean geometry in the modeling of contemporary architectural forms." *Journal Biuletyn of Polish Society for Geometry and Engineering Graphics 24* (2013): 35-43.

[11] Pasini, D., and S. C. Burgess. "Optimal structural features in trees and their application in engineering." In *1st International Conference on Design & Nature, Italy*, pp. 3-15. 2002.

[12] Otto, Frei. *Occupying and connecting*. Vol. 3. Fellbach, Germany: Edition Axel Menges, 2003.

[13] Xu, Feiyang, Shiqing Xuan, Wei Li, Xinmiao Meng, and Ying Gao. "Compressive performance of steel-timber composite L-shaped columns under concentric loading." *Journal of Building Engineering* 48 (2022): 103967.

[14] Asiz, Andi. "Sustainable Timber Construction: Challenges and Opportunities." *International Journal of Engineering and Science Applications* 10, no. 1 (2023): 13-21.

[15] Abed, Joseph, Scott Rayburg, John Rodwell, and Melissa Neave. "A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures." *Sustainability* 14, no. 9 (2022): 5570.

[16] Arslan, H. Derya. "Ecological design approaches in mosque architecture." *International Journal of Scientific & Engineering Research* 10, no. 12 (2019): 1374-1377.

[17] Cambridge Central Mosque Media Pack, June 2019. cited May. 19, 2024. Available from: https://cambridgecentral-mosque.org/wp-content/uploads/2021/10/Cambridge-Mosque-Press-Pack-v1.pdf

[18] Mangera Yvars Architects website, May. 19, 2024. Available from: 5th Studio: http://www.5thstudio.co.uk/projects/millroad-mosque-cambridge

[19] Ike Ijeh, "Cambridge Mosque," Building UK, 13 March 2019; and Jason Dibbs, "Cambridge Central Mosque / Marks Barfield Architects," arcspace, 16 March 2019.

[20] Ashraf, Salama. '*Substance and Sustenance*': The Cambridge Central Mosque in Earth Harmony. 52 (2019). cited May. 19, 2024. Available from: *https://www.researchgate.net/publication/336902990_'Substance_and_Sustenance'_The_Cambridge_Central_Mosque_in_Earth_Harmony*

[21] Archilovers | The professional network for Architects website, cited May. 19, 2024. Available from: https://www.archilovers.com/projects/29555/haesley-nine-bridges-golf-club-house.html

[22] PA | ParametricArchitecture website, cited May. 19, 2024. Available from: https://parametric-architecture.com/nine-bridges-country-club-by-shigeru-ban-architects/

[23] AV| Arquitectura Viva website, cited May. 19, 2024. Available from: https://arquitecturaviva.com/works/club-de-golf-haesley-nine-bridges-0

[24] ArchDaily | Broadcasting Architecture Worldwide website, cited May. 19, 2024. Available from: https://www.archdaily.com/490241/nine-bridges-country-club-shigeru-ban-architects

[25] Asiz, Andi. "Sustainable Timber Construction: Challenges and Opportunities." *International Journal of Engineering and Science Applications* 10, no. 1 (2023): 13-21.
[26] Abed, Joseph, Scott Rayburg, John Rodwell, and Melissa Neave. "A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures." *Sustainability* 14, no. 9 (2022): 5570.
[27]10atelier Architects website, cited May. 19, 2024. Available from: https://10atelier.cadg.com.cn
[28] ArchDaily | Broadcasting Architecture Worldwide. cited May. 19, 2024. Available from: https://www.archdaily.com/918443/hulunbuir-hailar-airport-united-design-u10-atelier
[29] Fligtradar24 website, cited May. 19, 2024. Available from: https://www.flightradar24.com/data/airports/hld
[30] PA | ParametricArchitecture website, cited May. 19, 2024. Available from: https://parametric-architecture.com/hulunbuir-hailar-airport-by-united-design-u10-atelier/