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IMPACT ANALYSIS OF BUILDING STRUCTURE ON BUILDING ENVELOPE DESIGN IN THE CONTEXT OF SUSTAINABILITY

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Abstract: This study examines the impact of the building structure on the building envelope in line with sustainable design goals. The building envelope plays a critical role in energy efficiency, conservation of natural resources, and reduction of environmental impacts with its design components such as form, facade, roof, and orientation. In the study, sustainable building examples accepted in the international literature were analyzed, and the building structure's design flexibility and performance advantages were evaluated. The findings show that innovative building systems such as steel, wood, and precast concrete provide significant advantages in sustainable design processes. Structural elements that allow for wide openings and are recyclable increase the building envelope's energy efficiency. The results reveal that the building structure is not only structural durability but also a strategic component in achieving sustainability goals. In this context, it is emphasized that structural elements should be planned at the early design stage.

Keywords: Building envelope, Building structure, Sustainable design, Energy efficiency

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1. Introduction

In the globalizing world, the depletion of resources due to the climate crisis, the misuse of developing technology, and the consumption and environmental pollution caused by the increasing population have led to the inclusion of sustainable approaches in country policies. In national and international meetings such as the UN Conference on the Human Environment-Stockholm Conference, 1972, the UN Conference on Environment and Development- Rio Conference, 1992, and the World Summit on Sustainable Development- 2002, it was emphasized that environmental pollution has become a widespread problem on a global scale, that ecological, social, cultural and economic development should be addressed together. That importance should be given to sustainable production and consumption (Ministry of Foreign Affairs of the Republic of Turkey, 2023). Increasing environmental awareness has also encompassed the disciplines of architecture, interior architecture, design and planning, and building practices with sustainability principles, which have become widespread. Settlements and buildings that cause global warming with 40% greenhouse gas CO_2 emissions, 12% water consumption, 65% waste production, and 71% electricity consumption draw attention to the necessity of sustainable building practices (Environmentally Friendly Green Buildings Association, 2023). Sustainable design in built environments, which constitute a significant amount of the energy used in the world, aims to save energy, resources, and water, to have minimum impact on the environment and economy, and to make a high level of contribution to society.

The most critical design criteria for achieving sustainable targets is to utilize external environmental conditions such as wind, sun, and humidity at a high level in building designs. The building envelope, which brings the external environment and the building together, is the most essential building component for efficiently using energy and resources. In recent years, there have been intensive studies on energy efficiency and user comfort in areas such as thermal insulation, envelope construction systems, materials, thermal utilization, and ventilation in the building envelope. Some of the studies that establish the contemporary technologies of the components that make up the envelope, such as external walls, roofs, windows, foundations, etc., discussed the efficiency conditions for different types of walls, such as trombe walls, solar chimneys, water walls, ventilated walls, and glazed walls (Khedari et al., 2005; Sadineni et al., 2011; Ma et al., 2019; Wang and Lei, 2019; Wang and Lei, 2020; Simões et al., 2021). Studies investigating the potential of window technologies to improve the thermal performance, sunlight, and solar properties of window technologies that allow the most heat flow from the building envelope and allow sunlight to be taken into the indoor environment have examined the physical and thermal transmittance properties of glass and the performance of window joinery (Jelle et al., 2012;

Aguilar-Santana et al., 2019; Aburas et al., 2019; Favoino et al., 2022). In addition to these studies, some studies discussed the efficiency of roofs that form the horizontal area of the envelope in areas such as green roofs, photovoltaic roofs, radiant-permeable barriers, and roof cooling systems. These studies discussed solar energy generation, energy efficiency, and ecological designs (Castleton et al., 2010; Shafique et al., 2020; Zheng and Weng, 2020; Catalbas et al., 2021). The area of research most related to the building envelope is energy efficiency and environmental effects of thermal insulation material's types and physical and chemical properties. These studies were in physics, chemistry, health engineering, and architecture, which examine the elements of building insulation materials used for heating and cooling according to climatic conditions, cost, thermal and mechanical properties, life cycle assessment, and health problems (Al-Homoud, 2005; Pargana et al., 2014; Abu-Jdayil et al., 2019; Anh and Pásztory, 2021). The study areas related to the building envelopes discuss the criteria for the design of the envelope together with the external environment. This study contributes to the design features of the building envelope by analyzing the relationship between the building envelope's structure and the building's structure with external environmental conditions for energy-efficient building envelope design with related building examples.

1.1. Research Problem

The increasing demand for energy, the rapid depletion of natural resources, and the growing environmental impacts of the construction industry necessitate the adoption of sustainable building designs. Buildings account for nearly 40% of global energy consumption, exerting significant pressure on natural resources and contributing to extensive environmental degradation. Within this framework, building envelope design plays a critical role in achieving energy efficiency and sustainability objectives. However, the interaction between key building envelope components—such as form, facade, roof, and orientation—and the flexibility and durability provided by structural systems remains insufficiently explored in existing literature.

This research problem raises fundamental questions about how the impact of structural systems on the building envelope can be optimized to align with sustainable design objectives. Furthermore, it is essential to assess the strategic role of structural elements in sustainable design processes. Addressing these issues is crucial to enhancing the effectiveness of sustainable building designs, ensuring both energy efficiency and long-term resilience.

1.2. Research Purpose

The primary objective of this research is to examine the influence of structural systems on the design of building envelope components within the context of sustainable design. This study aims to analyze how building envelope elements, including form, facade, roof, and orientation—are shaped by the flexibility and durability offered by different structural systems.

To achieve this goal, the study evaluates the contributions of various building materials—such as steel, wood, and precast concrete—to energy efficiency, resource conservation, and environmental impact reduction. Additionally, it seeks to optimize the relationship between structural systems and building envelopes, emphasizing the strategic planning of structural components in sustainable building design.

Through a systematic analysis of selected case studies, this research explores the role of innovative structural systems in achieving sustainability goals and aims to provide practical insights that can guide sustainable design processes.

1.3. Research Hypotheses

This study is based on the hypothesis that structural systems play a decisive role in the sustainability performance of building envelope design. Specifically, the research assumes that:

1. Innovative and flexible structural systems (such as steel, wood, and precast concrete) enhance sustainable performance by optimizing the design freedom of the building envelope.
2. The integration of structural and envelope components is essential for achieving energy efficiency, resource conservation, and environmental impact reduction in sustainable building designs.
3. Structural elements serve as strategic components in ensuring durability, adaptability, and resilience while supporting passive design strategies.

By testing these hypotheses, the study aims to clarify the role of structural systems in sustainable building performance and identify key factors that influence the optimization of building envelope components.

1.4. Research Scope

This study systematically examines the relationship between structural systems and building envelope components in sustainable building design. The research is based on an analysis of sustainable building projects recognized in international literature, with a focus on projects that provide accessible and detailed data for in-depth examination.

The study evaluates the contributions of different structural systems—including steel, wood, and precast concrete—to sustainable building performance, particularly in terms of:

- Energy efficiency,
- Resource conservation,
- Material recyclability, and
- Environmental impact reduction.

Additionally, the study explores the interaction between structural flexibility and passive design strategies, such as natural ventilation, daylight utilization, solar energy integration, and water recovery systems. The findings aim to provide a comprehensive understanding of how structural elements contribute to sustainability goals and offer guidance for optimizing sustainable building design processes.

1.5. Research Methodology

This study adopts a qualitative research framework to analyze the impact of structural systems on the building envelope in sustainable building design. The case study method was employed to identify sustainable building projects acknowledged in international literature, with a focus on projects that provide detailed and accessible data for in-depth analysis.

The selected case studies were examined based on key building envelope components, including form, facade, roof, and orientation, as well as the design flexibility and performance advantages offered by structural systems. The evaluation criteria for this analysis are as follows:

- Energy Efficiency: Assessment of natural ventilation strategies, solar energy utilization, and insulation performance of the building envelope.
- Material Performance: Examination of the sustainability contributions of structural systems, including steel, wood, and precast concrete.
- Design Flexibility: Analysis of the potential of structural systems to facilitate wide openings, recyclability, and adaptable orientation.

By conducting a systematic comparison of data obtained from case studies, this research aims to assess how the interaction between structural systems and the building envelope influences energy efficiency and sustainability outcomes. The integration of theoretical knowledge and empirical data from real-world projects ensures a comprehensive and practical evaluation of sustainable building strategies.

2. Materials and Methods

The structure, a fundamental component of architectural design as the load-bearing system of a building, must support the building envelope, form, and orientation to implement sustainable architectural design correctly. In addition to ensuring safety by protecting the building from loads, ground movements, and other external influences, the structure also plays a vital role in energy-efficient/sustainable architectural design. Various design strategies used to increase energy efficiency affect many elements, from the choice of materials for the structure to the layout of structural systems. The structure, which is the most critical building component that provides the formation of the building form, must have an appropriate design to facilitate the building envelope design according to climatic data. To achieve the desired level of sustainable design components such as building form and orientation according to climatic data, natural ventilation, and lighting strategies, thermal insulation design to maintain indoor conditions, and placement of solar energy generating systems, the structure should allow the free and flexible design to the building envelope. In addition, the building structure contributes to sustainable design with minimum environmental and economic impact during the construction, use, and disposal phases.

The structure is the main building element affecting energy-efficient/sustainable architectural design. The various design strategies used to improve energy efficiency affect many aspects of the structure, from the choice of materials to the layout of structural systems. For example, the structure should have an appropriate thermal mass and support the shell insulation materials for an efficient insulation system. For natural ventilation design, the structure should have openings or ventilation ducts that support natural airflow. Furthermore, there is a need for structural integration to place renewable energy systems, such as solar panels and wind turbines, used for energy generation in appropriate building areas. Therefore, important decisions to improve energy efficiency should be taken at the design stage of the structure and integrated with sustainable design. In line with this information, the issues that should be taken into consideration for energy-efficient/sustainable approaches in the structural design process are summarized below:

Material selection: Material efficiency is linked to savings in using materials by utilizing their strength and stiffness properties. Efficient structural forms are designed with attention to the geometry of the overall structure and its parts and provide the highest structural performance with the least amount of material (Huberman et al., 2015).

Structural system: Structural design and layout influence sustainable design strategies. The structural system should provide more strength with fewer structural elements to have the flexibility to allow for future changes and the energy efficiency of the building (Buschmeyer and Fastabend, 2004).

Insulation: The insulation system can affect the structure's thermal mass while improving energy efficiency. Proper design of the structural thermal mass saves energy by regulating heat transfer. Structural design can help to reduce heat losses and control external heat gains. Optimization of the dimensions of the structural components of a building at the initial design stage, aimed at minimizing operational and total energy consumption, increases the thermal insulation area. Using insulated facade systems or structural details that reduce thermal bridges can limit heat transfer and reduce the building's heating and cooling energy demand (Zilberberg et al., 2021; Kumar et al., 2020; Wang and Adeli, 2014).

Integration: For the construction of systems such as solar panels, wind turbines, or water collection systems used for energy generation, the structural design must be integrated. The layout and strength of the structure are factors to be considered in terms of system safety and enabling the creation of energy-generating systems. In addition, solar panels or collectors can be integrated into structural elements or have structural features (Wang et al., 2021).

Natural ventilation and lighting: The structure is an essential building component for the design effectiveness of natural air intake from the building envelope to the interior spaces. The structural elements of the building should have a design plan that will direct the airflow and provide comfortable air circulation in the interior spaces. Meeting the ventilation and lighting demands expected from the building envelope is possible with appropriate structural design. For example, structural elements with openings that facilitate natural airflow can reduce the need for artificial ventilation in spaces and energy consumption.

Water management: The structure contributes to implementing rainwater harvesting systems or water-saving measures by providing strength and flexibility. Structural design can be integrated into rainwater harvesting areas and drainage systems. It can also be designed to provide structural support for methods used for water saving. For example, structural support elements for green roofs can retain water and grow plants.

Construction Method: Access to the construction site and the duration and environmental impact of on-site construction contribute to the structural system's sustainability. The performance parameters expected from the structure design ensure that the structural element, produced in the factory and has a short transport distance, is assembled quickly and with less labor on-site. The structural design needs to be planned and optimized in line with building efficiency principles to achieve energy efficiency targets.

In order to analyze the research frequency and need for recent studies on building structures for sustainable built environments, the Web of Science website, which provides access to multiple databases and comprehensive citation data for many different academic disciplines, was used. As a result of the Web of Science search with the keywords "structure," "sustainability," "building," and "energy efficiency," 610 studies have been encountered since 2010, and the distribution of the research by years is given in Figure 1. It is seen that there is an increasing graph on the subject of research over the years.

Figure 2 shows the density of research areas of 610 publications on research topics encountered due to keyword searches. While the numerical majority of the studies covered the branch of materials science, it was seen that the numerical ratio of the studies in the fields of civil, chemical, and physical engineering was also high. Although sustainability and energy efficiency are among the keywords, the number of studies in this field could be higher for the research area, and there is no research area where architecture and design are the main branches of science. In the Green Sustainable Science Technology field, which is the closest research area to sustainable architectural approaches, 35 studies have been conducted.

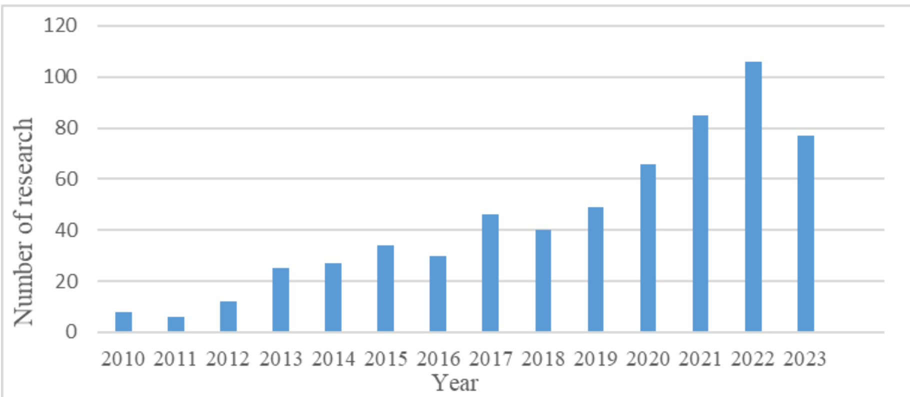


Figure 1. Distribution of research by years.

Figure 2. Scientific fields of published works on research.

To contribute to the limited number of academic studies that examine sustainable design approaches in the context of structure, this study analyses the design criteria for energy conservation and recovery of the structural system through sustainable building designs. In this direction, as a result of the analysis of the literature information, the sustainability features of the structural systems that are most widely used in built environments are explained. Timber, reinforced concrete, masonry, steel, and composite components are used as the primary structural systems in buildings. The structure materials have different environmental impacts and sustainable evaluations, and the envelope design has other effects on energy efficiency.

2.1. Wood

The selection of basic building materials is often made considering the importance of economic, environmental, functional, aesthetic, and health-related criteria, and wood is one of the modern construction materials that offer efficient, economical, and sustainable solutions (Kolb, 2008; Leśniak and Zima, 2018). Efficient, durable, and valuable wood products produced from trees are minimally processed at the construction site or composited and used as highly processed and highly engineered products in a large production facility. The most essential features of wood that contribute to sustainability are low embodied energy and low carbon impact. Wood, a material that requires a minimum amount of energy-based processing in its production, has a low level of embodied energy compared to many other materials used in construction (e.g., steel and concrete) (Falk, 2010). However, while it is used in buildings with fewer stories compared to the usage areas of other materials, it allows large spans to be crossed with small-sized products such as steel.

2.2. Masonry and Concrete

Carbon footprint and the use of natural materials as the material can be supplied near the construction site. In addition, thanks to the thick wall constructions, the insulation feature is provided, allowing the interior to remain warm or cold for a long time. This structure, used in low-rise buildings, has low-free design possibilities for natural lighting and ventilation. However, it can contribute to energy efficiency as a suitable material for passive design systems such as trombe walls (Wang and Adeli, 2014).

Concrete, which consists of aggregate and cement, has a long service life and is a durable system, but the chemical reaction that occurs during its formation can damage the environment by releasing CO_2 gas. In addition, the reinforced concrete system is less used in buildings with sustainable design due to its larger size and less wide span than steel and timber systems.

2.3. Steel

It is the most preferred structural system for sustainable designs thanks to its advantages, such as fast production and assembly of steel, high recycling, high strength and flexibility, and small column dimensions. Despite the high energy requirement to produce steel, its low cost and environmental impact throughout its life cycle due to its production and assembly speed and recycling capacity make it sustainable (Broniewicz and Broniewicz, 2020). While steel can be recycled up to 95% of the time, the amount of energy consumed per ton of steel produced decreases in the subsequent recycling process and reaches a constant value (Brimacombe et al., 2001).

Natural resource consumption, transport, energy consumption throughout the life cycle, waste production, and emission production are frequently discussed in the literature as indicators of the sustainability of steel (Burgan and Sansom, 2006; Landolfo et al., 2011; Aksel and Eren, 2015; Rossi, 2014). Another advantage of steel is that it allows flexible design. Thanks to the flexible design, the sustainable performances expected from the building envelope are realized quickly and efficiently. The ability of steel to pass through wide openings, transform into desired forms, and provide high strength with small dimensions allows passive and active energy efficiency and energy generation designs.

Wood, reinforced concrete, masonry, steel, and composite systems consisting of a combination of these building systems are the most common construction systems used in built environments. Since each system has different sustainable advantages and disadvantages, designers choose suitable construction systems for sustainable building design goals.

3. Results

In sustainable building designs, the contributions of the building envelope to energy efficiency, natural resource use, and environmental impact reduction are generally examined. However, this study differs from other studies in the literature by focusing on the sustainable advantages created by the building structure on the building envelope. In this context, the effects of the building structure on the building envelope design components were analyzed based on ecological values, energy efficiency, and user comfort.

The research examines examples used to achieve sustainable building design goals at different scales and structures. In the selected examples, the effect of the building structure on the building envelope was evaluated through the following four essential design components:

Form: The effect of the shape and geometry of the structure on energy performance and environmental compatibility.

Orientation: Positioning of the building envelope according to sunlight, wind, and other climate data.

Roof: Designs that increase energy efficiency and provide renewable energy integration.

Facade: Building elements that optimize natural ventilation, lighting, and energy gain targets.

The common feature of the selected sample buildings is that they focus on sustainable design targets. However, the methods of each building to achieve these targets differ. The research focused on buildings with composite structural systems selected from steel, timber, and concrete systems and buildings with steel systems only. These examples were analyzed in tables to evaluate each sustainable design feature in detail.

3.1. Example 1: The Edge Building

The EDGE is a 'smart building' designed for the Deloitte company, whose construction was completed in 2014. The design of the pentagonal office building with a 40,000 m^2 gross floor area and sloping facade belongs to PLP Architecture. Sustainability, comfort, and users' productivity were considered during design and construction. The Edge is one of the world's most significant buildings with BREEAM Outstanding certification. The building core constitutes the starting point of architectural design. The core consists of horizontally and vertically moving bridges and an atrium housing the open elevator. The atrium functions as a giant theater hall. There are offices arranged like an amphitheater around it. At the same time, this atrium turns into a natural gathering area. While the transparent atrium on the north side provides climate control, solar collectors on the south side are integrated into the facade and provide energy gain. The Edge uses energy concepts such as thermal storage, a heat pump system with a district heating connection, a PV in the building (Table 1) (URL-1; URL-2).

3.2. Example 2: Davies Alpine House

Davies Alpine House is an award-winning RIBA building that combines traditional practices with the latest technology, such as a greenhouse developed for the 21st Century. It was designed by Wilkinson Eyre to provide the dry, cool, and windy conditions that alpine plants need. The structural setup of this building, which is 16 meters long and 10 meters high, consists of four prominent steel arches connected to the reinforced concrete floor. Designing the maximum possible glass surface area on the facade allows 90% of the sunlight to be let in. Shading elements integrated into the transparent surface protect from unwanted sunlight during summer months. Three meters below the Alpine House is a maze of concrete slabs. The process mimics the natural system of termite mounds. That is a passive cooling system. Air from the outside is drawn into the 80-meter interlocking labyrinth. The maze cools overnight as the concrete creates thermal mass, which cools the incoming air. Four low-energy fans carry the air into the building through the displacement tubes above, and through these tubes, the cooled air enters the greenhouse at the plant level. Davies Alpine House is an award-winning RIBA building that combines traditional practices with the latest technology, such as a greenhouse developed for the 21st Century. It was designed by Wilkinson Eyre to provide the dry, cool, and windy conditions that alpine plants need. The structural setup of this building, which is 16 meters long and 10 meters high, consists of four prominent steel arches connected to the reinforced concrete floor. Designing the maximum possible glass surface area on the facade allows 90% of the sunlight to be let in. Shading elements integrated into the transparent surface protect from unwanted sunlight during summer months (Table 2) (URL-3; URL-4).

3.3. Example 3: Hawaii Preparatory Academy | Energy Lab

Designed to meet Hawai'i Preparatory Academy's request to create a high school science building that emphasizes energy conservation and recovery, the 6,100 sf Energy Lab offers students the opportunity to experiment with renewable energy technologies. The LEED Platinum building uses photovoltaics and wind turbines to meet its energy needs. It collects rainwater to meet drinking water needs, uses natural ventilation, and has an outdoor view from 100 meters—the percentage of occupied spaces. To promote environmental literacy, students can monitor the building's energy use in real time (URL-5).

The Energy Laboratory responds to the science curriculum it houses, with spaces from project rooms to an extensive research center and laboratory designed to encourage student exploration and experimentation. The building's configuration facilitates indoor and outdoor scientific study by connecting the interior spaces to the surrounding landscape. Students are surrounded by the systems they study and are constantly reminded of their methods (Table 3) (URL-6).

3.4. Example 4: The Crystal Building

Designed by Siemens in response to a green building request, Crystal is the first building to receive the highest sustainable building awards from BREEAM and LEED. Designed by Wilkinson Eyre, the glazed and sharp-lined building creates a new platform for discussion on sustainable urban living and development. With its crystalline shape representing complexities and challenges, the Crystal building is derived from the multifaceted urban life with its design. The facade wings with sporty triangular glass paneled surfaces form a similar external geometry with walls and roofs composed of multiple triangular planes, aiming to represent different aspects of sustainability and the complexity of urban life.

Six different types of highly insulated glass, each with different levels of transparency, have been used in the cladding to reduce solar gain and frame views into and out of the all-glass building facade, focusing more on using advanced technology. The building consists of two steel-framed parallelogram wings covered by a curtain wall. Box-section columns are designed along the roof ridge to maximize the column-free central area, tapering at the top and bottom on different axes. Cross beams, narrower at the bottom and broader in the perpendicular direction towards the top, are connected at the bases of the load-bearing system, providing strength and stability under wind load at the top and bottom (Table 4) (URL-7; URL-8).

3.5. Example 5: Adnan Menderes Airport

Izmir Adnan Menderes Airport International Terminal, put into service in 2006, serves passengers in an area of 107. 699 m^2. It claims that it can create an attractive, colorful/lively, spatially peaceful effect in terms of the character and design of the materials used, with transparent facades between the air side and passenger waiting for lounges and spacious and wide surfaces in terms of providing sufficient. There are transparent surfaces that will provide sufficient natural lighting in space. Thus, most of the lighting can be provided naturally.

The focal point of the terminal design is the diagrid vaulted roof measuring 200 m x 80 m in plan, covering the check-in hall at the departure floor entrance with a span of 72 m and the "elephant's foot" structure with four diagrid hyperboloid cones. The inside of the four vaulted elephant legs that form the design are commercial spaces; simultaneously, these legs act as vertical chimneys, providing light and ventilation to the check-in area (URL-9).

The glass canopies at the terminal entrance are made of composite material with photovoltaic cells, creating shade and generating green energy from solar energy to the terminal. The connection detail element at the end of the pin-supported steel pipe elements forming the carrying system of the canopy is formed with cast structural steel (Table 5) (URL-9).

4. Discussion

This study analyzes sustainable building examples that aim to reduce resource consumption, increase energy efficiency, and improve user comfort while minimizing environmental impact through an ecological and human-centered approach. The case study analysis highlights that climatic data, which provides critical information about external environmental conditions, plays a key role in sustainable design strategies. Integrating solar energy, wind, and air currents into architectural design reduces the need for mechanical systems and enhances the self-sufficiency of buildings by enabling passive heating, cooling, and ventilation.

The Role of Structural Systems in Climate-Responsive Design

A fundamental prerequisite for achieving high efficiency in form, orientation, and building envelope design is the appropriate structural system selection. The case study analysis demonstrates that for effective natural ventilation, lighting, and passive heating and cooling, the structural system should:

- Enable broad openings for enhanced airflow and daylight penetration,
- Minimize column sections to increase spatial flexibility,
- Allow variable roof slopes and envelope orientations to optimize solar and wind utilization.

Among the structural systems analyzed, steel structures were found to be particularly advantageous due to their small cross-sections, ability to span large distances, and flexibility. Additionally, wood was identified as a sustainable structural material due to its natural properties, small dimensions, and recyclability. However, its limited strength in high-rise buildings restricts its application to low-rise structures. While reinforced concrete remains the most commonly used structural material in traditional buildings, precast concrete has emerged as a preferred alternative in sustainable designs due to its lower environmental impact and reduced construction time.

Integration of Structural Systems and Energy-Efficient Design Strategies

The findings from the case studies, summarized in Table 6, illustrate how structural systems facilitate energy efficiency and environmental performance through various strategies:

- Natural lighting was achieved in all case studies through transparent roof surfaces.
- Natural ventilation via roof openings was incorporated in all cases except The Crystal Building.
- Solar panel integration was enabled by roof structures designed with optimal solar angles in all case studies except Davies Alpine House.
- Rainwater collection and drainage systems were structurally integrated into The Edge Building and The Crystal Building, demonstrating the role of structure in supporting water conservation strategies.
- Solar or wind chimneys, which are critical for enhancing indoor air circulation, were incorporated only in Adnan Menderes Airport.

These examples illustrate that structural systems are not merely load-bearing components but also active design elements that shape the environmental performance of buildings.

Structural Flexibility and Adaptive Building Envelopes

The facade designs of the analyzed buildings highlight the role of structural flexibility in enhancing energy efficiency. A key finding is that all five case studies benefited from the flexibility provided by steel structures, allowing for dynamic facade adaptations that improved solar exposure, ventilation, and lighting performance.

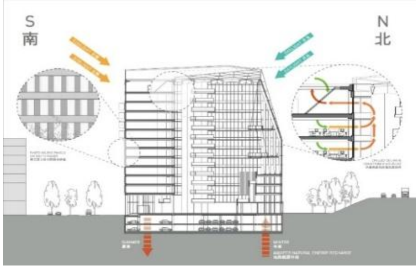
- The Edge Building, The Crystal Building, and Adnan Menderes Airport feature facades optimized for both structural efficiency and solar orientation, facilitating solar panel integration.

- The Edge Building and The Crystal Building implemented facade movements and increased facade surface area, improving daylight access and natural ventilation.
- Geothermal and wind energy systems were incorporated in all case studies except Adnan Menderes Airport, demonstrating the potential of site-responsive structural layouts.
- Atrium-based ventilation strategies and the chimney effect were effectively utilized in The Edge Building, Davies Alpine House, and Adnan Menderes Airport.

These findings highlight the importance of structural adaptability in integrating passive design strategies and reducing the reliance on active energy systems.

Table 1. The Edge Building (URL-1; URL-2)

INFORMATION		
Location	Amsterdam	
Year	2014	
Function	Office	
Architect	PLP Architecture	
Material	Precast concrete, Steel and Glass	
STRUCTURE		
Small-sized long span steel carrier system Solar pitched steel roof Steel laced beam Structural design allowing design objectives		 
DESIGN FICTION		
Design Objectives	Zero-energy building design Natural lighting and ventilation Structural design allowing flexible design Energy recovery with solar energy	
Form	Broad facade surfaces in the north-south direction Hollowing out the compact mass to form an atrium Natural ventilation openings in the direction of the prevailing wind	
Orientation	Orientation in accordance with the sun and wind Atrium to the north, solar panels to the south	
Recycling	Recyclable building structure Use of rainwater Recovery of energy consumed by utilising solar energy	
BUILDING ENVELOPE		
Roof	Solar Panels Rainwater collection system Roof windows	
Facade	Transparent surfaces on the north-facing atrium facade Small-sized transparent surfaces on the south-facing facade South facade covered with photovoltaic panels Preventing temperature rise indoors by reducing heat conduction Movements on the facade to control the air flow rate indoors and prevent strong air currents	



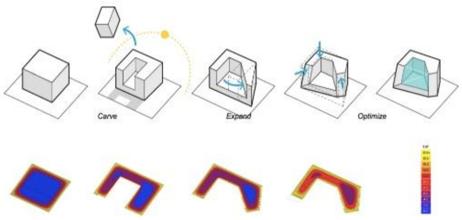
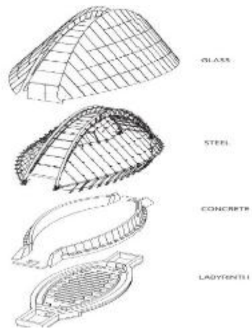
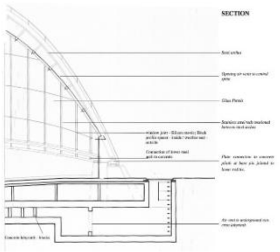


Table 2. Davies Alpine House (URL-3; URL-4)

INFORMATION	
Location	London
Year	2006
Function	Greenhouse
Architect	Wilkinson Eyre
Material	Steel, glass, Precast concrete
STRUCTURE	
	Small-sized long span steel carrier system Subsoil concrete labyrinth allowing air circulation Steel arch beams Structural design allowing design objectives Construction design allowing maximum daylight gain
DESIGN FICTION	
Design Objectives	Natural ventilation and lighting Movable structure design / two back-to-back arches Maximum utilisation of daylight Shading system design resembling a peacock
Form	Organic form in commune with nature Long facade extending on east-west axis Transparent surfaces allowing maximum sunlight transmission A structure that allows warm air to flow into the ventilation shaft on the roof
Orientation	Orientation in accordance with the direction of sun and wind Orientated from north to south so that it receives direct sunlight but does not overheat.
Recycling	Recyclable building structure
BUILDING ENVELOPE	
Roof	Roof windows



Facade	Bringing a high amount of sunlight into the interior with the structural system supporting the glass facade and glass joint details Shading element in white woven fabric that can cover 70% of the glass panels



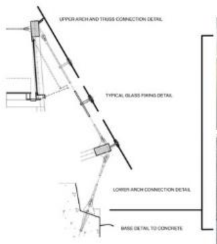



Table 3. Hawaii Preparatory Academy | Energy Lab (URL-5; URL-6)

INFORMATION	
Location	Kamuela, Hawaii
Year	2010
Function	Education
Architect	Flansburgh Architects
Material	Wood, Steel


STRUCTURE

Structural design allowing large area design
Pitched roof structure suitable for sunlight
Structural design allowing design objectives
Use of natural materials


DESIGN FICTION

Design Objectives	Net zero energy building design Provide natural ventilation To maximise the benefit of sunlight Avoiding energy consumption for active systems To educate students on the understanding of environmentally sensitive, sustainable living systems
Form	Form integrating with the ground Positioning on north-south axis Maximum benefit from natural ventilation Roof design that creates negative pressure with the prevailing wind and allows the heated air inside the building to flow out Plan design with courtyards and terraces to maximise the benefit of topography
Orientation	Orientation that creates a wind corridor interior by using the north wind Orientation that improves the efficiency of solar energy and photovoltaic panels
Recycling	Recyclable building structure

BUILDING ENVELOPE

Roof	Skylights allowing natural ventilation and lighting Pitched roof structure that increases the energy efficiency of photovoltaic panels
Facade	Natural lighting with high light transmission on transparent surfaces Wide eaves providing protection from sun rays

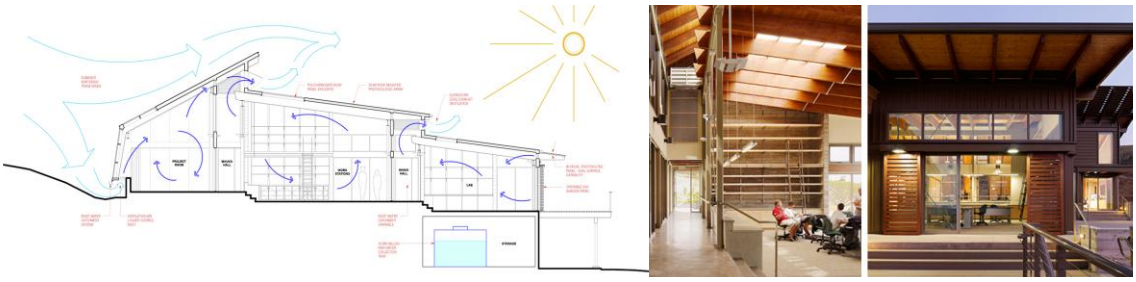


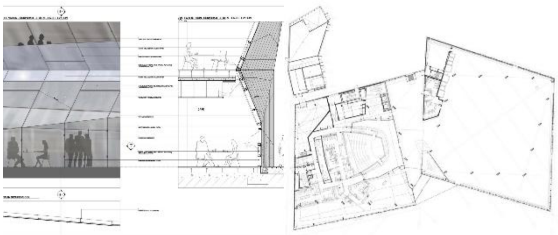
Table 4. Hawaii Preparatory Academy | Energy Lab (URL-7; URL-8)

INFORMATION

Location	London
Year	2022
Function	Mixed Use
Architect	Wilkinson Eyre Architects
Material	Çelik, cam

STRUCTURE

Steel structure combining many triangles
Steel laced beam
Cross steel beams and box section columns allowing wide span crossing
Structural design that allows for design
28 columns and all main beams including edge and ridge beams with box section profile
Frame design minimum steel utilisation and prefabricated system

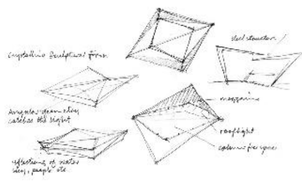


DESIGN FICTION

Design Objectives	Intelligent building management systems to minimise energy use Ensuring maximum gain from solar energy Zero-energy building design Natural ventilation through automatic windows Use of natural daylight in all spaces Structural design allowing flexible design
Form	Transfer of crystal geometry to architecture Broad facade surfaces in the north-south direction Two steel-framed parallelogram wings covered with glass curtain wall
Orientation	Sun and wind favourable orientation Atrium to the north, solar panels to the south
Recycling	Recyclable building structure Greywater recovery of dirty water (the building is 90% self-sufficient) Recovery of energy consumed by utilising solar energy

BUILDING ENVELOPE

Roof	Solar Panels Rainwater collection system Transparent roof with varying levels of transparency (six different panes)
Facade	Transparent surfaces with different levels of transparency Facade design that allows natural lighting Controlled sunlight gain Sloping facade structure in accordance with the sun



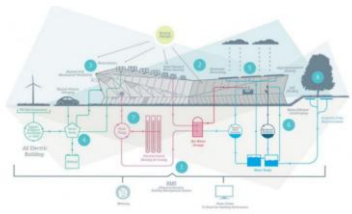


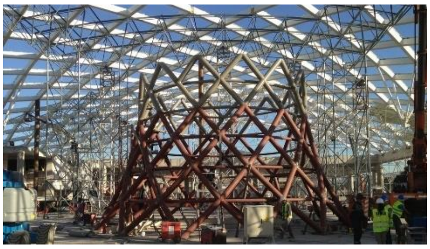
Table 5. Adnan Menderes Airport (URL-9)

INFORMATION

Location	İzmir
Year	2014
Function	Aırport
Architect	Hazan Architect
Material	Reinforced concrete, steel, glass

STRUCTURE

Steel laced beam
Steel frame light chimneys
Steel structure allowing skylight formation
Ventilation through chimney effect with hollow steel frame system



DESIGN FICTION

Design Objectives	Reducing the use of natural resources To ensure that sunlight reaches the depths of the building Maximising the use of natural lighting by increasing the transparent surface area Chimney effect design with vertical voids
Form	Compact form with linear plan scheme Design elements to ensure visual integrity with the exterior Structure allowing open space organisation
Orientation	Orientation to natural ventilation and lighting indoors
Recycling	Recycled Material Recovery of energy consumed by utilising solar energy

BUILDING ENVELOPE

Roof	Reflection of sunlight with white standing seam roof structure Solar Panels Roof windows Vertical structure forming light chimneys
Facade	Facade design that allows natural lighting Controlled solar gain - metal solar shading panels Energy production with PV panels on the entrance eaves

Table 6. Energy-efficient and productive approaches to sustainable building examples

	Example 1	Example 2	Example 3	Example 4	Example 5
STRUCTURE					
Wood			✓		
Steel	✓	✓	✓	✓	✓
Precast concrete		✓			
ROOF					
Natural ventilation	✓	✓	✓		✓
Natural lighting	✓	✓	✓	✓	✓
Roof window	✓	✓	✓	✓	✓
Roof solar panel	✓		✓	✓	✓
Rainwater collection	✓			✓	
Solar chimney					✓
FACADE					
Natural ventilation-lighting	✓	✓	✓	✓	✓
Facade solar panel	✓			✓	✓
Broad facade openings	✓	✓	✓	✓	✓
Shading elements		✓	✓		
FORM					
Gaps that increase the facade surface	✓			✓	
Utilising topography	✓	✓	✓	✓	
Broad facade parallel to the sun	✓	✓		✓	✓
Ventilation and lighting with vertical gaps	✓	✓			✓

ORIENTATION					
Roof slope towards the sun	✓		✓	✓	
Sloping facade suitable for sun angle	✓	✓		✓	
Natural ventilation with wind	✓	✓			✓
RECYCLING					
Recycled structure	✓	✓	✓	✓	✓
Recycled material	✓	✓	✓	✓	✓
Energy recovery	✓	✓	✓	✓	✓
Water recovery	✓			✓	

Environmental Adaptability Through Structural Design

The roof and facade slopes in the case studies were designed based on solar incidence angles and wind flow patterns, demonstrating the direct relationship between structural design and environmental adaptability.

- The Edge Building, The Hawai'i Preparatory Academy Building, and The Crystal Building optimized roof slopes for solar energy utilization.
- The Edge Building, Davies Alpine House, and The Crystal Building incorporated facade orientations responsive to wind and sun exposure, reducing energy demand.

Material selection also played a crucial role in sustainability performance. Steel, timber, and precast concrete were selected in the case studies for their recyclability and potential for reuse. The structural system's capacity to integrate renewable energy solutions was evident in:

- Solar panel integration across all case studies, facilitated by structural modulation and load-bearing optimization.

The Edge Building and The Crystal Building incorporated rainwater collection and storage systems, showcasing water efficiency strategies.

4. Conclusion

The high consumption of energy and natural resources, coupled with significant carbon emissions and environmental degradation, underscores the critical importance of sustainability in the built environment. Rapid technological advancements, population growth, and shifting demographic structures have further intensified the threat of resource depletion and environmental pollution, necessitating resource-efficient and ecologically responsible design strategies. Incorporating natural environmental components and climatic data into architectural design is fundamental to achieving sustainability goals related to ecology, human well-being, resource conservation, and economic efficiency. While solar energy is harnessed for heating and electricity generation, wind and air currents contribute to energy production, cooling, and ventilation, reducing reliance on mechanical systems.

Among all building components, the building envelope plays a pivotal role in mediating between outdoor and indoor environments, maximizing the benefits derived from climatic data. The placement of buildings on the land and the design of the envelope—which regulates the entry of solar radiation, wind, rain, and humidity under optimal conditions—are fundamental considerations for sustainable design. However, for the building envelope to function efficiently, the design of the roof, facade, building form, and orientation must be flexible and adaptable to environmental conditions. In this regard, the structural system is a crucial factor, as it not only determines the physical lifespan of a building but also facilitates the flexibility required for optimal envelope performance. The ability of structural systems to support adaptable design solutions directly impacts on the overall sustainability and efficiency of buildings.

The Role of Structural Systems in Sustainable Design

For the building structure to provide flexibility to the envelope, it must allow controlled integration of external environmental conditions into interior spaces. This can be achieved by:

- Optimizing the placement of structural elements in both the envelope and interior spaces.
- Designing the structure to accommodate diverse forms and configurations, ensuring adaptability to environmental conditions.
- Incorporating appropriately sized openings in the building shell to facilitate ventilation, lighting, and energy efficiency.

Wide column spacing and reduced column and beam cross-sections contribute to more adaptable interior layouts, while also enhancing environmental integration. Beyond structural strength and stability, sustainable design requires structural flexibility, enabling the building form and envelopes to respond dynamically to solar angles, wind flows, and climatic conditions. This adaptability allows designers to maximize solar gains, optimize passive ventilation, and integrate renewable energy solutions such as solar panels on facades and roofs.

Material Selection and Lifecycle Considerations

In addition to enhancing passive cooling, heating, lighting, and ventilation, sustainable building structures contribute to long-term environmental sustainability through responsible material selection. The ideal structural materials for sustainability should:

- Be sourced from natural origins.
- Have low energy consumption throughout their life cycle.
- Avoid harmful gas emissions during production and construction.
- Be fully recyclable at the end of their lifecycle.

Among structural materials, wood and steel stand out as highly sustainable options:

- Wood is a renewable material that can be sourced naturally, requiring minimal energy for production and construction. It generates low waste and offers reusability, making it an ideal choice for low-rise sustainable buildings.
- Steel has a long lifecycle, provides durability, safety, and cost efficiency, and is widely regarded as an environmentally friendly construction system. Additionally, steel's recyclability and adaptability make it one of the most versatile materials for sustainable structural design.

This study presents a new perspective in sustainable design research by analyzing the relationship between structural flexibility and the performance of other building components. Unlike conventional studies that primarily focus on material efficiency or energy consumption, this research underscores the fundamental role of structural elements in shaping the building envelope, form, and orientation.

A key conclusion of this study is that sustainable building design should begin with the selection and design of appropriate structural systems. By integrating low-impact, energy-efficient structural elements that respond to environmental conditions, architects and engineers can achieve high-performance, climate-responsive buildings. Moving forward, the consideration of structural sustainability should be given equal priority to structural strength, ensuring that buildings not only meet functional and safety requirements but also contribute to energy conservation and ecological balance.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	M.E.Y.	M.A.Y.
C	50	50
D	50	50
S	50	50
DCP	50	50
DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50
PM	50	50
FA	50	50

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Ethical Consideration

Since this study did not involve any studies on animals or humans, ethics committee approval was not obtained.

Conflict of Interest

The authors declared that there is no conflict of interest.

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