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CHAPTER 1

Environmental Emphathy and Behavirol Awareness Developed with Medicinal and Aromatic Plants

Rabia Nurefşan Açıkgöz[1] & Muhammed Akif Açıkgöz[2]

1. Introduction

Global environmental crises are forcing humanity to reestablish its connection with nature, and therefore environmental values must be addressed not only conceptually, but also emotionally, sensorially, and behaviorally (Clayton et al., 2014; Winter & Koger, 2014). In particular, the concept of environmental empathy, which triggers individuals' sensitivity and responsibility toward the environment, emphasizes the emotional aspect of the connection with nature and forms the psychological basis for environment-based behavioral change (Tanzer & Weyandt, 2020; Barragan-Jason et al., 2024; Guo et al., 2025).

The role of nature-based educational practices in developing environmental empathy cannot be denied. Research shows that direct contact with nature not only promotes cognitive learning but also triggers sensory and emotional experiences, leading to deeper and more lasting awareness (Ienna et al., 2022; Wang et al., 2023; Li et al., 2024). At this point, medicinal and aromatic plants (MAPs) integrated into learning processes strengthen environmental awareness through multi-sensory interactions (Gutiérrez-García et al., 2024a; Gutiérrez-García et al., 2024b; Rowland, 2024).

MAPs are natural components that reflect cultural memory, appeal to the senses, and build emotional bridges between people and nature (Inoue et al., 2017; Némethy et al., 2020). Due to these properties, they are used in education, therapeutic gardens, school projects, and landscape architecture applications (Miller et al., 2021; Elnesr & Said, 2023; Amprazis & Papadopoulou, 2025).

Plants such as lavender, bergamot, lemon oil, mint, thyme, sage, and ylang-ylang, which are particularly notable for their aromatic properties, support both individual awareness and harmony with the environment (Lizarraga-Valderrama, 2021; Agarwal et al., 2022; Sattayakhom et al., 2023). Landscape architecture offers various design models that bring together the educational, ecological, and

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aesthetic dimensions of MAPs to develop environmental empathy in individuals (Wolsink, 2016; Mann et al., 2021; Johnstone et al., 2022). Healing gardens, vertical plant systems, and scent parks provide multifaceted benefits in terms of health, environmental education, and sustainability (Dushkova & Ignatieva, 2020; Nieberler-Walker et al., 2025).

In countries rich in biodiversity, such as Türkiye, the use of local medicinal plants is extremely important for cultural sustainability. For example, *Achillea arabica*, *Alliaria petiolata*, *Allium kharputense*, *Aquilegia olympica*, *Capsicum annuum*, *Coronilla scorpioides*, *Eremogone ledebouriana*, *Fritillaria imperialis*, *Fumaria officinalis*, *Geranium tuberosum*, *Gladiolus atroviolaceus*, *Hypericum lydium*, *Hypericum scabrum*, *Iris persica*, *Lotus corniculatus*, *Malva neglecta*, *Melilotus officinalis*, *Muscari comosum*, *Papaver macrostomum*, *Papaver rhoeas*, *Potentilla recta*, *Rumex scutatus*, *Rumex scutatus*, *Saponaria officinalis*, *Satureja hortensis*, *Sedum album*, *Scabiosa argentea*, *Scorzonera tomentosa*, *Sophora alopecuroides*, *Vicia peregrina*, *Urtica dioica*, *Origanum onites*, *Lavandul*a spp., and *Foeniculum vulgare* a species traditionally used in Anatolia, is actively used both in healthcare and natural landscape design (Tuna et al., 2020; Erzurumlu, 2021; Tanfer & Yener, 2024). This plays a critical role in integrating local knowledge into modern environmental education. At the global level, plants such as ginseng (*Panax ginseng*) in China (Flagg, 2021; Saras, 2023), neem (*Azadirachta indica*) in India (Gupta et al., 2021), and shiso (*Perilla frutescens*) in Japan (Jimura, 2021) are being incorporated into educational projects to establish the link between cultural heritage and nature education. These practices serve as examples for the design of intercultural environmental education policies.

This book chapter aims to discuss how MAPs can be used in landscape architecture to develop environmental empathy and behavioral awareness. Thesene with UNESCO's Education for Sustainable Development (ESD) framework (UNESCO, 2020), the use of these plants in sensory landscapes and thematic educational areas will contribute to the development of multidimensional sustainability skills (Amprazis & Papadopoulou, 2025).

Therefore, landscape-based educational approaches that enable reconnection with nature are an important step in supporting both individual behavioral change and social ecological transformation. Throughout this section, scientific literature obtained from reputable databases such as Elsevier, Springer, MDPI, PubMed, Wiley, and Taylor & Francis will be used as a basis to discuss the educational, spatial, and cultural ways of reconnecting with nature.

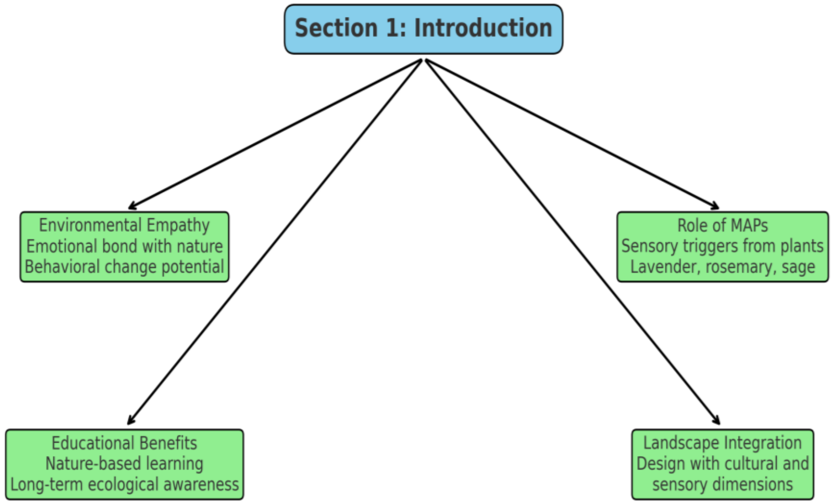

Figure 1. A schematic summary of the key elements presented in Section 1. The visual outlines the conceptual foundations of environmental empathy, highlighting the role of medicinal and aromatic plants (MAPs) in triggering sensory awareness. The diagram also emphasizes the educational and landscape integration dimensions, reflecting how MAPs support behavioral change and environmental consciousness through experiential and multisensory design.

2. Environmental Empathy Developed with Medicinal and Aromatic Plants (MAPs) in the Context of Landscape Architecture

Landscape architecture is a field that encompasses not only the aesthetic arrangement of spaces but also planning that strengthens the relationship between humans and nature (Chen & Wu, 2009; Prominski, 2014). The way we connect with nature is directly related to design. Therefore, it is extremely important for landscape architects to develop approaches that support environmental empathy (Xi & Wang, 2022; Nguyen-Dinh & Zhang, 2025).

MAPs have the potential to be both visually and sensorially appealing in landscape design (Krzepowska-Moszkowicz et al., 2025). The scent of thyme in gardens, the texture of lavender encountered on walking paths, or the colors of mint observed in vertical gardens facilitate the formation of a sensory connection with nature in individuals (Lygum & Xiao, 2025). This connection lays the groundwork for environmental awareness and empathy (Rushing, 2011).

Healing gardens are notable examples of this approach. These spaces, which are often designed for hospitals, rehabilitation centers, or schools, provide users with not only peace of mind but also the opportunity to establish a sensory connection with nature (Marcus & Sachs, 2013; Souter-Brown, 2014; Dinu Roman Szabo et al., 2023).

In recent years, there has been an increase in sensory landscape design around the world. These landscape elements, which appeal to the senses of touch, smell, sight, and hearing, arouse curiosity and emotion in users toward nature. This experience contributes to individuals developing more environmentally conscious behaviors (He et al., 2022; Li, 2024).

In Turkey, medicinal plants are traditionally included in many parks and gardens. Designing these plants with a functional and thematic approach further enhances the educational and cultural value of these parks. For example, some "sensory gardens" established in Izmir are successful examples of this approach (Gülgün & Öztürk, 2020).

In an international context, the "Zen Gardens" designed in Japan (Tagsold, 2017; Khalilnezhad, 2025; Tagsold, 2025), the "Aromatic Thematic Parks" in Portugal (Camejo-Rodrigues et al., 2003), or the "Healing Landscape Institute" in China (Jiang, 2014) are examples of landscapes that enhance sensory empathy with nature.

Landscape architecture requires designing not only ecological but also social and emotional dimensions in line with sustainability principles. The use of MAPs in this context is valuable not only for creating green spaces but also for building meaningful and sensory connections (Dinu Roman Szabo et al., 2023; Tabassum, 2025).

In summary, landscape architecture is not only a guide on the journey back to nature, but also a discipline that helps us develop empathy. The connection established with MAPs has the potential to shape not only space but also the human being.

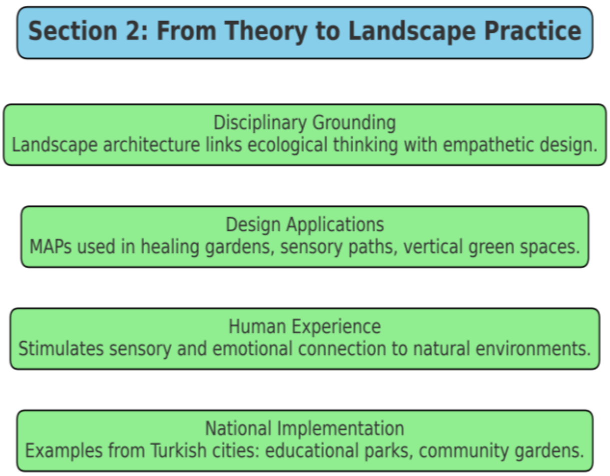

Figure 2. Enhanced flowchart for Section 2.

3. Behavioral Awareness and Nature-Based Education Methods

Behavioral awareness refers to individuals reflecting their relationship with nature not only on an intellectual level, but also in their daily behaviors through the influence of their emotions and attitudes (Otto & Pensini, 2017; Collado et al., 2020; Najmina et al., 2025). It is a widely accepted fact that human activities contribute to environmental degradation. In this context, understanding and encouraging individual behaviors toward sustainability is of great importance for environmental protection strategies. Environmental education is used as an effective tool in addressing environmental issues, but it does not merely aim to transfer knowledge; it seeks to strengthen individuals' connections with nature and guide them toward lasting and meaningful behaviors (Sachyani & Gal, 2025; Saefudin et al., 2025; Southey, 2025).

In line with sustainable development goals, education should be considered not only as a technical requirement but also as a fundamental component of social transformation (Akinsemolu & Onyeaka, 2025; Alam, 2025).

As Profeti & Toth (2025) point out, individuals must be internally motivated to address environmental issues (Yin et al., 2025). This is because external incentives (incentives, sanctions, etc.) often have limited and short-term effects and may encounter resistance (Underhill, 2016). Supporting individuals' intrinsic motivation is one of the fundamental goals of environmental education to foster sustainable environmental behaviors (Barszcz et al., 2023; Bukhari et al., 2023). Considering that environmentally friendly values acquired during childhood shape an individual's lifelong attitudes, environmental education provided at an early age plays a critical role (Evans et al., 2018). Educational environments that involve direct interaction with nature, such as forest schools and nature conservation centers, contribute to children establishing a deeper connection with the environment and developing their ecological behaviors.

Landscape architecture offers concrete solutions for how this awareness can be reflected in physical spaces. Designs that incorporate MAPs strengthen the individual's behavioral connection to nature (Ebadi & Mohebi, 2024). In nature-based education, the field of landscape architecture offers strategies that enhance the educational and sensory functionality of natural spaces (Falzon & Conrad, 2024). Thematic areas featuring aromatic plants support cognitive-emotional integration in the learning process (Nuiden, 2018; Xiao & Liu, 2025). Some of the educational methods are as follows:

Garden-Based Learning: Educational gardens featuring plants such as lavender, basil, and thyme enhance children's environmental awareness and empathy (Amprazis & Papadopoulou, 2025).

Sensory Gardens: Sensory landscape projects implemented in urban school areas support learning through contact with nature and encourage environmentally conscious behavior (Hussein, 2012; Marinho et al., 2024).

Participatory Design: Processes that involve students in decisions such as plant selection and placement reinforce a sense of belonging and responsibility (Stephenson Reaves et al., 2022).

Studies conducted in the UK have shown that designs using aromatic plants in nature-based learning areas stimulate children's senses and increase behavioral awareness (Ullerup Mathers, 2022). Studies in Sweden have shown that aromatic gardens strengthen emotional connection and awareness with the environment (Pálsdóttir et al., 2021). Similarly, studies in France have shown that green spaces strengthen emotional connection with the environment and social relationships (Fu et al., 2025).

All these studies reveal that environmental awareness and behavioral change are not limited to classroom knowledge transfer; they can be made permanent through interactive, sensory, and participatory spaces designed by landscape architects. For this reason, medicinal plants are considered multifunctional landscape components that promote behavioral awareness and combine the pedagogical and spatial power of nature-based education with landscape architecture.

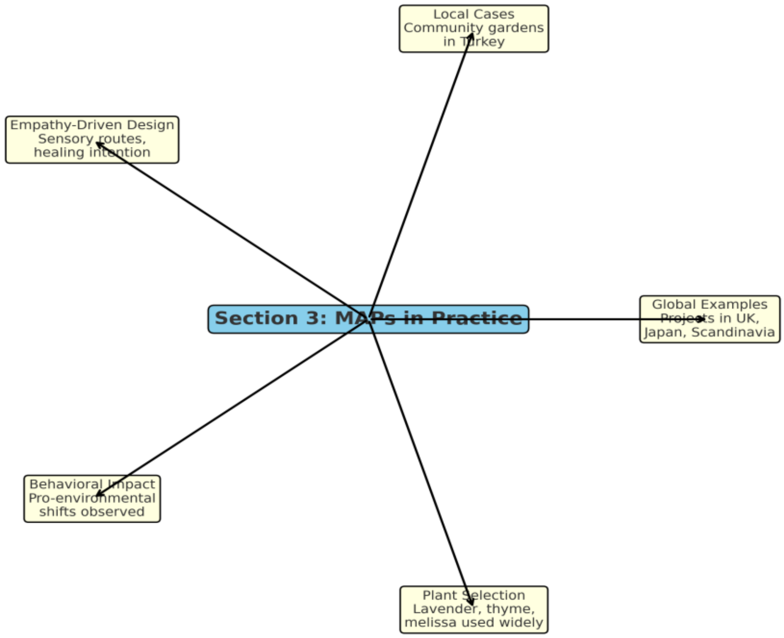

Figure 3. This circular schematic summarizes Section 3, emphasizing the application of medicinal and aromatic plants (MAPs) in real-world settings. It includes international case studies from the UK, Japan, and Scandinavia, alongside community-based projects in Turkey. The diagram illustrates how empathy-driven design elements such as sensory pathways and healing gardens enable behavioral transformation. Specific plant choices, including lavender and thyme, are shown to reinforce emotional bonds and ecological awareness.

4. Evaluation of Medicinal and Aromatic Plant-Based Designs in the Context of Sustainability

MAPs play an important role not only in terms of health and traditional knowledge, but also in sustainable landscape design (Mahato et al., 2025). Today, these plants are increasingly being integrated into urban landscape design in line with sustainability and well-being goals. This approach aligns with contemporary ecological urbanization principles that promote green infrastructure and socio-cultural resilience through multi-functional spaces (Beatley, 2011; Eroğlu, 2025).

The inclusion of medicinal plants in public and private green spaces not only contributes to the conservation of biological diversity but also provides cultural ecosystem services such as aesthetic value, spiritual enrichment, and heritage preservation (Plieninger et al., 2015). This study evaluates medicinal plant-based designs in terms of ecological, social, and cultural sustainability. It serves purposes such as the conservation of natural resources, reduction of water consumption, and support for local plant species (Marcelino et al., 2023; Shukla et al., 2025). Landscape architects are creating designs that integrate with nature by transforming these plants into green spaces that are both aesthetically pleasing and produce ecosystem services (Ebadi & Mohebi, 2024).

In today's urban landscapes, there is growing interest in the use of MAPs in line with sustainability principles. These plants offer effective solutions, particularly in combating drought, thanks to their ability to easily adapt to different climatic and soil conditions and their low water requirements (Hernández-Bolaños et al., 2025). Additionally, they contribute to the preservation of landscape areas aimed at balancing the density of structures resulting from rapid urbanization.

In the landscape design process, plant selection is based not only on the morphological characteristics of plants (such as flowers, leaves, and fruits) but also on their functional contributions to the ecosystem and their versatile uses (Uprety et al., 2012). Medicinal and aromatic species establish a connection between humans and the environment through their visual richness and sensory effects (Arslan et al., 2018). These plants have the potential to support the local economy beyond their aesthetic contributions. For example, landscape designs using native species reduce maintenance costs and minimize water requirements, thereby promoting efficient use of resources (Hardberger et al., 2025). Kokkinou et al. (2016) emphasize that green roof systems established with MAPs have positive environmental, economic, and visual effects.

The fundamental principles of sustainable landscaping environmental balance, biodiversity, and low maintenance requirements are reinforced by the integration of medicinal plants into landscapes. Drought-resistant plants such as lavender, thyme, and sage enable green space design that is compatible with the climate crisis (Chace, 2022; Cavanaugh, 2025). Therefore, sustainability encompasses not only resource efficiency but also establishing a connection between users and nature (Islam, 2025).

Medicinal plant-based designs serve as tools for environmental education, intergenerational knowledge transfer, and supporting cultural continuity (Rexhepi & Bajrami, 2025). They promote environmental empathy, a psychological structure that deepens emotional connections with nature and fosters empathy with the environment, thereby increasing environmentally friendly behaviors and public interest in green spaces (Xiao & Liu, 2025).

The sensory dimension of these designs is very important. By appealing to the five senses sight, smell, touch, taste, and sound they provide a sense of belonging to the space and mental renewal (Morgan, 2023). In multicultural urban contexts, these gardens reflect biocultural diversity and develop inclusive sustainability narratives that respect local practices (Barthel et al., 2010).

Such designs contribute to urban ecological networks by providing habitats that support local biodiversity and promoting resource cycling. They also offer benefits such as reducing the urban heat island effect and promoting the use of native plants by supporting ecosystem-based adaptation strategies in the face of climate change (Saaroni et al., 2018). When selecting plants for landscapes, ecological indicators such as secondary metabolite production and phenological compatibility should be prioritized (Kumar & Pandey, 2013).

Despite all their benefits, medicinal plant-based designs face limitations in terms of standardization, quantitative assessment of abstract benefits, and integration into mainstream landscape policies. Cultural ecosystem services derived from these areas, such as spiritual value or cultural heritage, may be overlooked in traditional environmental valuation systems (Cheng et al., 2019; Yang & Cao, 2022). Additionally, insufficient interdisciplinary collaboration between landscape architects, ecologists, and ethnobotanists hinders the full realization of this integration.

Another challenge is maintenance and social participation. Without social participation, the cultural value and ecological functions of these gardens may diminish over time. Participatory design processes and adaptable management frameworks are necessary for long-term sustainability and resilience (Jansson & Lindgren, 2012; Kohout & Kopp, 2020).

Medicinal plant-based green spaces contribute not only to biodiversity but also to ecosystem services such as mental health, air quality, and carbon sequestration (Sen & Samanta, 2014; Singh et al., 2025). Huang & Yuan (2025) emphasize the capacity of gardens with aromatic plants to reduce stress levels and enhance psychological well-being among urban individuals. They also note that such gardens contribute to urban agriculture, education, and participatory planning.

Landscape architecture plays a key role in the design of sustainable cities that are in harmony with nature. Thematic areas created with medicinal plants will clearly offer multidimensional benefits such as education, health, cultural identity, and empathy with nature. These approaches are one of the fundamental strategies for building not only today's but also tomorrow's nature-based cities.

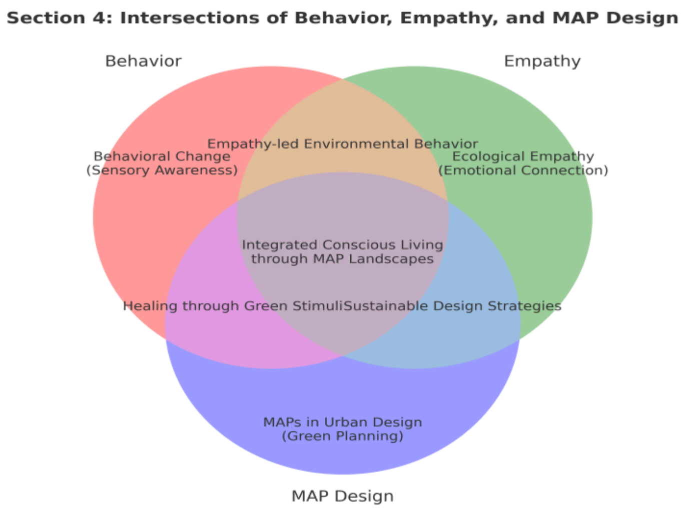

Figure 4. This Venn diagram visualizes the conceptual intersections explored in Section 4. It illustrates how behavioral change, ecological empathy, and medicinal/aromatic plant (MAP) landscape design overlaps to foster integrated environmental awareness. Central convergence highlights 'conscious living' as an outcome of sensory engagement, emotional connectivity, and design-based ecological planning.

5. General Evaluation and Conclusion

Medicinal and aromatic plants play an important role not only in traditional health practices but also in the development of environmental awareness, empathetic bonds, and sustainable behaviors. As discussed throughout this study, revealing the sensory, psychological, and educational aspects of these plants through landscape architecture enables the establishment of meaningful and lasting bonds between individuals and nature.

Healing gardens, theme parks, and environmental education projects implemented in Turkey and other countries demonstrate that sensory contact with nature can positively influence individuals' attitudes toward the environment. Plants such as lavender, thyme, and sage evoke memories with their scents, enrich the experience with their textures, and represent cultural continuity.

Therefore, MAPs should be considered not only as ornamental plants in landscape architecture but also as one of the fundamental tools of environmental education. It is important to promote sensory learning environments based on such plans to develop empathy, foster a sense of responsibility towards nature, and facilitate behavioral transformation, especially in children.

It is imperative that landscape architects develop design strategies that recognize local vegetation, preserve cultural values, and promote environmental awareness. At this point, multidisciplinary collaborations, nature-based solutions, and inclusive practices that encompass different segments of society should come to the fore.

In conclusion, this book chapter provides a comprehensive framework enriched with current literature on how MAPs can trigger environmental empathy and behavioral awareness within the scope of landscape architecture. Future applications and research will further highlight the spatial and emotional functions of these plants.

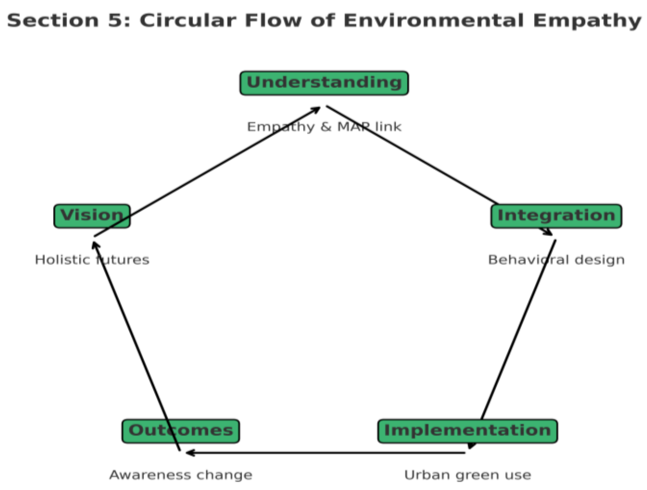

Figure 5. This circular flow diagram illustrates the dynamic relationship between key phases in environmental empathy development. Beginning with understanding the empathy-MAPs connection, the model flows through behavioral design integration, practical urban implementations, perceived outcomes, and concludes with a vision for sustainable, empathy-centered landscape futures.

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CHAPTER 2

Multisensory and Perceptual Landscape Design: Green View as an Index for Liveability

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1. Introduction

Contemporary urban planning considers the relationship between individuals and their physical environment not only in terms of visual aesthetics but also in terms of the integrity of sensory experiences (Qu & Ma, 2024; Aelbrecht et al., 2025). The concept of livability is evaluated based on multidimensional criteria such as psychological well-being, social interaction, and environmental justice, while the "green view" sheds light on the neuroscientific and psychosocial foundations of this concept through the individual's visual contact with nature (Bai et al., 2024; Papastergiou et al., 2025). The stress-reducing, attention-focusing, and emotional balance-providing effects of natural landscapes play a critical role in reducing the mental burden experienced under urban density (Korpillo et al., 2024; Tomasso et al., 2025).

Therefore, the sensory landscape offers a perception of the environment that goes beyond mere visuality, integrating auditory, olfactory, tactile, and even gustatory senses into the experience of nature (Shuoxian, 2024). Concepts such as "smellscape" and "soundscape" reveal the cultural, phenomenological, and neuroaesthetic dimensions of spatial designs (Wang et al., 2024; Kou et al., 2025), the green view index enables these experiences to be quantitatively evaluated at the urban scale (Özyılmaz Küçükyağcı, 2025). Thus, the sensory landscape becomes an interdisciplinary field that structures individuals' connections with nature through both scientific and artistic approaches (Kühne et al., 2023a; Zheng et al., 2025).

Theoretical fields such as sensory geography and cultural ecosystem services support the process of understanding the sensory dimension of individuals' multi-layered relationships with space (Cao et al., 2025; Xu et al., 2025). These approaches indicate that spatial perception is not only based on physical coordinates but also intertwined with memory, identity, and cultural context (Yingying & Pillai, 2025). Therefore, landscape design is now evolving into a

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form of architecture that goes beyond aesthetics and focuses on lived experiences (Zhang et al., 2025).

The sensory effects created by the olfactory and aromatic profiles of secondary metabolites play a role in stress reduction, emotion regulation, and memory triggering in neuroscientific studies (Hao et al., 2025). These biochemical components should be considered not only for their ecological benefits but also for their psychological benefits in the plant selection process (Rabeh et al., 2025). Especially in therapeutic and educational landscapes, the integration of these components with multi-sensory architecture can create ideal living spaces for both children and the elderly (Malhotra & Abrol, 2024; Lu et al., 2025).

Sensory landscapes can also become a pedagogical tool in terms of sustainability and environmental awareness (Beery, 2025; Hu & Mou, 2025). Designs that engage the five senses help develop skills such as empathy, attention, and a love of nature in children, while in adults they help reduce stress and fulfill the need to reconnect with nature (Masters et al., 2023; Spangenberger et al., 2024). In this regard, sensory design emerges as an effective approach in transforming environmental attitudes and behaviors.

This book chapter aims to address the topic of sensory landscape at both theoretical and practical levels, with the goal of filling various gaps in existing literature. Comprehensive research conducted in international databases such as Elsevier, Springer, MDPI, PubMed, Taylor & Francis, and Wiley indicate that the topic is gaining increasing importance; however, they also reveal that studies comprehensively addressing the relationship between the green view index and sensory experience are limited in number. Current studies typically focus on a single sensory dimension, often neglecting intermodal transitions and neuroscientific backgrounds.

In this context, the book chapter aims to go beyond visual dominance and demonstrate how the landscape gains meaning through its auditory, olfactory, tactile, and gustatory sensory elements; it seeks to explain the physical, psychological, and cultural effects of sensory design on individuals through a multidisciplinary approach. By bridging the fields of urban planning, architecture, environmental psychology, art, and health sciences, it seeks to contribute to redefining sensory landscapes not only in terms of aesthetics but also in terms of social inclusivity and ecological ethics.

2. Sensory Liveability Approach: Conceptual Framework and the Role of Visual Greenery

Liveability is shaped not only by the quality of the physical environment, but also by individuals' psychological well-being, social interactions, and perceptions of environmental justice (Yamaguchi & Oshima, 2024; Dobson & Redman, 2025). In urban planning, livability is evaluated based on multidimensional criteria such as sustainability, accessibility, and aesthetics (Alidoust, 2024; Sádaba et al., 2024). Therefore, livability should be addressed within an interdisciplinary framework.

Green views create effects such as stress reduction, attention focus, and emotional balance through individuals' visual contact with nature (Fleming et al., 2024; Jing et al., 2024). In particular, the presence of green spaces in window views has been associated with shorter recovery times and reduced medication use in hospital patients (Jafarifiroozabadi et al., 2023; Suess & Maddock, 2025).

Landscape perception is not only visual; it is shaped by auditory, olfactory, tactile, and proprioceptive stimuli (Kühne et al., 2023a; Berr, 2023). Concepts such as smellscape and soundscape highlight the dimensions of sensory landscape that should be considered in urban planning (Palmese et al., 2024).

The sensory landscape experience depends not only on physical stimuli but also on the individual's responses at the levels of perception, emotion, and behavior. In this context, Agapito et al. (2013) have identified three fundamental components that shape destination image: cognitive, affective, and conative. This model considers an individual's knowledge and beliefs about a place (cognitive), their feelings toward that place (affective), and the potential for those feelings to translate into behavior (conative) as a whole.

Chan et al. (2012) emphasized that intangible values are not adequately represented in ecosystem services research and developed a comprehensive framework to fill this gap. This framework aims to integrate spiritual, aesthetic, identity, and relational values into decision-making processes.

The green view index is an indicator that quantitatively measures the amount of green space individuals see from their windows. This index is important for ensuring spatial justice and planning green access in urban density areas (Bolte et al., 2024). The green view index provides multi-scale analyses supported by 3D modeling and LiDAR data.

Functional magnetic resonance imaging (fMRI) studies show that natural landscapes activate the brain's reward centers (Zhang et al., 2019). This activation reveals the neuroscientific foundations of the emotional connection individuals form with nature. Different brain regions are activated between artificial and natural landscapes (Vartanian et al., 2015).

Sensory perception is shaped by an individual's social context and cultural background. The same landscape can elicit different emotional and cognitive responses in different individuals (Liao, 2025). Therefore, cultural sensitivity and social participation are important in landscape design.

3D visualization and sound simulations can be used to predict the user experience in landscape design (Lindquist & Lange, 2014). These simulations increase sensory realism in the planning process and support participatory processes.

Interactions with nature have historically focused on visuality. However, in recent years, the multidimensional nature of sensory experiences has begun to receive more attention. Franco et al. (2017) addressed the multisensory aspects of nature experiences, noting that visual dominance overshadows other senses. Their research reveals that senses such as hearing, smell, touch, and even taste are integrated into nature experiences and have significant effects on health and psychological well-being. The theoretical foundations of this approach are also emphasized in Rodaway's work "Sensuous Geographies," which details how senses such as touch, smell, hearing, and sight shape spatial perception (Rodaway, 2002).

Therefore, sensory landscape perception should encompass not only what is visible, but also the overall experience. This approach, which goes beyond the visual, allows for the development of innovative strategies that encourage inter-sensory transitions in landscape design.

3. Sensory Landscape Perception: Sensory Geography, Microclimatic Effects, Plant Selection, and the Role of Secondary Metabolites Multiple Senses

The sensory landscape experience is not merely the passive perception of environmental stimuli, but also the active interaction between the individual and the lived space (Koegst et al., 2023). The theoretical foundation of this approach draws from the discipline of phenomenology (Evans et al., 2023). Batool & Bahauddin (2025) point out that space is not merely a physical coordinate system, but a lived space woven with the individual's memories, emotions, and sensory responses. Kim et al. (2021) argue that sensory patterns emerging in everyday life reinforce spatial loyalty and a sense of belonging. These theories provide a vital framework for understanding how the sensory landscape facilitates the transition between an individual's inner world and their external environment. The sensory landscape constructs the human-nature relationship not only through physical senses but also through the individual's psychological and cultural layers (Wu et al., 2024; Liu et al., 2025). Studies by Olivos & Clayton (2016), Sierra-Barón et al. (2023), and Bratman et al. (2024) demonstrate that natural environments create spiritual calmness, a sense of identity, and belonging in individuals through scent, sound, and visual elements.

How the senses shape landscape perception is an increasingly important area of research within the discipline of sensory geography. Zheng et al. (2024) lay the foundation for sensory geography by critiquing the limitations of visually focused landscape approaches and highlighting the role that senses such as hearing, smell, and touch play in spatial experience. This approach enables individuals to perceive their surroundings not only as visual images but also as sensory patterns (Guo et al., 2024; Ito et al., 2024). In sensory landscape design, microclimatic factors such as temperature, humidity, wind, and sunlight directly affect the quality of the sensory connection an individual establishes with their environment. These factors manifest themselves not only at the physiological perception level but also in psychological comfort, spatial preferences, and behavioral interaction patterns (Junfeng & Nuo, 2025).

Expanding on this theoretical line, Palat Narayanan (2023) explains how landscape perception is constructed in a multisensory manner through social patterns. His research reveals that individuals focus on different senses depending on their socio-cultural context, and that these differences are decisive in the relationship established with the landscape. Therefore, the sensory landscape is not only biophysical but also a culturally shaped structure of perception (Hegetschweiler et al., 2023).

The systematic functioning of the sensory landscape is also important for its understanding. In this context, Lämmchen (2023) addresses the multisensory nature of landscape within the framework of systems theory, defining the interaction between visual, auditory, olfactory, and tactile components as a complex but meaningful network of relationships. Landscape is not merely an environment; it is the perceived and interpreted surface of a system.

This approach encourages treating the landscape as a sensory whole rather than dividing it into parts. The transitions and interactions between different senses enhance the depth of the individual's connection with their environment. Especially in urban planning processes, the simultaneous and balanced design of sensory components can increase the livability of space. This systematic perspective allows for the evaluation of sensory landscapes in terms of both sensory diversity and functional integration.

In the context of cultural ecosystem services, lavender and basil trigger childhood memories and create nostalgic connections (Hølleland et al., 2017; Gould et al., 2025). Elements such as the sound of flowing water or birdsong help reduce mental stress (Ratcliffe et al., 2013; Fan & Baharum, 2024). Color schemes, texture transitions, and visual rhythms provide psychological balance beyond simply evoking aesthetic pleasure (Nemcsics et al., 2023). These sensory-based spiritual experiences strengthen individuals' connections with nature. In this sense, the sensory landscape is not merely a physical space but transforms into a cultural and spiritual space that is lived and felt. Zhang et al. (2024) and Alharthi et al. (2025) state that the microclimatic comfort levels of urban open spaces determine how individuals use the space, and that elements such as shading, airflow, and heat reflection increase the livability of the sensory landscape. Wu et al. (2023) and Pandya et al. (2025) emphasize that thermal comfort affects sensory perception and shapes the individual's relationship with the natural environment. Extreme temperatures or wind can diminish the quality of the spatial experience. Farhadi et al. (2025), Lenzi et al. (2025), and Sádaba et al. (2025) emphasize the necessity of considering human adaptation to different climatic conditions in design to sustain the sensory appeal of the landscape.

Shade-providing plants (*Platanus* spp., *Ginkgo* biloba) combine visual aesthetics and thermal comfort to reduce the negative effects of temperature on sensory perception (Lam et al., 2020; Wang et al., 2023; Elsadek et al., 2024). Aromatic moisture-loving plants (*Mentha* spp., *Pelargonium graveolens*) offer both olfactory richness and the potential to thrive in humid microclimate conditions (Kafa et al., 2022). Wind-filtering shrubs (*Rosmarinus officinalis*, *Viburnum* spp.) balance the perceived airflow, thereby reducing physical discomfort (Shabani et al., 2019). Integrating these variables into design processes enables the landscape to be conceived not only as aesthetically pleasing but also as a sensorially comfortable and sustainable environment. The success of sensory landscapes is directly related to the extent to which the selected plants can stimulate the five senses. International literature emphasizes not only aesthetic criteria but also multi-dimensional criteria such as ecological suitability, maintenance requirements, and sensory richness in plant selection. Dunnett & Hitchmough (2004) argue that plants with visual appeal, as well as olfactory, auditory, and tactile qualities should be preferred for multi-sensory landscapes. Dinu Roman Szabo et al. (2023) note that in sensory gardens designed specifically for children and the elderly, the tactile and olfactory properties of plants play an important role as neurological stimuli. Marcus & Sachs (2013) suggest that in therapeutic landscape design, plants that directly appeal to the senses can be effective in reducing individuals' stress levels.

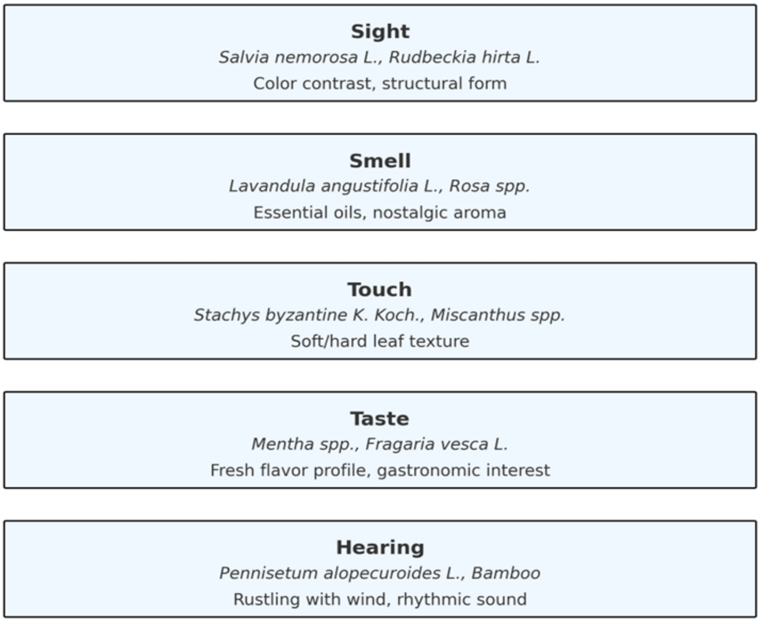

Figure 1. This diagram represents sensory experiences associated with various plant species. Each box includes a sensory type, corresponding plant names, and their sensory attributes.

Species that are compatible with the region and plants that harmonize with the local flora are important in terms of sustainability. Xerophytic species, which require little maintenance and conserve water, are particularly advantageous in arid regions. Wildlife-supporting species, such as those that attract pollinators like bees, birds, and butterflies, enrich the sensory landscape with ecosystem services. This framework allows for the evaluation of plant selection not only based on aesthetic considerations but also on sensory, ecological, and cultural dimensions. The experience created by sensory landscapes is not limited to visual and physical characteristics. Secondary metabolites produced by plants have a powerful effect on the senses. These compounds transform the chemical communication established by the plant with its environment into an experience perceived by humans at sensory and cognitive levels.

Simsek & Whitney (2024) and Upadhyay et al. (2025) emphasize the effect of secondary metabolites on animals (and humans) through their odor and taste profiles, in addition to their role in plant defense mechanisms. Huang et al. (2022) note that alkaloids, flavonoids, and terpenoids play both pharmacological and sensory roles. Rodríguez-Landa et al. (2023) and Samal et al. (2024) highlight the effects of secondary metabolites in fields such as aromatherapy and landscape therapy, revealing the potential of these compounds for emotional regulation and stress reduction. These compounds have functions such as creating aroma zones to guide or mark relaxation areas in a space, emphasizing seasonal transitions with visual pigment richness, and providing mental relaxation by utilizing olfactory stimuli in sensory therapy areas (Semmar, 2024). These compounds ensure that sensory landscapes offer not only an aesthetic experience but also one that is effective at the bioactive and psychological levels (Khade et al., 2023).

Table 1. Sensory Effects of Secondary

Compound Type	**Compound Type**	**Compound Type**	**Compound Type**
Linalool	*Lavandula angustifolia* L.	Relaxing scent	Stress-reducing, sedative
Menthol	*Mentha* spp.	Refreshing taste and aroma	Mild analgesic, stimulant
Geraniol	*Pelargonium graveolens* L.	Floral, sweet scent	Anti-bacterial, emotional balance
Anthocyanin	*Salvia splendens* L., *Rubus* spp.	Red-purple pigments	Visual aesthetics, antioxidant
Camphor	*Rosmarinus officinalis* L.	Sharp scent, mild cooling	Muscle relaxant, stimulant

4. Neurological Impact, Social Inclusion, and Sustainable Behaviors

The effects of sensory landscapes on humans also depend on how the brain perceives, interprets, and transforms these stimuli into emotional processes. Neuroscientific studies show that environmental components perceived through the senses are closely related to mental health, attention levels, stress regulation, and memory (Olszewska-Guizzo et al., 2023; Kühn & Gallinat, 2024). Gaekwad et al. (2023) and Razumnikova et al. (2024) have demonstrated that natural landscapes regulate stress response regions in the brain cortex and trigger rapid emotional recovery. Marchioro et al. (2024), McDonnell & Strayer (2025), and Piedimonte et al. (2025) have indicated that natural environments reduce cognitive fatigue and reorganize attention capacity. Friedman & Robbins (2022) and Funahashi (2022) have shown that natural sounds, textures, and visual components have positive effects on the prefrontal cortex, which is associated with executive functions. Rodríguez-Landa et al. (2023) have shown that aromatic plants and scents trigger emotional memory through the limbic system and create inner peace in individuals.

This neurological interaction plays a critical role in reducing sensory stress by creating neural relaxation zones. Selecting plant species according to neuroaesthetic principles ensures that balanced combinations of color, form, and texture cognitively optimize visual perception (Bhowmick et al., 2024; Nayak et al., 2025). This approach enhances brain-body interaction through multisensory routes that bring together sensory components. Smell, tactile stimuli, microclimatic elements, and visual composition increase the psychological and physiological effects of the landscape on users. Thus, such spaces become areas of mental restoration that contribute to individual well-being within the scope of cultural ecosystem services.

Table 2. The neuroscientific effects of sensory components

Plant Type	Sensory Stimulus	Brain Region	Effect
Acer palmatum, *Lavatera* spp	Natural visual motifs	Prefrontal cortex	Attention restoration, mental clarity
Stachys byzantina, *Carex* spp.	Soft textures	Somatosensory cortex	Physical comfort, tactile security
Lavandula spp., *Thymus* spp.	Aromatic scents	Limbic system	Memory trigger, emotional balance
Phragmites australis, Bamboo	Rhythmic natural sounds	Temporal lobe	Sound-based emotion regulation Visual aesthetics

Sensory landscapes gain deeper functionality when designed as spaces that promote social inclusion. Sensory-based design approaches for different age groups, people with disabilities, and people from diverse cultural backgrounds increase spatial justice and participation. Capolongo et al. (2023) and Marques et al. (2023) emphasize the physical and sensory accessibility of therapeutic landscapes, focusing on the design of safe, stimulating, and meaningful spaces for older adults. Oji et al. (2023) argue that sensory barriers must be removed beyond physical barriers. For example, aromatic plants and tactile surfaces can facilitate spatial orientation for blind individuals. Lee et al. (2025) examine the cross-cultural variability of aesthetic experience, highlighting that sensory landscapes can be interpreted through different cultural codes.

Sensory landscapes are powerful tools that facilitate the perception of ecosystem services that contribute to environmental sustainability. The visual, olfactory, auditory, and tactile stimuli provided by plants lay the groundwork for developing ecological empathy in individuals, thereby fostering a more responsible relationship with nature. Bratman et al. (2025) emphasize that ecosystem services offer not only economic but also cultural and psychological benefits. Løvoll & Sæther (2022), Ohlsson (2022), and Buchtova et al. (2024) argue that sensory and spiritual experiences have the potential to transform people's behavior toward nature. Zhang & Song (2022), Holzer et al. (2024), and

Schilhab & Esbensen (2025) report that nature connection developed through sensory stimulation positively influences environmentally friendly decision-making processes.

5. Pedagogical Approaches, Aesthetic Philosophy, and Interdisciplinary Integration

Sensory landscapes have high pedagogical potential in terms of environmental education. Landscapes that engage the five senses make the learning process more participatory, experiential, and lasting (Beery, 2025). Such spaces facilitate the process of connecting with nature, particularly for children, the elderly, and disadvantaged individuals (Thomas, 2018). Colbert (2008) draws attention to the cognitive and emotional effects of children's disconnection from natural environments with the concept of "nature deficit disorder" and views sensory landscapes as the key to connecting with nature. Holzer et al. (2024) argue that nature-based learning has a lasting impact on environmental education, empathy development, and problem-solving skills. D'Amore & Chawla (2018) and Rosa & Collado (2019) reveal that sensory experiences established with natural areas during childhood support positive attitudes and behaviors toward the environment in later years.

Children explore nature through curiosity and play thanks to trails that include sensory stimuli such as texture, smell, and color (Moore, 2020). Each plant species can be introduced to children as a "character" and used to create narratives within an ecological context (*Melissa officinalis* - "Soothing Melissa," *Menth*a - "Cooling Mint") (Prins et al., 2022; Vella-Brodrick et al., 2024). Sensory-based activities such as producing scents with aromatic plants, painting with tactile plants, and capturing sounds with the wind deepen the pedagogical experience (Gutiérrez-García et al., 2024). Conveying plant characteristics in multiple languages to make learning inclusive for different cultural groups. Sensory stimuli can increase children's ability to focus (Vella-Brodrick et al., 2024). Individuals who engage with nature sensorially develop a sense of responsibility toward the environment. Sensory connections with non-human living beings support social skills such as empathy and sensitivity. In this context, sensory landscapes become not only a place of learned knowledge but also an environment of wisdom that is felt, experienced, and reflected in behavior (Vasilaki et al., 2025).

The experience offered by sensory landscapes is not merely a stimulation that appeals to the senses; it is also an aesthetic experience that activates the existential, cultural, and emotional contexts of human beings (Ren et al., 2025). In this context, "sense of place" and aesthetic philosophy position sensory landscapes as spaces where spatial belonging, identity, and meaning are produced (Erfani, 2024). Sutton (2024) and Batool & Bahauddin (2025) argue that "place" is not merely a location; it is a lived space shaped by human memory, emotions, and social context. Sensory elements are the carriers of this experience. Kühne et al. (2023b) define the concepts of "placelessness" and "placeness," revealing how connections established through the senses influence spatial identity. Brinck (2018), Nanay (2024), and Pizzolante et al. (2024) interpret aesthetic experience not merely as observation but as participation and feeling. From this perspective, landscape is an art form that is "experienced" through the senses. Kwon & Iedema (2022) and Mistry & Gupta (2024) describe spatial experience as an emotional relationship that develops over time and deepens through the senses. Certain aromatic plants create associations with the past in individuals, establishing an emotional connection with space. When color and form elements are combined with cultural symbols, the sense of definition and belonging to space is strengthened. Natural acoustic elements such as the sound of water and the interaction of wind with plants make the space recognizable and perceptible (Mumcu et al., 2017). Designing with the understanding that space is not merely a physical entity, but an experience shaped by the individual's perception. Planning elements that allow visitors to interact with the landscape on a sensory level (touchable plants, sound surfaces). Contributing to social identity by incorporating local motifs in plant selection and spatial design. Within this framework, sensory landscape is not merely a space where the senses are nourished; it also becomes an existential stage where emotions, identity, and memory are shaped. It offers a field enriched by interdisciplinary collaborations spanning a wide range of disciplines, from visual arts to architecture, environmental psychology to health sciences, and even literature and neuroscience. This versatility enables a deeper understanding of sensory experiences at both the individual and collective levels.

Studies on the effects of sensory stimuli on cognitive and emotional processes contribute to the positioning of landscape not only as an aesthetic tool but also as a tool for mental healing (Schreuder et al., 2016; Costa-López et al., 2021; Yin et al., 2024). Integrating sensory landscape into physiological relaxation and stress reduction processes through practices such as therapeutic gardens, aromatherapy, and horticultural therapy (Marcus & Sachs, 2013; Padilla et al., 2022). Evaluating sensory designs through interactional aesthetics strengthens the understanding of participatory art (Carrasco-Barranco, 2025). Holistic spatial experiences can be designed by integrating color, texture, sound, and smell elements into architectural spaces. Nature conservation strategies with plant diversity, microclimate, and ecosystem services enable sensory landscapes to become a tool for nature-based solutions (Kim & Hait et al., 2023).

6. General Conclusions

This comprehensive assessment of the theoretical foundations and practical approaches of sensory landscape clearly demonstrates how multidisciplinary, emotionally rich, and ecologically meaningful the field is. The connection established between the five senses and environmental components transforms the individual's perception of space at both physical and psychosocial levels. This transformation manifests itself in areas such as neuroscientific relaxation, social inclusivity, sustainable behaviors, pedagogical awareness, and aesthetic participation. Based on data from literature and design examples, sensory landscape is not merely a design approach but also an existential relationship with space. Further research into the experimental, cultural, and ethical dimensions of sensory landscape in the future will expand its social and environmental impact.

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CHAPTER 3

Innovative Approaches to Experimental and Alternative Materials in Architecture

Ahmet Cihat Ari[1]

Introduction

Materials have an important place in the design of architectural structures. The properties of materials shape the production processes of structures and affect their performance. With the advancement of material science, some innovations occur in architectural design (Bechthold & Weaver, 2017). For example, polymer composite materials are preferred over traditional materials in the repair and rehabilitation of structures due to their resistance to environmental effects and low-cost production (Rupal et al., 2022). The superior mechanical and aesthetic properties of ultra-high performance concrete over traditional concrete allow for easier construction of curved, complex and large-scale architectural structures (Kravanja, Mumtaz, & Kravanja, 2024). Improvements in the properties of materials through nanotechnology pave the way for new applications in the field of construction. Thanks to nanomaterials such as nanosilica, microsilica and titanium dioxide, materials that have the ability to detect and respond to changes in environmental effects are being developed (Ali & Kharofa, 2021).

In recent years, the use of industrial waste in the production of building materials has become increasingly common. Composites produced from waste materials have some advantages over other composites. For example, by incorporating waste into composites, it contributes to meeting the need for raw materials in construction, reducing environmental pollution and reducing production costs. Additionally, by recycling waste materials into the economy, significant benefits are provided for sustainability development goals (Raut, Ralegaonkar, & Mandavgane, 2011). Among the waste materials, wastes resulting from construction and demolition of buildings also cause serious environmental pollution. Construction waste constitutes 25-30% of all waste. (Sormunen & Kärki, 2019). For this reason, scientific studies are being conducted to reduce the harmful effects of construction waste. The use of construction waste in composites is considered as an alternative solution to the environmental pollution problem caused by waste. While mineral wool and wood are generally used as filling elements for composites produced from construction waste, thermoplastic and gypsum are used as matrix (Sormunen & Kärki, 2019). These composites have higher resistance to moisture (Hyvärinen, Ronkanen, & Kärki,

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2019). However, since the proportions of filler and matrix material affect the properties of composites positively or negatively, experimental investigations must be carried out on these materials before they can be used in the construction industry (Keskisaari, Butylina, & Kärki, 2016). It is also seen in the literature that new materials are developed by evaluating industrial and construction wastes in composites and these materials are suggested for applications in various fields in the construction industry. For example, in the study conducted by Ari (2025), the usability of composites produced using ignimbrite and pine waste as fillers and epoxy resin as matrix was examined in the restoration of civil architecture examples in Anatolia (Türkiye). In the same study, it was concluded that epoxy matrix composites can be used in the restoration of historical buildings thanks to their water resistance and high mechanical strength. In the research conducted by Kamble and Behera (2021), it was stated that improvements were achieved in the mechanical and thermal properties of the composites obtained by mixing waste glass cotton fibers in epoxy resin and that these composites could be used instead of timber. In another study conducted by Jain, Bhadauria, and Kushwah (2023), composites were developed using plastic wastes and it was found that these composites had higher compressive strength than traditional bricks and fly ash bricks. As seen in the studies in the literature, it has been stated that composites produced from waste materials can be potentially used in construction applications due to their superior properties compared to traditional materials. Researchers have emphasized that determining the optimum ratio between filler and matrix is important for the properties of composites. Moreover, relevant studies in the literature have stated that composites produced using waste materials provide significant benefits to sustainable construction.

In this study, innovative approaches to experimental and alternative materials in architecture are examined. The scope of the study includes composites, nanocomposites and smart materials produced using waste materials that have significant potential in terms of innovative approaches in material production. In this study, the production methods for each type of these materials were investigated in terms of their properties and application areas in buildings. Additionally, different properties of these materials and future study topics for their wider use in the construction industry are discussed.

Composites Produced Using Waste Materials

With the increase of industrialization in cities, there is an increase in the population rate. Despite this population growth, there is not enough building stock to accommodate people. For this reason, new buildings were built rapidly in cities. However, this increase in construction activity also causes a significant increase in construction waste. Furthermore, the increase in industrialization in cities has led to an increase in industrial waste. Construction and industrial waste have negative effects on the environment. In order to reduce and prevent the environmental impact of these wastes, they are recycled by reprocessing (Figure 1) (Khan, Balunaini, & Costa, 2024).

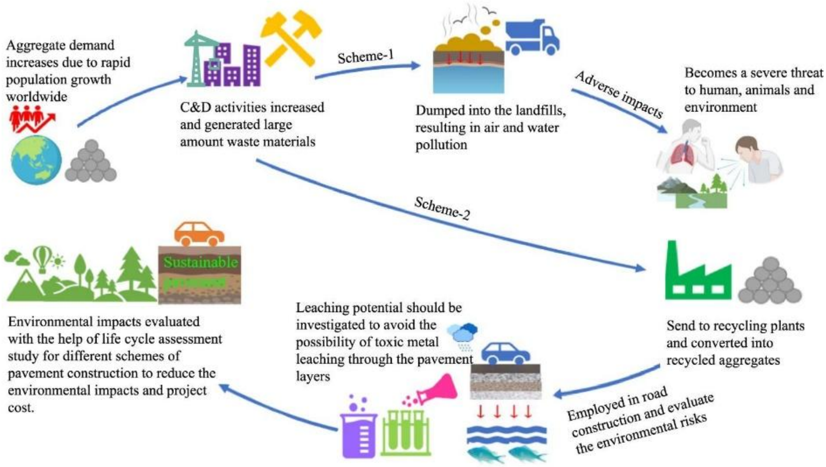

Figure 1. Schematic representation of construction and industrial waste collection and recycling (Khan et al., 2024)

New methods are being researched to recycle waste and use it in the construction industry (Althoey & Hosen, 2021). For example, the fact that agricultural waste ash-based composites are qualified in terms of mechanical strength and drying-shrinkage behavior properties enables them to be used as mortar in buildings (Figure 2) (Athira, Charitha, Athira, & Bahurudeen, 2021). Additionally, the ecological structure, biodegradability, low cost and high thermal conductivity of natural fiber materials such as agricultural waste enables the development of composite insulation materials. Therefore, it enables these materials to be shown as alternative materials in the construction industry (Sangmesh et al., 2023).

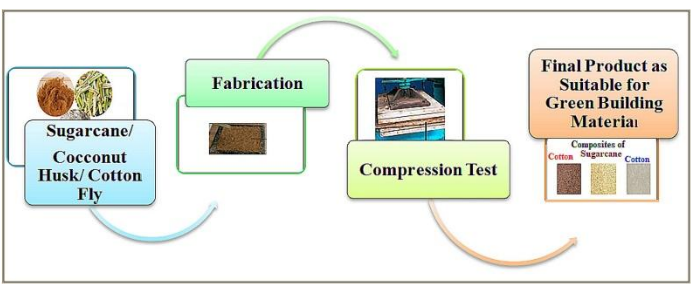

Figure 2. Schematic diagram of the development process of composites using agricultural waste materials (Sangmesh et al., 2023)

Fly ash, which is a waste of coal-fired power plants, and blast furnace slag, which is a waste of iron and steel production, contribute significantly to the improvement of the physical and mechanical properties of concrete (Figure 3) (Dey, Srinivas, Panda, Suraneni, & Sitharam, 2022). However, it has been stated that it is important to choose the correct binder ratios to produce durable composites (Ismail et al., 2014).

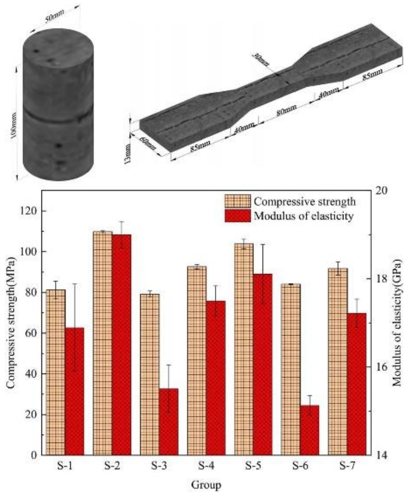

Figure 3. Improvement of mechanical properties of composites produced using fly ash and blast furnace slag (Lin et al., 2024)

Among the methods of utilizing waste materials, mixing them with another material is considered a good option. For this reason, scientists have researched high strength and low density materials (Dubey, Mishra, & Sharma, 2021). Polymer materials stand out as an alternative product to traditional materials due to their physical, mechanical and abrasion resistance and their usability in various applications. For example, in the study conducted by Alves, Strecker, Pereira, and Panzera (2020), the properties of composites produced with steatite powder and three different polymer matrix materials (epoxy polymer, white Portland cement, and pozzolanic Portland cement) for the restoration of historical buildings were investigated. Among these composites, it was determined that the composites consisting of 30% epoxy polymer and 70% steatite powder had the highest quality in terms of mechanical and physical properties. Additionally, it has been determined that epoxy matrix composites have the highest application potential in the restoration of historical monuments. By mixing plastic waste with polymer materials, improvements are made in properties such as strength and water absorption. It has been stated that these compositions can be used in structures with small square meter areas such as non-structural panels, partition walls and floor tiles (Figure 4) (Lamba, Kaur, Raj, & Sorout, 2022).

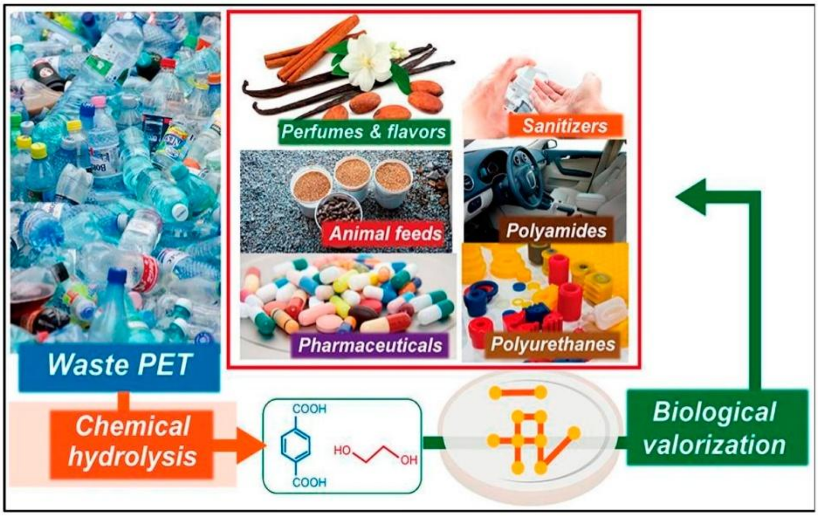

Figure 4. Schematic diagram showing the production of composites by mixing plastic waste and polymer materials (Maitlo et al., 2022)

Nanocomposites

Nanocomposites prepared using nanomaterials such as nanoclay, graphene, carbon nanotubes, molybdenum disulfide, tungsten disulfide, black phosphorus and nanofibrils are important for the development of high-performance materials (Figure 5) (Gong, Ni, Jiang, & Cheng, 2017). Materials with one-dimensional nanometers are referred to as nanocomposites (Shameem, Sasikanth, Annamalai, & Raman, 2021). Moreover, these composites have many advantages such as saving energy, reducing carbon emissions, reducing environmental pollution and increasing the service life of the building (Dong & Ma, 2025). For example, Azkorra et al. (2015) showed in their study that nanocomposites have significant potential in providing sound insulation of structures. In the study conducted by Novais, Senff, Carvalheiras, and Labrincha (2020), it was determined that the developed nanocomposites had superior qualities than many binder materials in terms of compressive strength and thermal conductivity.

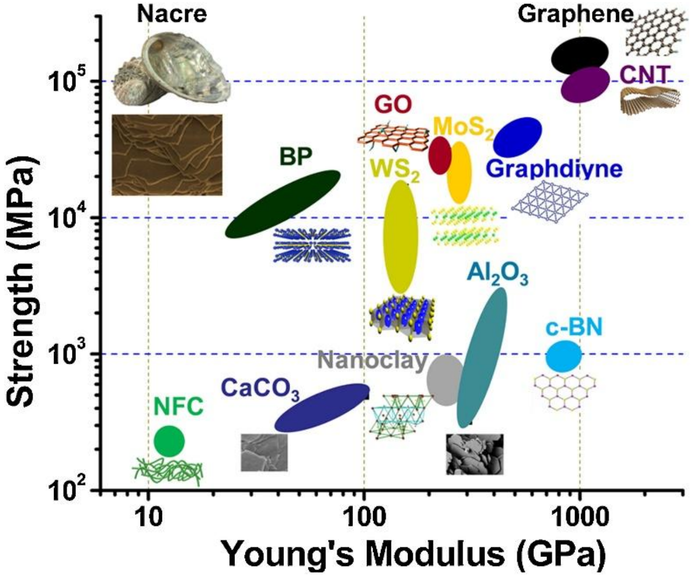

Figure 5. Graph showing the high mechanical properties of nanocomposites (Gong et al., 2017)

Nanocomposites create a strong barrier against heat and oxygen, ensuring that structures are resistant to fire. Composites produced by incorporating biopolymer matrix into nanomaterials such as nanoclay, graphene oxide and metal oxides show improvements in thermal stability and fire resistance properties (Figure 6) (Kolya & Kang, 2024). For instance, in the study conducted by Amirabadi et al. (2023), it was determined that in composites produced using nanofibers, the matrix became resistant to combustion thanks to the graphitized layer. In the research conducted by Laachachi, Leroy, Cochez, Ferriol, and Cuesta (2005), it was determined that the heat release rate of nanocomposites formed by adding nano-fillers such as titanium dioxide and iron oxide to PMMA was reduced by 50%. It was found that by adding only iron oxide nanofiller to the nanocomposites, the heat release rate was reduced by 35%. It has also been shown that the addition of titanium dioxide nanofillers to these composites increases the ignition time, while the addition of iron oxide nanofillers to the nanocomposites does not cause any change on the ignition time.

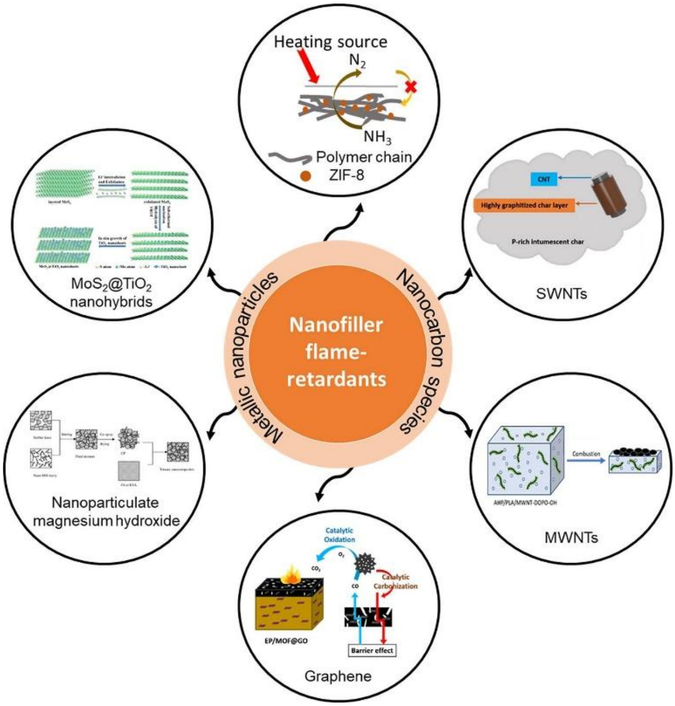

Figure 6. Schematic diagram showing that nanocomposites form a strong barrier against heat and oxygen (Kim, Lee, & Yoon, 2021)

Nanocomposites are self-cleaning thanks to their photocatalytic properties, making structures more resistant to environmental degradation effects. For example, Li, Yang, Huang, and Lu (2024) determined in their study that cement-based composites obtained by adding C_3N_4 nanomaterial were resistant to contamination under ultraviolet lights. Krishnan, Zhang, Cheng, Riang, and Yu (2013) investigated the effects of silicate coatings with TiO_2 content on photocatalytic degradation. In the same study, it was determined that the addition of TiO_2 nanomaterials in silicate coatings reduced photocatalytic degradation by approximately 40% (Figure 7).

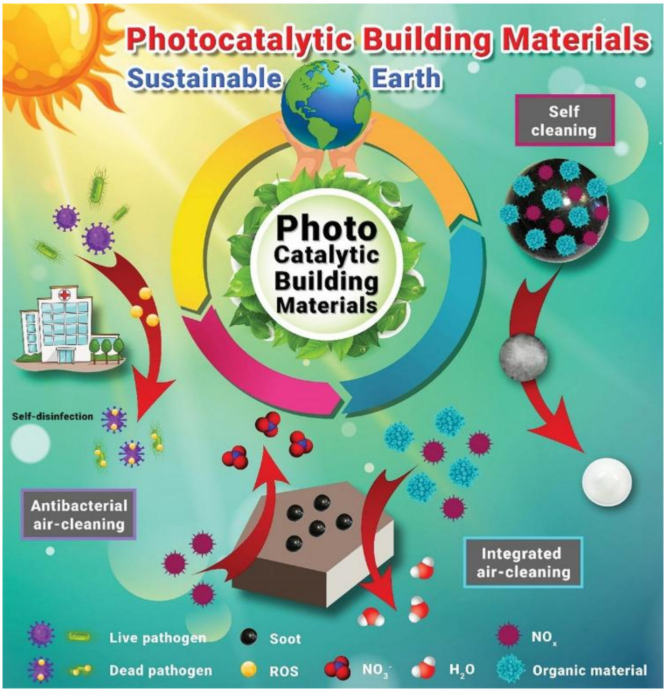

Figure 7. Schematic diagram showing the self-cleaning properties of nanocomposites due to their photocatalytic properties (Arif, Hannan Zahid, Saghir, & Mahsud, 2025)

Smart Materials

In the construction industry, the depletion of raw materials and the inadequacy of existing structures due to global population growth have influenced the emergence of smart materials. Smart materials respond to stimuli from the external environment by changing their physical and chemical properties (Sobczyk, Wiesenhütter, Noennig, & Wallmersperger, 2022). These materials stand out because the structures are energy-saving and resistant to environmental conditions (Sommese, Badarnah, & Ausiello, 2023). For instance, in the study conducted by Cuce, Cuce, Wood, and Riffat (2014), it was determined that aerogel-based materials provided significantly better insulation in residential buildings compared to traditional insulation materials (Figure 8).

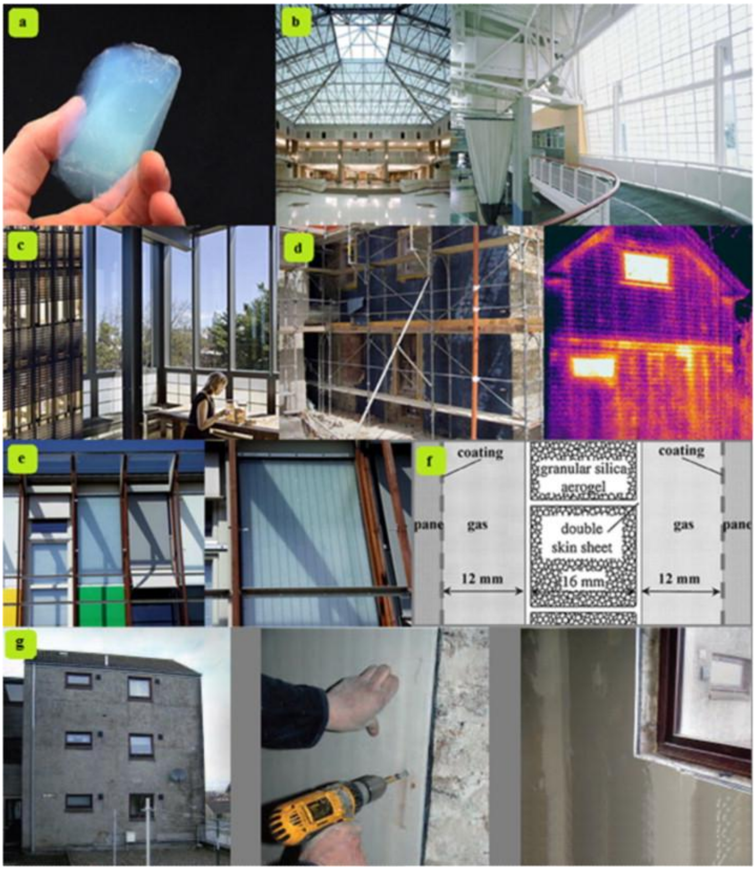

Figure 8. Ensuring energy efficiency by using aerogel materials in residences (Cuce et al., 2014)

Self-healing coatings, which are among the types of smart materials, provide significant benefits in the long-term use of structures. These types of coatings have the ability to heal in response to damage and damage (Figure 9) (Patel & Goyal, 2018).

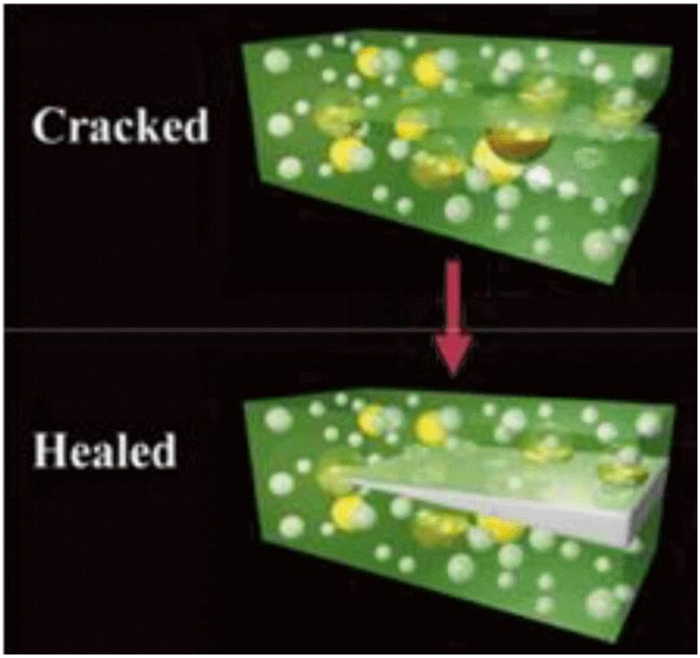

Figure 9. Self-healing in response to damage to the coating material (Patel & Goyal, 2018)

Shape-changing smart materials stand out in terms of user comfort because they make structures resistant to climatic effects. Additionally, these materials detect changes in the sunlight angle and change shape accordingly, effectively optimizing the ambient light in the interior. These materials provide natural ventilation to buildings and reduce energy consumption (Figure 10) (Li, Zhao, Chi, Hong, & Yin, 2021).

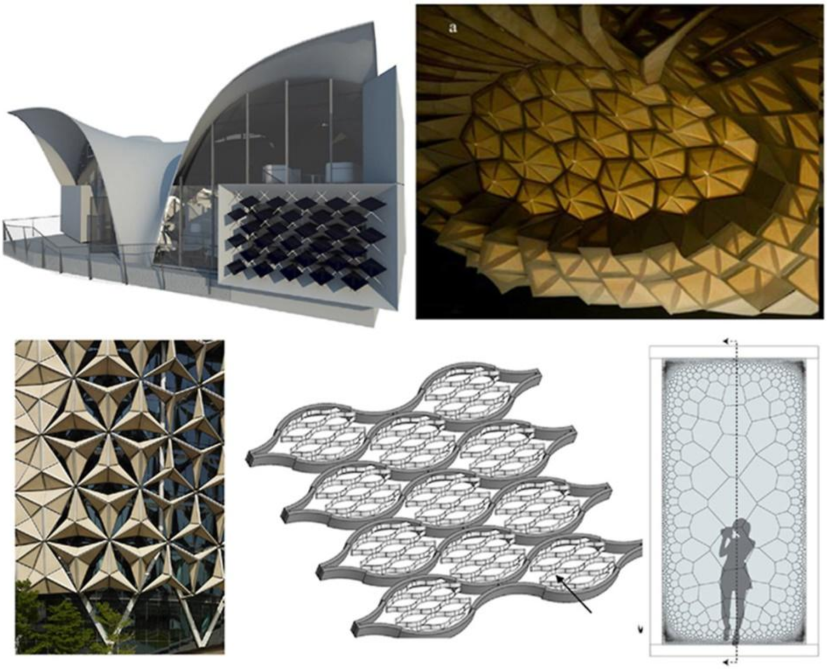

Figure 10. Shape-changing smart materials can sense changes in daylight and efficiently optimize indoor ambient light (Li et al., 2021)

Conclusion and Recommendations

This study focuses on examining experimental and alternative materials such as composites, nanocomposites, and smart materials produced from waste materials. These materials, produced with an innovative approach, have significant potential due to the advantages they provide over traditional materials in terms of functionality and aesthetics in buildings. In the light of the information obtained from the literature, the properties of materials produced with an innovative approach in architecture and the advantages they provide in terms of application are summarized below.

- Composites produced using waste materials contribute to the production of sustainable materials by providing raw material requirements in the construction industry, reducing environmental pollution, and reducing production costs. Furthermore, the superior qualities of waste material-based composites in terms of mechanical and physical properties provide benefits in the strength of structures.
- Nanocomposites provide better heat and sound insulation than traditional insulation materials, which reduces the energy consumption of buildings. Additionally, nanocomposites can significantly improve the mechanical, physical and fire resistance

properties of structures. However, it seems that there is not enough research on whether these composites have negative effects on humans and the environment.

- The performance of structures is improved thanks to the ability of smart materials to detect and respond to changing stimuli in the environment. The self-healing and deformation abilities of these materials provide significant benefits both in user comfort and in the long-term use of structures. Moreover, when the studies in the literature on smart materials are examined, it is seen that they contribute better to the construction of sustainable structures than other materials (composites and nanocomposites produced using waste materials).

As a result, it is recommended to increase studies on the properties of experimental and alternative materials such as composites, nanocomposites, and smart materials produced using waste materials and to expand their application areas in structures. Moreover, it is expected that in future research studies on these innovative materials, more emphasis will be placed on reducing production costs and being sustainable and environmentally friendly.

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CHAPTER 4

Analysing the Efficiency of BIM Usage in Various Architectural Phases

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1. Introduction

Nowadays, technological developments cause changes in the methods used in the construction industry. Building Information Modeling (BIM) technologies stand out as one of the most important components of this evolution. Architects, engineers and other construction professionals use BIM effectively at every stage of their projects, making processes more efficient and increasing the quality of project outputs (See, 2007). Construction projects may be meticulously planned and managed from the start thanks to BIM technology, which is the process of creating a three-dimensional (3d) virtual model of a building in a digital environment. Models created with BIM contain critical information on materials, systems, costs and scheduling, as well as the geometric features of the building. This comprehensive data set enables effective communication and collaboration between project stakeholders. Thus, errors and costs in projects are minimized and construction processes become more predictable (Kuytan & Yıldız, 2021).

Another area where the use of BIM has become widespread is the building life cycle process. The lifecycle of a building includes different phases such as design, project design and construction, facility management, repair or demolition. BIM provides data that can be used effectively in each of these phases. Many processes such as concretizing creative ideas during the design phase, creating detailed plans and monitoring every step of construction during the project design and construction phase, determining maintenance and repair needs in facility management can become more transparent and manageable thanks to BIM technology. In addition, all the data collected throughout the life of a building constitutes a valuable source of information for future projects (Karaoğlu, 2020).

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1.1. Research Aim

More scholarly and applied research is being conducted in this area as a result of the growing importance of BIM technology in the building industry. In particular, current trends such as digitalization and sustainability further increase the importance of BIM. In this context, the future development potential of BIM is a matter of great curiosity for all stakeholders in the sector. This study has been prepared to analyze the current status of BIM technologies in the construction sector and to evaluate its future development potential. By examining the impact of current trends such as digitalization and sustainability on BIM, it aims to reveal the contributions and promising aspects of this technology to the sector.

1.2. Research Scope

In the study, the usage areas of BIM technology in the construction sector and the benefits it provides in these areas are discussed. For this reason, within the scope of the study, the concept of BIM and the phases of its use in the architectural profession are examined in detail. Then, the use phases that constitute the building life cycle and the effectiveness of this technology in the use phases were analysed through the projects prepared using BIM. In line with these analyses, an assessment has been made about the value that BIM adds to the construction industry and its future potential.

1.3. Research Hypothesis

BIM technology reduces errors and costs in the construction industry, making processes more efficient and transparent. It also makes significant contributions to sustainability and digitalization at every stage of the building life cycle.

2. Building Information Modeling (BIM) Technology

In recent years, BIM has emerged as a key technology in the engineering, design, and construction sectors. There are many definitions of BIM in the literature. The most commonly used definitions of these definitions in the literature, which are found to differ according to user expectations, are presented in Table 1.

Table 1. Definitions of BIM

Reference	Definition
(Reed & Gordon, 2000)	It is a technique for the integrated design process that stresses the interdependencies between various building components and views a building as a whole.
(Karaoğlu, 2020)	It is a process of managing all project-related information in a digital environment that enables architects, engineers and construction professionals to collaborate, including graphics and documentation throughout the building life cycle, providing building performance estimates, cost estimates and construction planning, creating and using coordinated, consistent and calculable information about the project.
(Gsa, 2007)	It expresses all processes involving the sharing, reuse, supervision and control of knowledge created during the building life cycle through an object-oriented AI knowledge model.
(Barnes & Davies, 2014)	BIM is a process used in the construction industry that is based on a computer-aided 3d visual building model that responds by accurately representing how a built structure behaves.
(Ofluoğlu, 2014a)	BIM is a method of working that uses alphanumeric data like cost, material, and physical environment control along with graphical data like form and geometry to generate a three-dimensional (3d) model that can be used collaboratively by all project stakeholders in the building industry.
(Boukara & Aziz, 2015)	It is a model-based intelligent process that presents information about buildings and infrastructures, providing support in the planning, design, construction and management phases.
(Kopuz, 2015)	It is a process that supports interdisciplinary cooperation, creates project products in 3d form with the integrated use of various software and hardware, enables data sharing, provides advantages in terms of

	cost and time when used effectively, reduces the error rate, and continues to exist continuously from the design phase of the building to the demolition phase.
(Sacks, Eastman, Lee, & Techolz, 2018)	It is an information technology (IT) environment that includes setting up libraries and document templates, configuring systems, and modifying design review and approval processes.
(Bimsoft, 2025)	It is a method for exchanging 3D data that may be used collaboratively by individuals engaged in the planning, building, and maintenance of various architectural projects.
(Bsi, 2025)	Through the use of digital modeling from the beginning to the completion of the construction process, it is the continuous management of information about a developed structure.
(Bentley, 2025)	It is a process in which all visual and non-visual aspects of the building life cycle are combined and modeled within a database management system.

When the definitions in the table are examined, in its simplest definition, By facilitating interdisciplinary collaboration, data sharing, and information management through 3D digital models during the design, construction, and operation phases of buildings, BIM can be defined as an integrated process that offers a coordinated and calculable information environment throughout the entire life cycle, from cost analysis to building performance predictions.

2.1. History of BIM

The significance of integrating design and construction has been the subject of numerous scholarly investigations in the construction industry and associated sectors since the early 2000s. Nonetheless, a review of the development of Building Information Modeling technology reveals that 3D geometry modeling, the foundation of BIM, was a significant area of study in the 1960s.

Computer Aided Manufacturing (CAM) software, which forms the basis of BIM, was developed in 1957 and Computer Aided Design (CAD) software was developed in 1961 (Karaoğlu, 2020). Douglas C. Engelbart, known as the pioneer of the computer and the internet and the inventor of the computer mouse, introduced the term BIM in his article "Auginging Human Intellect: A Conceptual

Framework" published in 1962 (Sarıçiçek, 2019). The technology called "Sketchpad", developed by Ivan Sutherland at MIT Lincoln Lab in 1963, was the first system to be used with CAD and to have a graphical user interface (Sutherland, 1963). In 1973, solid volume modeling was developed, which is considered the first generation of 3d design tools (Sacks et al., 2018). In 1974, the idea of the Building Description System (BDS) was introduced. Developed by Eastman, this system is recognized as the first project in the history of BIM to be successfully designed using a building database (Eastman, 1974). In the late 1970s, building modeling based on a 3d solid model was made (Sacks et al., 2018). In 1982, ArchiCAD software was programmed. Although this software was introduced in 1984 as Graphisoft Radar, it was reintroduced in 1987 under the name ArchiCAD. It, which allows use on personal computers, is the first BIM software with this feature (Quirk, 2012). In 1988, Pro/ENGINEER was released, considered the first parametric modeling software marketed in the history of BIM. In 1992, the name Building Information Modeling (BIM) was officially introduced. In 1997, ArchiCAD produced a teamwork solution where multiple architects could work on the same building model simultaneously. In 2000, the Revit program, named after the phrase "Revise it", was introduced. With the Formit application developed in 2012, access to BIM projects via mobile devices was started to be provided (Karaoğlu, 2020). The history of BIM described above is shown in Figure 1.

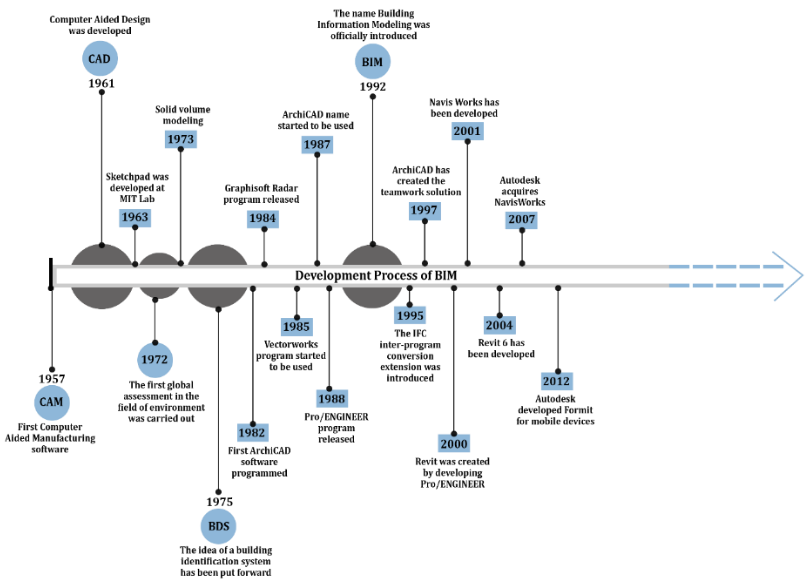

Figure 1. Development process of BIM (Edited using the Karaoğlu, 2020 reference)

2.2. Key Features of BIM

BIM is a system of digital "objects". The created model provides a detailed description of the physical building elements. Thus, the project's virtual representation enables foreseeing the real construction process and resolving spatial conflicts and other issues before they happen. It is sufficient to use fewer elements to define an infinite number of building elements because BIM objects are parametric. The use of parametric objects makes it possible to define the project parametrically. By establishing relationships between individual parameters, complex rules can be applied to the project. In this way, the flexibility and customization capability of the project can be increased through the use of a parametric structure in BIM. In addition, there is direct communication between the computer-aided tools and the BIM that make up the building components. Each building component has a digital counterpart. In this way, designers can directly control the production during the construction process (Çetiner, 2010; See, 2007).

In BIM, the principle of storing all project information in databases is adopted. The data of the structure can be converted into spreadsheets, graphs, tables and text formats. In this way, the data can then be converted into various formats for usage in other software programs. Thus, building data may be easily shared and utilized with other software programs. Furthermore, data gathered throughout the project is kept in a central repository for later use. This model includes information generated by architects, contractors, engineers, manufacturers, fabricators, owners, consultants, etc. This feature of BIM facilitates, communication and collaboration between stakeholders and increases the efficiency of the project. Thanks to BIM technology, it is seen that labor productivity increases. With the models created, the cost can be predicted before starting the construction process. If necessary, existing product options can be revised with more financially viable alternatives (Çetiner, 2010; See, 2007) (Figure 2).

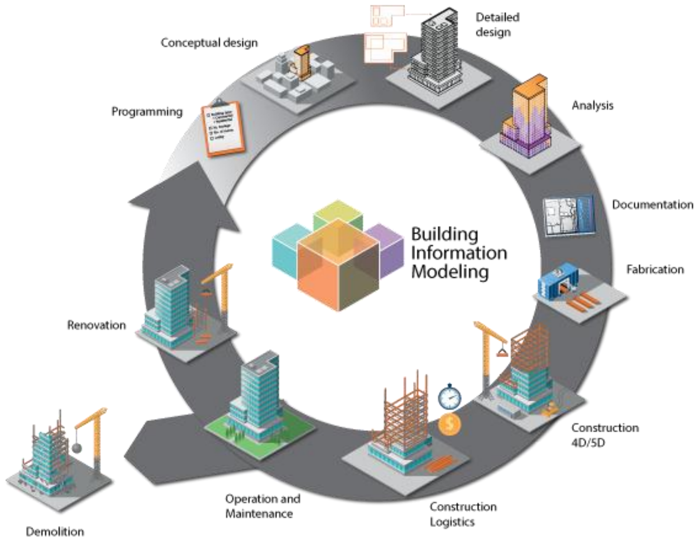

Figure 2. Key features of BIM (Seewhen, 2023)

2.3. Benefits and Challenges of BIM

The control and management of a building is based on access to information about the building from pre-design to post-design phases. BIM plays an important role in the building life cycle by providing access to this critical information. It should be noted that BIM technology, which offers the opportunity to work more effectively on projects, has challenges as well as benefits.

The benefits of BIM can be listed as follows;

- Being able to easily access and share information creates a more efficient and effective process.
- It increases the realism rate in predictions.
- It offers the opportunity to access data in pre-construction, design, construction and post-construction processes through the model.
- It provides convenience to the business owner in matters such as preliminary design studies, concept and feasibility.
- Schematic modeling studies prepared together with employer decisions before construction have the potential to improve building performance and quality.
- Numerical data compatible with reality can be obtained.

- By using parametric rules during the design phase, potential errors can be identified and prevented in advance.
- It facilitates accurate data sharing between stakeholders.
- It is possible to make cost estimates during the design phase.
- Design revisions can be responded to quickly.
- It enables improvements to be made in sustainability and energy saving.
- In tenders, it facilitates the synchronization between the design, construction and tender process of the project.
- It contributes to better integration of operation and management activities (Çetinkaya, 2017; Kopuz, 2015; Kuytan & Yıldız, 2021).

The challenges of BIM are as follows;

- When not implemented in an organized and systematic manner, it may lead to increased risks.
- Construction companies are concerned about the disruption of productivity during the transition to BIM.
- The fact that BIM programs are difficult to learn causes some prejudices.
- The inability to perform static analysis in BIM programs reflects an additional cost to the budget of the project by requiring the purchase of a separate program.
- Design offices need to create their own libraries for special projects beyond the standard smart object libraries offered by BIM program manufacturers. Because it is stated that the existing objects are not intended to meet the requirements of specialized projects.
- Data loss during the exchange of information between programs causes incomplete transfer of project information (Kuytan & Yıldız, 2021; Sarıçiçek, 2019).

2.4. Usage Dimensions of BIM

The BIM working system was created with varied dimensions from the 3D model to the 7D model, according to earlier studies on the use of BIM. By taking a more thorough approach to building design and production processes, it has been found that the features of BIM technology help to increase efficiency (Figure 3) (Sade, 2021).

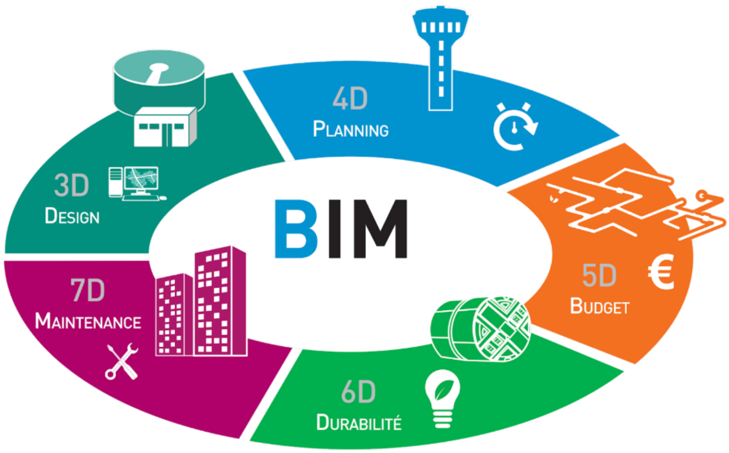

Figure 3. Usage dimensions of BIM (Sade, 2021)

The usage dimensions and features are as follows;

- The 3D dimension is used for "modeling". It is the most well-known dimension of BIM technology. In this classification, a three-dimensional model is created by collecting graphic data. Data from various disciplines can be combined and linked to a single master model. In this way, conflict-free projects can be developed. The production outputs obtained in 3D dimension are model visuals, conflict tests and pre-production schedules.

- The 4D dimension is used for "planning". In this classification, duration information is added to the model. The work schedule of the project generated by the simulations is used in activities related to site planning. Thanks to the 4D dimension, deliveries can be realized in full time thus they can be reduced storage needs and costs.

- The 5D dimension is used for "cost accounting". By including cost data in the model, budget control in this classification can be achieved. Since the material quantities of the project can be calculated before the construction phase, waste control is ensured and waste can be prevented.

- The 6D dimension is used for "sustainability/energy assessment". In this classification, analyses such as sunlight, duration and amount of shading can be done through the model. Thanks to the 6D dimension, strategies to optimize the water, heat and light consumption of the building can be created by the performance of the building can be better analysed.

- The 7D dimension is used for "facility management". Using the project data, a model is created for the building's operation and maintenance phases in this classification. The model helps gather all the information that will be useful during the course of a building life cycle.
- In the studies conducted, it is predicted that the usage dimensions of BIM will not be limited to 7D and many dimensions will be added in the future. Nowadays, it is known that studies are being carried out for the 8D dimension, which is aimed to be used in the fields of occupational safety and health (Ademci, 2018; Çetinkaya, 2017; Kuytan & Yıldız, 2021; Toklu, 2022).

2.5. Purposes of Use of BIM

Forbes and Ahmed (2011) grouped the usage purposes of BIM technology under nine headings;

- *Visualization:* 3d overlays can be easily created.
- *Production / Workplace Drawings:* Workplace drawings for different building systems can be made easily.
- *Automated Production:* Information from BIM files can be utilized as input data for producing materials that need numerical control in projects involving suppliers with cutting-edge technology.
- *Regulation-Related Evaluations:* This model can be used by fire and other authorities to examine local building project portions.
- *Forensic Analysis:* Situations such as potential failures and evacuation plans can be prepared for graphical representation.
- *Facility Management:* It can be used by facility management departments for operations such as renovation, maintenance-repair, space planning.
- *Cost Calculation:* BIM software can update the cost calculation by automatically renewing the material quantities in case of any changes in the model.
- *Building Array:* For all building items, BIM-created models can be utilized to efficiently create plans for material ordering, manufacturing, and delivery.
- *Conflict, Intervention and Overlap Investigation:* The interaction of large systems such as walls, steel beams, piping systems and ducts can be visually inspected (Atabay & Öztürk, 2019; Köse, 2016).

3. BIM in Various Architectural Phases

Building Information Modeling technology can be used at different stages throughout the building life cycle of a building. It is possible to analyse these phases of use under four main headings (Figure 4).

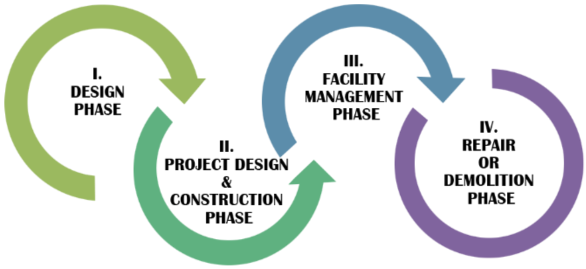

Figure 4. Building life cycle usage phases of BIM (Ofluoğlu, 2014b)

3.1. Design Phase

BIM can contribute to the process of shaping the form in different ways during the design phase. The first method is to develop the 3d mass and shell to the conceptual design using the geometric modeling commands of BIM software. The second method is to utilize parametric design principles to create the form. BIM programs can shape the shape with coding and serial command steps supported by add-on software. The third method is to evaluate the performance of the model by subjecting it to environmental simulations such as wind, solar and energy use. Building performance analysis allows design decisions to be revised and the form and site layout to be improved to create a more sustainable building through simulations (Karaoğlu, 2020; Ofluoğlu, 2016).

3.2. Project Design and Construction Phase

BIM enables the determination of whether the construction site processes are realized as planned before the start of construction. It enables load analysis and development of electromechanical projects by bringing together the data of architectural, static and mechanical projects. Conflicts that may occur between models produced by different disciplines can be detected through both reports and graphics. In this way, time, cost and labor losses that may occur in the following stages can be prevented (Karaoğlu, 2020; Kuytan & Yıldız, 2021; Ofluoğlu, 2016).

3.3. Facility Management Phase

BIM can also be used for post-construction maintenance and operation purposes. The detailed design model is updated in accordance with the actually constructed building. Using the information obtained from this model, databases can be created for various needs. The information in the databases can be used for real estate and space-human resources management, installation of building security and monitoring systems, maintenance of electro-mechanical systems, preparation of disaster and emergency evacuation plans by the company undertaking facility management (Karaoğlu, 2020; Kuytan & Yıldız, 2021; Ofluoğlu, 2016).

3.4. Repair or Demolition Phase

BIM provides the opportunity to determine some alternative uses in case of reaching the fourth stage in the building life cycle. In this phase, it can be used to obtain data for situations such as repair and retrofitting of the building, spatial performance improvement, giving a new function to the building or demolishing the building and recycling waste materials (Ofluoğlu, 2014b).

4. Comparative Analysis of BIM Effectiveness in Architectural Phases

In this section, projects of buildings prepared using BIM and having different functions were examined. The effectiveness of BIM in the usage phases was analysed through the examples discussed.

4.1. Sample Building for Design Phase: Charles Perkins Centre

Located in Sydney, Australia, the building was built as a research and education centre affiliated with the University of Sydney. The 50,000 m² centre was designed to collaborate with researchers working on diseases such as diabetes, obesity, and cardiovascular disease and to create an educational environment. Archicad, Autocad, Revit, Grasshopper, Rhinoceros, MicroStation, and Navisworks software were used in the project prepared by making use of BIM programs (Fjmt, 2025) (Figure 5).

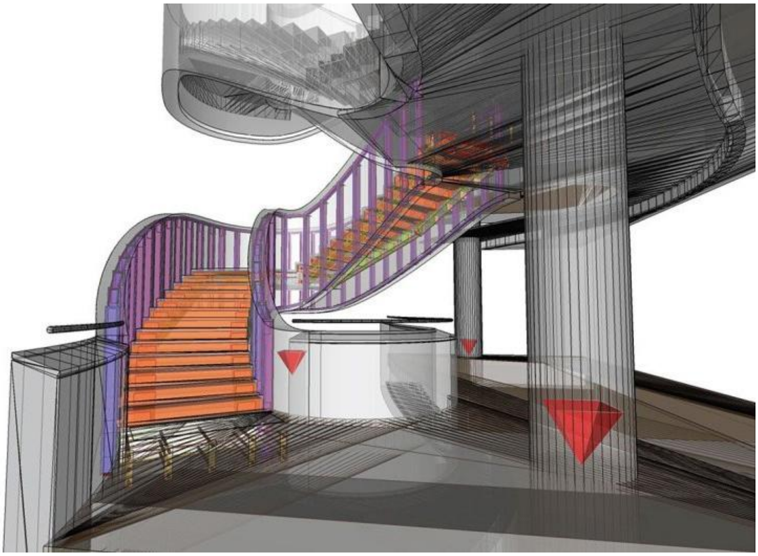

Figure 5. Structural/architectural model of one of the stairs created in Rhino-Grasshopper (Fjmt, 2025)

Archicad, which was used in many stages of the project, increased efficiency with its teamwork feature. The program, which allows changes to be quickly transferred to the project, also contributed positively to the team members working on different interfaces according to their working areas. The design phase started by utilizing Archicad software. While the architects modelled their design ideas in 3d, the connection between the Rhino-Grasshopper-Archicad programs provided significant convenience. Digital three-dimensional models were used to coordinate with contractors or building owners and to strengthen the narrative in presentations (Figure 6). By dint of BIM software, project participants were able to make changes to the model even though they were far away from the office. Thanks to the use of Archicad, the project was able to speed up the process, especially under a busy design and construction schedule. By combining data from different disciplines in a single model, the most up-to-date version of the project could be checked for conflicts (Fjmt, 2025).

Figure 6. Charles Perkins Centre (Fjmt, 2025)

4.2. Sample Building for Project Design and Construction Phase: Irina Viner-Usmanova Rhythmic Gymnastics Centre

The design of the building, which was completed in Mexico in 2019, won first place in the sports facilities category at "BIM 2016", a national BIM technology competition held in Russia in 2016 (Figure 7). CPU Pride, the company that undertook the project, gave importance to the effective use of BIM technologies. It was utilized BIM programs for all phases of the building life cycle of the 23,500 m² gymnastics centre. Archicad & BIMx, ElumTools, Grasshopper, Autodesk, Rhinoceros, Autodesk Navisworks & 3ds Max, Allplan Engineering, SolibriTekla, SAPFIR-3D, LIRA-SAPR, and Revit Structure & MEP software were used in the project (Pride, 2025).

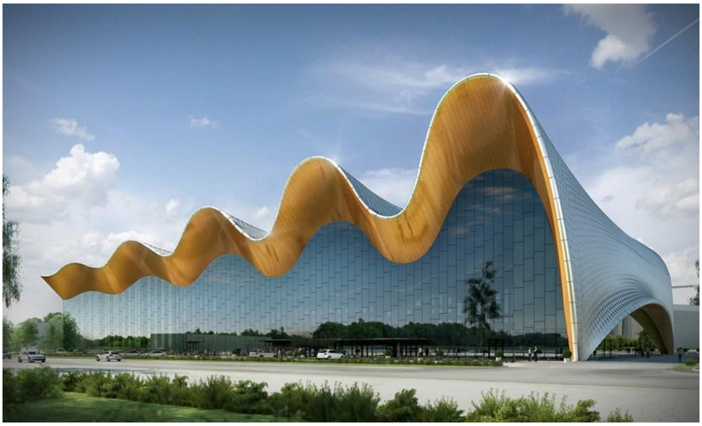

Figure 7. 3d model image of Irina Viner-Usmanova Rhythmic Gymnastics Centre (Pride, 2025)

The primary tools for design development and construction documentation were Rhinoceros/Grasshopper and Archicad. Rhinoceros/Grasshopper was used to develop the intricate roof design, while Archicad was used to simulate the structural components. Rhinoceros/Grasshopper software provided great convenience to the user by allowing a quick selection of all desired features. Thanks to the bidirectional data exchange with Archicad, the complex geometry of the building could be transformed into an understandable format for architects and at the same time complex calculations could be made. 3ds Max program was used in the visualization and rendering phase of the project modelled in Archicad. In the first meeting organized with the building owners, designer-client coordination was provided with BIMx software used to view BIM models on mobile devices. Separate models were prepared in Archicad for each project participant. Then, Solibri Model Checker application was used to identify errors in the models and conflict detection analysis was performed with this software (Figure 8). Via Rhinoceros and Grasshopper-Archicad Live Connection, a parametric model of the roof was created by determining the optimization options of the metal frame elements. Following the Allplan program used for reinforced concrete structural design, the model was transferred to the LIRA-SAPR program, a local analytical program, via SAPPHIRE. The metal structural model of the project was created using Tekla Structures software. When the project design and construction phase started, the work was started on the model in a single BIM file. Thanks to the use of BIM, interdisciplinary collaboration was facilitated and many errors were prevented by constantly exchanging data. In addition, the building was constructed in accordance with the architects' design (Pride, 2025).

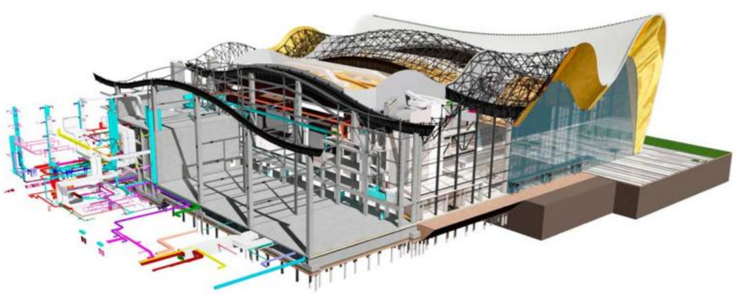

Figure 8. Combination of models prepared by different disciplines (Pride, 2025)

4.3. Sample Building for Facility Management Phase: Medina-Prince Mohammed Bin Abdulaziz Airport

The project is the first airport in the Middle East and North Africa to receive LEED Gold certification. Additionally, it won the 2015 Airports/Ports category of ENR's (Engineering News-Record) Global Best Projects award (Figure 9). The runway, taxiway, and apron area make up the project's 1.5 million square meter total area. For the facility management (FM) phase, just the 156,940 m² terminal building and lounges were modeled. The FM team is one of the project contractors. This group assisted the BIM department in taking the project requirements into account (Kula, 2019).

Figure 9. Prince Mohammed Bin Abdulaziz Airport (Kula, 2019)

There was no BIM model and just 2d drawings accessible because the BIM-FM integration was started at the conclusion of the building phase. Information on the construction phase was collected from the main contractor's field staff. An Object Identification scheme for airport assets was developed for proper labeling. Each BIM model element was given an object identity as a parameter value. Autodesk Revit software package was used as a BIM authoring tool for modeling (Kula, 2019) (Figure 10).

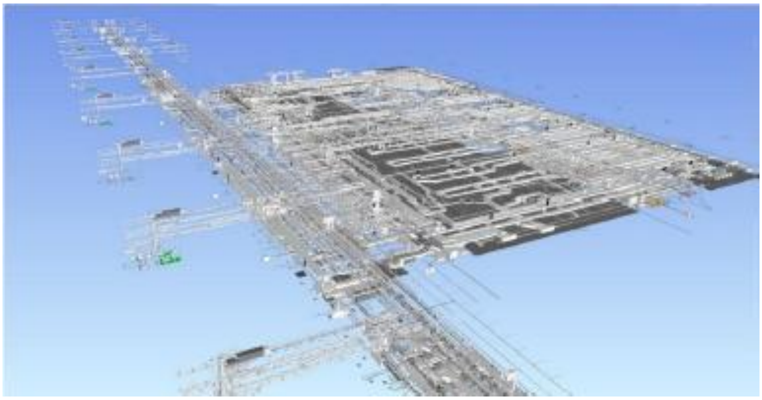

Figure 10. 3d model study of Prince Mohammed Bin Abdulaziz Airport

Revit ID codes were used to match geometric and non-geometric data. In this instance, a plugin in the BIM authoring program might be used to move the model to the BIM-FM platform. The BIM-FM systems stored the data in COBie format. Mobile handheld devices like smartphones, tablets, or office computers can be used on-site with the integrated BIM-FM system. The BIM-FM platform allows for the creation and tracking of work orders and inspections (Kula, 2019) (Figure 11).

Figure 11. BIM-FM integration of Prince Mohammed Bin Abdulaziz Airport (Kula, 2019)

4.4. Sample Building for Repair or Demolition Phase: Södersjukhuset (South Hospital)

One of the biggest emergency hospitals in Scandinavia is Södersjukhuset, which is situated in Stockholm, the capital of Sweden. The 753,500 m² structure was finished in 2019 (Figure 12). Along with the demolition of some older structures and the construction of new ones on the property, the project also included the extension and renovation of already-existing structures. Archicad, Velux Daylight Visualizer, BIMeye, Solibri, Revit, MagiCAD, Vico Office BIMcollab, Bentley software were used in the project (Link, 2025).

Figure 12. Södersjukhuset (Link, 2025)

While the hospital was being renovated, it was aimed to make innovations in accordance with the Swedish Green Building Council's Miljöbyggnad certification criteria. The client and project stakeholders had to closely monitor the process of designing for the certificate, which focuses on indicators related to energy consumption, environmental impacts and air noise quality. For this reason, various simulations (sun, daylight, accessibility, and energy), model-based cooperation with consultants, clash control, cost and time projections, and relevant studies for facility management were developed in order to assess the design's performance using BIM. BIMeye software was used for data exchange, which is integrated with Archicad and increases efficiency in the information management process (Figure 13). Archicad Teamwork was used to overcome the difficulties encountered due to the existing structure and complex design of the building. Separate teamwork projects were created for each building. At the points where the buildings are connected to each other, three-dimensional models were prepared in addition to two-dimensional plan drawings and each model was attached to the main model. A model manager was assigned to the teamwork of each building and regular checks were made in Archicad and Solibri. As potential problems could be identified in advance when all 3D models were overlaid, it was seen that BIM had positive reflections on the client in terms of saving money (Link, 2025).

Figure 13. Archicad & BIMeye Model Study of Södersjukhuset (Link, 2025)

4.5. Evaluation

In this section, the use of BIM in sample buildings used in different architectural usage phases and having various functions has been analysed. BIM software that could be determined to be used in the projects is given in Table 2.

Table 2. BIM Software and Effectiveness Used in Buildings

Building	Usage Phase	Software	Effectiveness
Charles Perkins Centre	Design Phase	- Archicad - Autocad - Grasshopper - MicroStation - Navisworks - Revit - Rhino	- Teamwork and productivity increased with Archicad. - Changes are quickly integrated into the project. - Integration between programs facilitated design. - 3D models strengthened coordination and presentations. - With BIM software, changes can be made to the model from outside the office.

			- Up-to-date conflict control was ensured with interdisciplinary data.
Irina Viner-Usmanova Rhythmic Gymnastics Centre	Project Design and Construction Phase	- Allplan Engineering - Archicad - Autocad - BIMx - Grasshopper - Lira-Sapr - Navisworks - Revit - Rhino - Sapfir-3d - Solibri - 3d Max	- Archicad was used as the main tool in the design and documentation process. - Structural elements are modeled parametrically. - Complex geometry is made understandable with bidirectional data exchange. - Visualization support was provided with Archicad and 3ds Max integration. - Designer-client coordination is facilitated with mobile models. - Errors can be detected with conflict analysis. - Reinforced concrete and metal elements can be modeled and analyzed. - Interdisciplinary cooperation is provided in a single model.
Medina-Prince Mohammed Bin Abdulaziz Airport	Facility Management Phase	- BIMx - Revit	- BIM software was used for modeling. - Assets are tagged with object IDs, and data can be matched with ID numbers and transferred to the BIM platform. - Data is stored in COBie format, making management easier. - Mobile access in the field and in the office.

			- The platform allows for the creation and tracking of work orders. - Information about the construction process can be recorded.
Södersjukhuset (South Hospital)	Repair or Demolition Phase	- Archicad - BIMeye - Bentley - MagiCAD - Revit - Solibri - Velux Daylight Visualizer	- Design performance was tested through solar, daylight, accessibility and energy simulations. - Model-based coordination and conflict control with project stakeholders. - Cost and time estimates were made to save money. - Data exchange and information management process were made efficient with an integrated system. - Collaboration was facilitated with teamwork in complex designs. - Errors were detected in advance by regular checks with the model manager. - The main model can be combined with 2d plans and 3d models.

As can be seen from the table, it was determined that Revit software, which enables both 2d and 3d work, was used in all phases. Archicad or Autocad software, which are frequently used in the 2d phase, are also encountered in various phases. The reason why it is not used in the airport project, which is examined as an example of the facility management phase, is that 2d drawings are available due to the fact that the BIM-FM integration of the project was started at the end of the construction phase. BIMx, which is used to view BIM models on mobile devices, is another software used in different phases. However, in the examinations conducted, it was determined that the data belonging to the software used in the projects was obtained from the project stakeholders. It is thought that this situation may cause insufficient information about both the software used and its benefits due to confidentiality agreements in the projects and limited data sharing by stakeholders.

5. Conclusions

With the advancement of technology, Building Information Modeling (BIM) has begun to be employed extensively in the constantly evolving and revitalized construction sector. With all of its data, the BIM-created model is a digital twin of the real structure. In addition to being employed in one or more stages chosen for particular objectives, BIM systems can be used actively throughout a project's building life cycle, from the design stage to demolition.

As can be understood from the sample buildings with different functions and dimensions, BIM can be used in different phases according to the project requirements and various positive contributions can be observed according to the process. It has been determined that the design process is shortened with the use of BIM-based programs in the design phase. The project's documentation of the plan, section, facade and 3D models can be made during the design phase. It provides convenience in design by working together with parametric design tools in amorphous masses. Thanks to the model created, employers can understand the design more easily. Via the overlap tests and analyses performed on the model, problems can be detected before construction starts, and cost increase is prevented by producing solutions. With BIM used in the project design and construction phase, advantages are provided for both manufacturing and prefabrication. Thanks to the data stored in BIM-based programs, workflow can be easily followed by project stakeholders on site. In addition, with its teamwork feature, it enables multiple project teams to work together in large-scale structures. It is seen that the principle of interdisciplinary working is also positively affected in this phase. The facility management phase covers the maintenance and operation process of the building. All information about the usage phase of the building and maintenance-operation problems can be analysed and solved through the model. In addition to new projects, maintenance-operation models can be prepared for existing buildings. Especially in existing buildings, the ability to combine all information in a single model provides convenience to project participants in the facility management phase. In the repair or demolition phase, which is the last phase of the building life cycle, a 3D model can be developed using BIM while the building is in use. Possible problems can be observed through the model and cost increase is prevented.

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CHAPTER 5

Architectural Simulation and Simulation-Based Optimization Methods

Şeyda Açıl[1] & İdil Ayçam[2] & Asena Soyluk[3]

1. INTRODUCTION

As in all fields today, the architecture and engineering disciplines are expected to meet increasingly demanding performance requirements due to the balance between supply and demand. Within this context, buildings must simultaneously achieve perceptual and experiential comfort, structural integrity, energy efficiency, and cost-effectiveness. The Architecture, Engineering, and Construction (AEC) industry accounts for approximately 40% of global energy consumption throughout construction and operation processes, making it one of the most influential sectors in mitigating climate change (International Energy Agency, 2019). Approximately 30% of the global final energy consumption (130 EJ Exajoule) is attributed to building operations, including heating, cooling, ventilation, hot water, lighting, and appliances (Sornek, Papis-Frączek, Calise, Cappiello, & Vicidomini, 2023), while residential buildings account for nearly 70% of this share (Sornek et al., 2023) . These activities generate about 26% of total global carbon emissions, with 8% resulting directly from building operations and 18% stemming from energy use for electricity and heat production (IEA, 2019).

Residential buildings are often designed primarily based on cost and functionality, while environmental factors and energy awareness are largely neglected due to insufficient architectural consciousness (Abdeen et al., 2019). Achieving a balance among these diverse parameters is possible through a series of decisions made during the early design phase. In construction projects, various techniques are employed to optimize trade-offs between time and cost (Akyıldız & Ekici, 2022). Sustainable building design, due to the uniqueness of each structure, the goal of achieving high performance with minimal cost, and the inherent contradictions between physical processes, is a complex task that benefits significantly from computational optimization methods (Evins, 2013).

The analysis of building energy performance through simulation software plays a key role in making sustainable design decisions (Ayçam, Akalp, &

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Görgülü, 2020). Architectural Design Optimization (ADO), which integrates building performance simulations and parametric design, contributes significantly to improving energy and material efficiency by identifying optimal design combinations (Wortmann, Cichocka, & Waibel, 2022). By employing simulation and optimization technologies, three-dimensional digital models of buildings can be generated in the design phase, enabling energy analyses that predict the building's lifetime energy demand. This allows for design interventions that promote energy conservation and local energy use-now among the most critical indicators of development-while ensuring that buildings, the largest contributors to environmental energy demand, are subject to effective energy control (Açıl & Polat, 2023).

With today's technological tools and software, it is possible to perform detailed analyses on virtual models created during the early design stage. However, while single-parameter analyses are relatively straightforward, the increase in the number of parameters leads to greater labor, cost, and time requirements. Managing numerous and interdependent design parameters complicates the search for optimal design conditions. Computer-aided simulation and optimization tools enable complex systems to be tested under various scenarios in the early design phase, facilitating the identification of optimal condition sets. The simulation-based optimization process typically proceeds through three stages: the preprocessing phase, the optimization phase, and the post-processing phase.

1.1. Simulation-Based Optimization Stages

Before creating a digital model of an architectural structure, the parameters to be tested using the model are determined. After defining our objective (energy efficiency, space utilization, daylight efficiency, etc.), a simulation tool is selected. Once an appropriate simulation software for the objective is chosen, data must be input into the simulation program or cloud-based software. For the model to produce realistic results, climate data, material properties, and user profiles must be integrated into the system. Analysis parameters such as facade orientation, material type, and fenestration ratios are determined, and the generated scenarios are simulated to identify the most suitable option. Single simulations provide results for only one scenario; however, considering that numerous parameters affect building performance, parametric simulation comes into play. The parametric simulation method examines the effect of each design variable on objectives while keeping others constant, but due to complex and non-linear interactions between variables, it is typically time-consuming and provides only partial improvement (Nguyen, Reiter, & Rigo, 2014); moreover, as parameters and consequently the number of combinations increase, cost and labor also increase. At this stage, DoE (Design of Experiments) is introduced. When there are numerous parameters, DoE statistically generates the most suitable set of options. This approach both saves time and yields more accurate results. Consequently, not all scenarios are tested; rather, the statistically most significant ones are selected and simulated. The next phase is the metamodeling stage. Through approximation functions created using methods such as RSM, Kriging, RBF, or ML-which learn simulation behavior and make rapid predictions-users make selections within the surface generated by fast prediction models.

Finally, the process is preferably transferred to optimization algorithms (Genetic Algorithms, Multi-Objective Optimization, etc.), and optimal solutions are sought. One of the methods-Deterministic, Heuristic (Empirical) Methods, or Evolutionary Algorithm approaches-is selected, and optimization is performed by defining objectives and constraints. In the final processing stage, analysts interpret optimization data through graphs, tables, or diagrams to obtain information about optimal solutions; visualization methods such as convergence diagrams, solution probability graphs, fitness and average fitness graphs, parallel coordinate diagrams, and bar charts can be used in this process (Nguyen et al., 2014). The process flow diagram is visualized in Table 1.1.

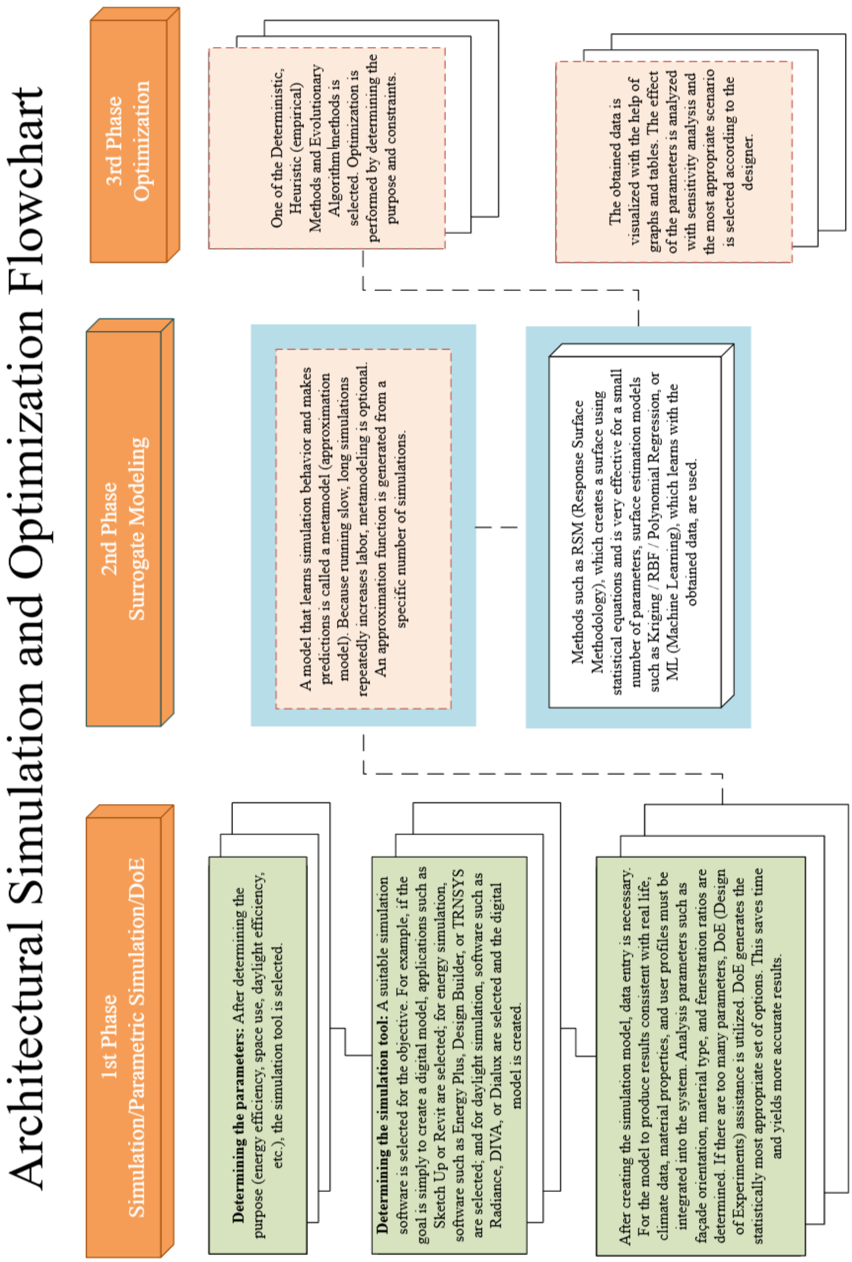

Table **Hata! Belgede belirtilen stilde metne rastlanmadı.**.1Simulation Based Optimization Flow Chart (created by the author)

2. SIMULATION

Simulation refers to the process of creating a mathematical model of a real or hypothetical system using computer programs or software to analyze its behavior under realistic environmental conditions. The outputs -such as heat distribution, velocity profiles, or energy production- allow for the evaluation of system performance.

Architectural simulation involves creating a digital representation of a building, building component, or urban space through computational modeling to evaluate its design from aesthetic, technical, and functional perspectives, as well as to assess its energy efficiency, cost, and sustainability performance. In architecture, simulation methods are generally classified into three main categories (Table 2.4).

1. Visual (Perceptual/Spatial) Simulations
2. Performance Simulations
3. Behavioral Simulations

2.1. Visual (Perceptual/Spatial) Simulations

These simulations enable the experience of architectural spaces before construction, focusing on aesthetics and the relationship between the building and its users, thereby supporting the decision-making process. They can be examined under four main headings:

3D Modeling and Visualization	Modeling tools such as SketchUp, Autodesk 3ds Max, Lumion, Rhino, Enscape, and Revit are used to generate three-dimensional representations of building geometry.
Virtual Reality (VR) and Augmented Reality (AR)	Through VR headsets, users can navigate inside the building, experiencing spatial perception and scale. Commonly used software includes Unreal Engine, Unity 3D, Enscape, Twinmotion, and Autodesk Revit Live.
Lighting and Daylight Simulation	This simulation type analyzes the effect of natural and artificial lighting on interior spaces, including light-shadow distribution and the influence of the sun's daily and annual movements. Programs such as Radiance, Autodesk Ecotect, DIALux, and Relux are used.
Color and Material Simulation	It examines how color, texture, and materials affect spatial perception. Software tools include 3ds Max + V-Ray, Lumion, Blender, and Adobe Substance 3D.

Table **Hata! Belgede belirtilen stilde metne rastlanmadı.**.2 Visual (Perceptual/Spatial) Simulation Types

2.2.Performance Simulations

This group of simulations evaluates the technical performance of a building and its environmental and user-related impacts. They can be categorized into five subfields: energy, thermal comfort, acoustics, structural safety, and environmental sustainability.

Energy Simulation	The efficiency of HVAC systems and energy consumption levels are analyzed using programs such as EnergyPlus, DesignBuilder, and TRNSYS to evaluate the building's energy performance.
Thermal Comfort Simulation	Thermal comfort within spaces is analyzed in terms of temperature, air movement, and humidity. Tools such as EnergyPlus, OpenFOAM, and ANSYS Fluent are used to conduct analyses based on ASHRAE standards.
Acoustic Simulation	This analysis investigates sound propagation within spaces to enhance quality through parameters such as reverberation time, sound insulation, and noise control. Common tools include ODEON, CATT-Acoustic, and COMSOL Multiphysics.
Structural Simulation	Using the finite element method, the resistance of the building's structural system against seismic, load, and wind effects is evaluated. Software includes ANSYS Mechanical, ETABS, and ABAQUS.
Environmental and Sustainability Simulations	Life Cycle Assessment (LCA) is used to evaluate the building's carbon footprint, material life cycle, and green building performance criteria. Tools include Green Building Studio and OpenLCA.

Table **Hata! Belgede belirtilen stilde metne rastlanmadı.**.3 Performance Simulation Types

2.3. Behavioral Simulations

These simulations analyze the accessibility and usability of buildings, focusing on user-centered interaction with space. They can be grouped under four subcategories:

Pedestrian and Crowd Simulation	Used to predict congestion and safety issues in high-occupancy areas by analyzing pedestrian movement and evacuation strategies. Commonly used software includes Pathfinder, AnyLogic, and MassMotion.
Spatial Usage Analysis	This analysis examines where users tend to concentrate and how circulation networks are formed, allowing designers to modify early design decisions. Tools such as Space Syntax and DepthmapX are utilized.
User Experience Simulation	Virtual reality environments are used to assess spatial perception, scale, orientation, and openness from the user's perspective. Software includes Unity 3D, Unreal Engine, Enscape, and Twinmotion.
Accessibility Simulation	Evaluates building usability for individuals with disabilities or the elderly by analyzing compliance with accessibility standards related to ramps, elevators, and circulation axes. Software includes Simulex, Pathfinder, and Revit Accessibility.

Table **Hata! Belgede belirtilen stilde metne rastlanmadı.**.4 Behavioral Simulation Types

Simulation Types and Program/Software Types

Category	Simulation Type	Program / Software Types
Visual (Perceptual/Spatial) Simulations	3D Modeling and Visualization	SketchUp, Autodesk 3ds Max, Lumion, Rhino, Enscape, Revit
	Virtual Reality (VR) and Augmented Reality (AR)	Unreal Engine, Unity 3D, Enscape, Twinmotion, Autodesk Revit Live
	Lighting and Daylighting Simulation	Radiance, Autodesk Ecotect, DIALux, Relux
	Color and Material Simulation	3ds Max V-Ray, Lumion, Blender, Adobe Substance 3D
Performance Simulations	Energy Simulation	EnergyPlus, Design Builder, TRNSYS
	Thermal Comfort Simulation	Energy Plus, Open FOAM, ANSYS Fluent
	Acoustic Simulation	ODEON, CATT-Acoustic, COMSOL Multiphysics
	Structural Simulation	ANSYS Mechanical, ETABS, ABAQUS
	Environmental and Sustainability Simulations	Green Building Studio, Open LCA
Behavioral Simulations	Pedestrian and Crowd Simulation	Pathfinder, AnyLogic, MassMotion
	Spatial Use Analysis	Space Syntax, DepthmaX
	User Experience Simulation	Unity 3D, Unreal Engine, Enscape, Twinmotion
	Accessibility Simulation	Simulex, Pathfinder, Revit Accessibility

Table **Hata! Belgede belirtilen stilde metne rastlanmadı.**.5 Simulation Types (created by the author)

2.4. Design of Experiments (DoE)

The Design of Experiments (DoE) is a statistical method used to systematically determine and analyze the influence of multiple variables on a given outcome. It identifies optimal parameter configurations while reducing the number of required simulations. By using DoE, interactions between parameters can be discovered, allowing more information to be obtained from fewer experiments.

In modern simulation tools, optimization modules (e.g., ANSYS Design Explorer) can automatically generate and apply DoE data to simulations. The resulting datasets provide the foundation for optimization processes such as RSM or MOGA. The steps in a typical DoE procedure are as follows:

- ✓ Identify design parameters.
- ✓ Select the appropriate DoE method (e.g., Full Factorial Design, Latin Hypercube Sampling).
- ✓ The software executes simulations for each design variant.
- ✓ Collect results and perform optimization based on the outputs.

3. METAMODELING (SURROGATE MODELING)

A metamodel (approximation model) is a predictive model that learns the behavior of a simulation to estimate outcomes without requiring time-consuming full simulations. Since performing numerous consecutive simulations is computationally expensive, metamodeling is used as an alternative. A limited number of simulations are performed to build an approximate mathematical function representing the system behavior.

Common metamodeling techniques include Response Surface Methodology (RSM)-effective for a limited number of parameters-along with Kriging, Radial Basis Function (RBF), Polynomial Regression, and Machine Learning (ML) models trained on simulation data. Within these predictive surfaces, users can select optimal configurations based on design objectives.

3.1. Response Surface Method (RSM)

The RSM approach constructs second-order polynomial equations to define the relationships between inputs and outputs. It analyzes the combined effects of multiple parameters (e.g., cavity width, air gap) on performance indicators (e.g., airflow velocity) using mathematical modeling. By creating quadratic equations, 3D surface plots are generated to enable prediction without running new simulations.

Simulation results are used to develop mathematical models that can subsequently be used in optimization algorithms (e.g., MOGA). RSM is not a program itself but a method implemented within various software tools or as standalone modules. Examples include:

- ✓ Within Simulation Software: ANSYS Design Exploration module enables DoE creation, simulation, RSM modeling, and optimal design extraction.
- ✓ Standalone Implementation: Tools such as MATLAB, Python, Minitab, and JMP can perform RSM analyses based on exported CFD results.

For example, CFD outputs can be exported to Python and analyzed using Polynomial Features and Linear Regression methods to construct surface plots and derive prediction equations for optimization.

4. OPTIMIZATION

Optimization is the process of finding the optimal design model by combining selected parameters to enable a system to achieve a specific objective (maximum energy, minimum cost, maximum efficiency, etc.). The optimal values of a system, whose behavior is determined through simulation methods, are investigated using optimization methods.

Optimization is the process of finding the best design parameters of a system according to a specific objective. After the study is simulated in any simulation program, the problem is identified, and an optimization algorithm is selected to search for the optimal solution or solution set.

In traditional methods, the modeled design is simulated, and parameters are modified using trial-and-error methods to find the most suitable model. This approach requires additional labor, cost, and time. By using simulation-based optimization methods (programs/software), it is more likely to reach optimal values, and labor is significantly reduced while more reliable data are obtained. In these methods, compared to traditional approaches, multiple parameters can be selected as evaluation criteria simultaneously. Thus, the simulated architectural structure is not only experienced before construction, but design decisions can also be modified to make the building more suitable in terms of efficiency and sustainability, in addition to aesthetic evaluation. Through simulation, the performance of the building can be predicted, and through optimization, the most efficient design model can be developed. Table 4.1 categorizes optimization algorithms according to problem types.

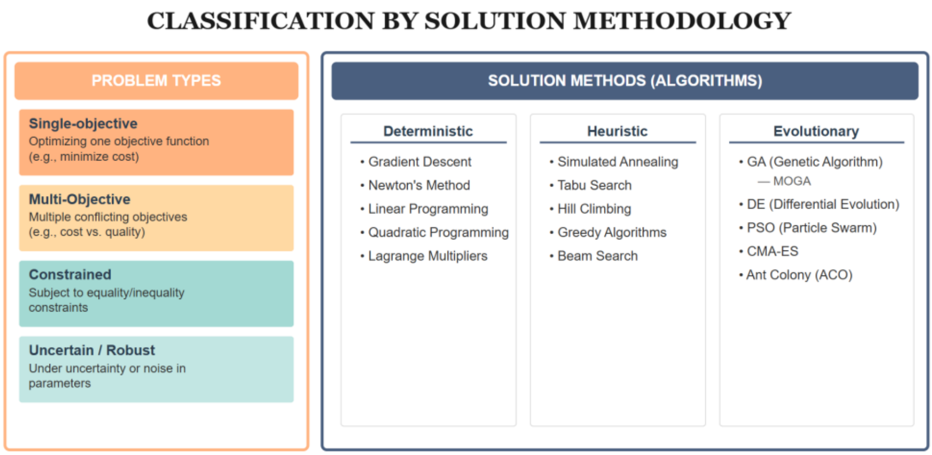

Table 4.1 Classification of Problem Types and Solution Methods (Optimization Algorithms) (created by the author)

To find the optimal combination, the value to be optimized is determined, design parameters are selected, and the process is initiated. Real-world boundary conditions such as budget, local regulations, and static requirements are defined. Subsequently, the algorithm method (deterministic methods, heuristic methods, evolutionary algorithm methods) is determined. Finally, depending on the method used, data obtained from the simulation software are transferred to the optimization software, and the most suitable option is selected from among the obtained data.

4.1. Optimization Algorithms

Building design optimization is a complex and multidisciplinary process that integrates mathematics, engineering, environmental science, economics, and computer science (Nguyen et al., 2014). Manual optimization is often time-consuming and limited to local solutions, as it cannot comprehensively explore the entire design space (Roy, Hinduja, & Teti, 2008). Recently, Multidisciplinary Design Optimization (MDO) tools have emerged, providing greater design diversity in shorter computation times (Díaz, Alarcón, Mourgues, & García, 2017).

Optimization goals often include form-finding, energy efficiency, daylight optimization, and solar performance (Wortmann et al., 2022). Deterministic, heuristic, and evolutionary algorithms are typically used depending on the nature of the design problem:

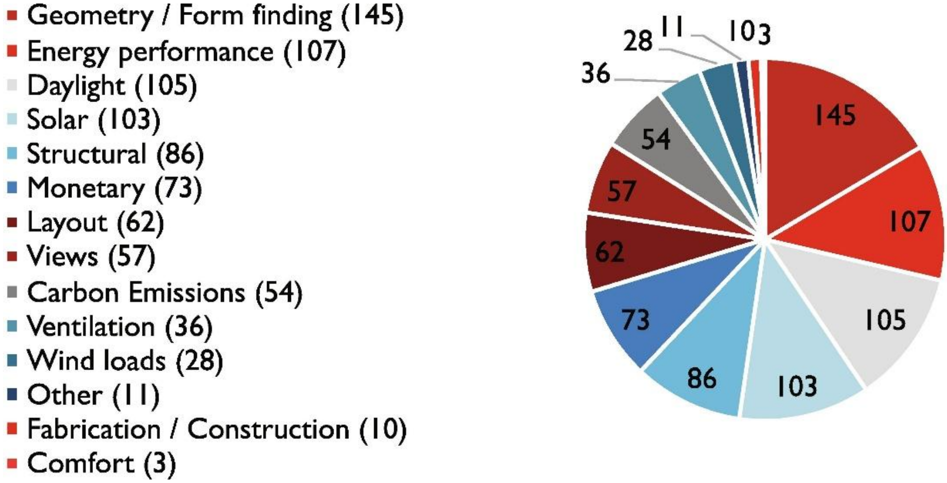

Figure 4.1 Objectives that respondents optimize (multiple choice) (Wortmann et al., 2022)

According to (Wortmann et al., 2022), the expected features of optimization tools can be ranked in order of importance as follows: efficiency, clarity, option for different design alternatives, interaction and overview, and multi-objectivity. The optimization process enables designers to find optimal design solution sets using available technologies by reflecting the current state of quantifiable design options (Machairas, Tsangrassoulis, & Axarli, 2014).

Optimization algorithms can be classified into deterministic, heuristic, and evolutionary approaches. Deterministic methods are generally applied to well-defined problems and provide clear and reproducible results based on mathematical equations. Heuristic methods do not guarantee a solution; these algorithms, which offer practical solutions following failed deterministic algorithms or in high-cost situations, provide reasonably good rather than sufficiently optimal solutions. Evolutionary algorithms, on the other hand, offer solutions to multidimensional problems using nature-inspired and population-based algorithms. Table 4.2 presents the classification of algorithm types, and Table 4.3 demonstrates the suitability of optimization algorithms for different problem types.

Approximately 60% of building optimization studies have employed a single-objective approach; for example, in an optimization study, only one parameter can be optimized (Evins, 2013). However, in the real world, designers are concerned with many parameters simultaneously, and the optimization of one parameter may deteriorate the status of another. Therefore, multi-objective optimization is more important than the single-objective approach in most cases. In a study conducted with 74 articles, (Evins, 2013) concluded that the most commonly used algorithm is the genetic algorithm (GA) and that 40% of the articles within the scope of the study employed multi-objective optimization.

PART I: Classification by Solution Methodology

DETERMINISTIC METHODS	HEURISTIC METHODS	EVOLUTIONARY METHODS
Gradient-Based Methods	**Single-Solution Based**	**Evolutionary Algorithms**
• Gradient Descent • Steepest Descent • Conjugate Gradient • Newton's Method • Quasi-Newton (BFGS, DFP)	• Simulated Annealing • Tabu Search • Hill Climbing • Variable Neighborhood Search • Guided Local Search	• Genetic Algorithm (GA) • Genetic Programming (GP) • Evolution Strategies (ES) • Differential Evolution (DE)
Mathematical Programming	**Constructive Methods**	**Swarm Intelligence**
• Linear Programming (Simplex) • Quadratic Programming • Interior Point Methods • Sequential Quadratic Programming	• Greedy Algorithm • Beam Search • Branch and Bound	• Particle Swarm Optimization (PSO) • Ant Colony Optimization (ACO) • Artificial Bee Colony (ABC) • Firefly Algorithm
Constraint Handling	**Problem-Specific**	**Multi-Objective Specific**
• Lagrange Multipliers • Penalty Methods • Barrier Methods	• Domain knowledge-based • Rule-based strategies	• NSGA-II, NSGA-III • MOEA-D • SPEA-2
Exact solutions given some assumptions Require mathematical properties Computationally efficient Fast convergence for suitable problems	Do not guarantee global optima No guarantee of optimality Cost-effective/Need setting Often problem-specific	Population-based search Handle complex/non-linear landscape Good for multi-modal problems No derivative information needed

Table 4.2 Hierarchical classification of optimization algorithms (Evins, 2013) (Roy et al., 2008) (created by the author)

PART II: Algorithm Suitability for Problem Characteristics

Algorithm	Smooth Convex	Non-Convex Multi-Modal	Constrained Problems	Multi-Objective	Derivative-Free
DETERMINISTIC METHODS					
Gradient Descent	✓	—	—	—	—
Newton / Quasi-Newton	✓	—	—	—	—
Simplex Method (LP)	✓	—	✓	—	✓
Interior Point Methods	✓	—	✓	—	—
Sequential Quadratic Programming	✓	—	✓	—	—
HEURISTIC METHODS					
Simulated Annealing	✓	✓	✓	—	✓
Tabu Search	✓	✓	✓	—	✓
EVOLUTIONARY METHODS					
Genetic Algorithm (GA)	✓	✓	✓	✓	✓
Differential Evolution (DE)	✓	✓	✓	—	✓
Particle Swarm Optimization (PSO)	✓	✓	✓	—	✓
Ant Colony Optimization (ACO)	—	✓	✓	—	✓
NSGA-II	✓	✓	✓	✓	✓
MOEA-D	✓	✓	✓	✓	✓

✓ Suitable / Well-Established — Not Suitable / Not Recommended

Table 4.3 Suitability of optimization algorithms for different problem characteristics (Evins, 2013) (Roy et al., 2008) (created by the author)

4.1.1. Deterministic Algorithms

Used for well-defined, single-objective problems where solutions are based on precise mathematical equations, yielding repeatable results. Examples: MATLAB fmincon, Python SciPy, Excel Solver, COMSOL Optimization Module.

4.1.2. Heuristic (Experience-Based) Algorithms

Applied to problems involving multiple variables where deterministic solutions are not feasible. These methods explore larger search spaces but are slower. Examples: MATLAB GA/PSO, Grasshopper Galapagos, ANSYS DesignXplorer.

4.1.3. Evolutionary Algorithms

Evolutionary algorithms are a widespread meta-heuristic optimization method that applies the Darwinian principle based on the elimination of the weakest solutions in each generation and the survival of the fittest, and employs operators such as mutation (addition of random changes) and crossover (exchange of elements from different solutions) to generate new solutions (Evins, 2013). In the general optimization process, the optimal combination is sought, an objective is defined, and it is optimized. In multi-objective optimization, however, there is no single combination for achieving multiple objectives simultaneously. In this optimization approach, a balance line (Pareto optimum) is established, and the solution set that provides the best balance is determined. Each of these solutions, called Pareto optimal solutions, represents good solutions from different perspectives.

In these methods used for systems with multiple objectives, there is generally a Pareto curve where the best solutions cluster, and the user makes a selection from this set (Fig. 4.2). For example, in systems where both low cost and high efficiency are desired simultaneously, the software examines parameter inputs and generates the set of most suitable matches/solutions. Software such as MATLAB gamultiobj, Python PyMoo/Platypus, Grasshopper Octopus, and ModeFrontier are utilized.

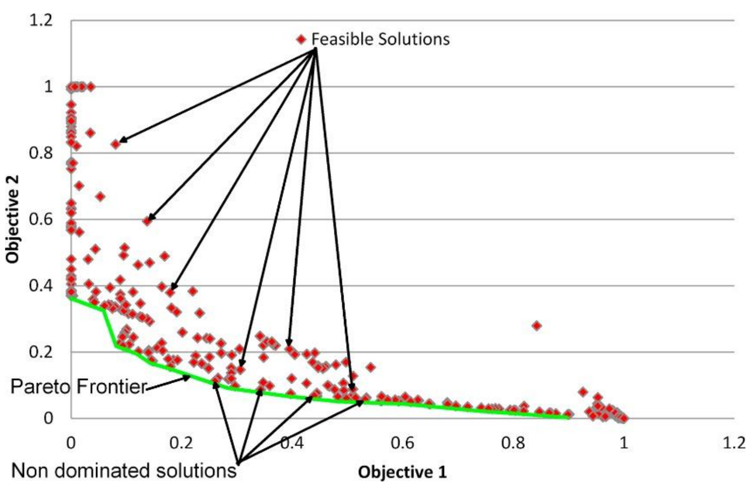

Figure 4.2 An example of Pareto frontier (Machairas et al., 2014)

***Multi Objective Genetic Algorithym* (MOGA)**

The optimal design parameters are determined by running MOGA (Multi-Objective Genetic Algorithm) with the obtained RSM (Response Surface Methodology) equations. Multi-objective optimization is used for systems that seek to optimize multiple objectives simultaneously (e.g., maximizing air velocity while minimizing heat loss).

- ✓ The term "genetic" derives from the emulation of the evolutionary mechanism.
- ✓ Populations (design combinations) are generated.
- ✓ The best-performing ones are selected from among them.
- ✓ Combinations are created through crossover.
- ✓ The newly generated combinations are also evaluated internally.
- ✓ Finally, "Pareto optimal solutions (designs where none is completely superior to another, but each is optimal from different perspectives)" are produced.

In systems with numerous parameters, trial-and-error approaches are not feasible. MOGA scans all findings, analyzes them, and identifies optimal solutions. Consequently, performance increases, comfort improves, and aesthetic and energy-efficient designs emerge with a cost-performance balance.

5. CONCLUSIONS

The results indicate that using appropriate optimization algorithms (deterministic, heuristic, and evolutionary) in combination with simulation data (visual, behavioral, and performance-based) enables a holistic evaluation and improvement of the architectural design process. Simulation-based optimization demonstrates high effectiveness in evaluating multi-dimensional criteria such as energy efficiency, thermal comfort, daylight performance, and economic feasibility.

The study confirms that each algorithm type performs differently depending on the problem characteristics. Deterministic algorithms are suited for well-defined, single-objective problems, while Genetic Algorithms (GA) excel in exploring large design spaces and are particularly effective for multi-objective building optimization. Particle Swarm Optimization (PSO) is effective for continuous-variable problems, whereas Differential Evolution (DE) provides more balanced results. For large-scale problems, Machine Learning (ML)-based surrogate models significantly reduce computational time and accelerate decision-making. Among all, MOGA stands out for its ability to optimize multiple conflicting objectives simultaneously, generating balanced design solution sets for building performance optimization.

Ultimately, the success of the optimization process depends on correctly managing each phase-from accurate problem definition and simulation tool selection (pre-optimization) to appropriate algorithm choice and visualization of results (post-optimization). However, the current lack of user-friendly interfaces and integration between simulation and optimization software complicates the process. Future integration of simulation programs with optimization tools capable of algorithm selection will accelerate workflows and enhance accessibility for designers and researchers.

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