CONTEMPORARY METHODOLOGICAL APPROACHES IN ARCHITECTURE, PLANNING AND DESIGN

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Contemporary Methodological Approaches in Architecture, Planning and Design

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CHAPTER 1

Spatial Perception and Neural Responses: A Bibliometric Analysis of Neuroarchitecture

Serpil Akan[1] & Menşure Kübra Müezzinoğlu[2]

1. Introduction

People are constantly exposed to many architectural features, variables, and differences that influence them throughout their daily lives. In response to the effects of built environments, different cognitive and emotional reactions occur in people (Ghamari, Golshany, Naghibi Rad, & Behzadi, 2021). The importance of built environments in unconsciously affecting perceptual processes stems from their power to change emotional and behavioral expression. Emotions arising from experiences and situational attributes often manifest unconsciously, triggering visceral responses and subsequent somatic responses, which are conscious physiological changes, and crucial for life's continuity.

As Jordan (2000) defines, emotions are feelings shaped by experiences and may vary in response to objects such as chairs, trees, houses, or lamps. Pallasma (2005) underscores the necessity for architecture to engage with human feelings, melding personal and worldly experiences, as articulated by Le Corbusier and Petit (1959), who view architecture as a conduit for confronting the world through "plastic feelings".

When the relationship between architecture and the environment is considered in this context, if the effects of the variables of a building design on the human brain are understood, then it will be possible to create spaces that reduce the individual's stress level, increase their well-being, trigger their creativity, focus their attention, facilitate their learning, and increase other positive aspects (Sirvent et al., 2023).

Disciplines about architecture and environmental interactions have created a new multidisciplinary research field by developing together and are supported by technological developments. A new multidisciplinary approach, which is called "neuroarchitecture" by the Academy of Neuroscience for Architecture (ANFA), is in the forefront with the recent experimental method applications and even if there are not visible common attributes, it has united neuroscience with the fields of architecture (Sternberg & Wilson, 2006).

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Unlike earlier environmental psychology studies based on perception and instinct (Müezzinoğlu, Hidayetoğlu, & Yıldırım, 2020, 2021), contemporary research utilizes neuroscience to scientifically analyze cognitive and sensory impacts (Coburn et al., 2020; Shemesh, Leisman, Bar, & Grobman, 2021).

The relationship between people and their environment was pioneered by Richard Neutra, who designed the Lovell Health House for Dr. Philip Lovell in 1929, emphasizing psychological and physiological needs (Neutra, 1954). Following World War II, architecture focused more on human-centric designs, expedited by the reconstruction of Europe (Sigerist, 1955). The "International Congresses of Modern Architecture" (CIAM) held between 1947 and 1953, concluded that each individual has unique physical and psychological characteristics and that this situation requires different spatial environments (Sigerist, 1955). Kevin Lynch developed the concept of cognitive map in the following process to understand the readability of urban space and to learn more about what the individual perceives while traveling (Lynch, 1964). Jonas E. Salk felt a sense of relief and pleasure while staying at a Franciscan Monastery where he worked in a small laboratory to find a cure for polio, and the experimental designs of his work came to life in his mind. Salk believed that this monastery, which inspired him, had an effect on his mind. In 1965 he met architect Louis Kahn and asked him to design the Salk Institute just like the monastery that inspired him. The "Salk Institute for Biological Studies" building addresses people and their senses with a holistic approach; therefore, it has been evaluated as a study that represents the first concrete example of the relationship between neuroscience and architecture (Quesada-García, Valero-Flores, & Lozano-Gómez, 2023; Tektas, 2023). Neuroscience discoveries by Eriksson et al. (1998) and Epstein and Kanwisher (1998) revealed ongoing neuron production and the brain's special recognition process for architectural structures. According to these developments and discoveries experienced, the neuroarchitecture field of study emerges at the intersection of neuroscience and architecture (Figure 1).

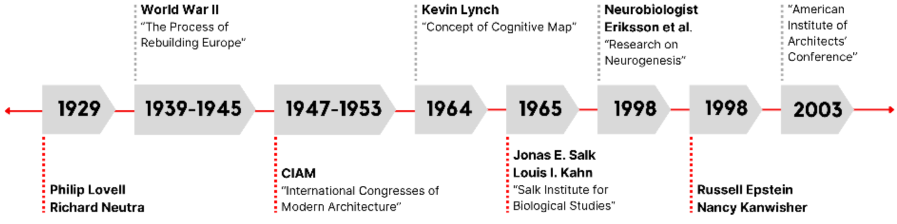

Figure 1. The process of development in neurosciences is based on perception in architecture (Authors' own illustration based on the literature).

Environmental psychology has long explored the effects of built environments on behavior and emotion, but neuroarchitecture introduces neuroscientific tools for deeper insights (Ghamari et al., 2021; Madani Nejad, 2007). These tools include techniques for assessing brain activation, such as Functional Magnetic Resonance Imaging (fMRI), Functional Near-Infrared Spectroscopy (fNIRS), Electroencephalogram (EEG), Magnetoencephalography (MEG), and Transcranial Magnetic Stimulation (TMS) as well as methods for measuring physiological responses, including Electrodermal Activity (EDA) or Galvanic Skin Response (GSR), Heart Rate Variability (HRV), Eye Tracking (ET), and pupillometry (Figure 2) (Banaei, Hatami, Yazdanfar, & Gramann, 2017; Kim, Cheon, Bai, Lee, & Koo, 2018; Laeng, Sirois, & Gredebäck, 2012).

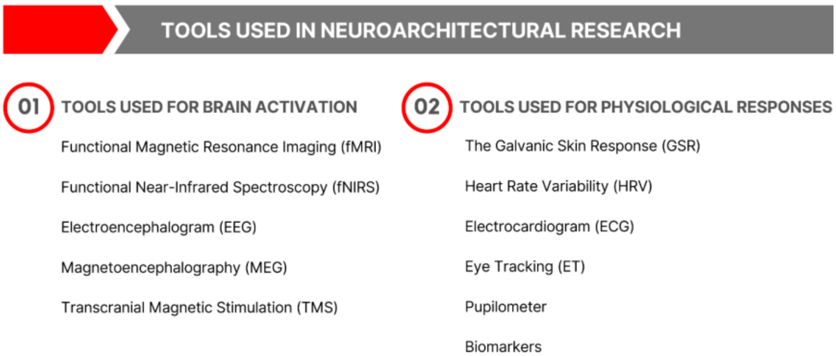

Figure 2. Tools used in neuroarchitectural research (Authors' own illustration based on the literature).

fMRI tracks neural activity associated with emotional changes and visualizes them as mental images to analyze brain functional activation in response to pleasant and unpleasant architectural environments (Bermudez et al., 2017). Similarly, fNIRS employs near-infrared spectroscopy, like fMRI, to detect changes in blood oxygenation indicative of neuronal activation (Banaei et al., 2017). EEG records electrical activity in the brain, and when combined with fMRI modeling, provides clearer insights into neural networks and stimulated brain regions during visual perception and emotional changes (Vecchiato et al., 2015). MEG measures magnetic fields generated by ionic currents, while TMS stimulates brain regions across various domains (Figure 3).

Figure 3. Devices used for brain activation and measurement in neuroarchitecture research (Authors' own illustration based on the literature).

Physiological responses are primarily measured through EDA/GSR, which tracks changes in skin electrical conductivity and is particularly useful for studying attention (Boucsein, 2012); HRV, which gauges variations in heart rate and is commonly used to assess stress and related phenomena (Kim et al., 2018); and pupillometry, which measures pupil diameter as an indicator of cognitive load and stimulation (Laeng et al., 2012). Eye Tracking (ET) devices complement these measurements by recording eye movements and gaze patterns (Figure 4).

Figure 4. Devices used for measuring physiological responses in neuroarchitecture research (Authors' own illustration based on the literature).

The neuroscience devices and related technologies described above allow researchers to record and interpret human behavioral, physiological, and neurological reactions with a high level of objectivity and continuous monitoring (Higuera-Trujillo, Llinares, & Macagno, 2021). Data obtained from devices measuring brain activation can be analyzed with relevant device software, expert opinions in the field, and various statistical methods.

Neuroarchitecture, a nascent field, aims to uncover the neural mechanisms triggered by environmental stimuli, thereby diverging from conventional architectural approaches. This interdisciplinary understanding combines neuroscience and architectural design by reframing architectural design principles in the context of their effects on the human nervous system (Figure 5). Llinares, Higuera-Trujillo, and Serra (2021) explored virtual reality's (VR) impact on student cognition, linking classroom width to cognitive performance and emotional response. Bower, Hill, and Enticott (2023) conducted an EEG investigation on scale and color manipulation, revealing variations in theta-band connectivity across brain regions that reflected differential neural responses to stimulus contrasts.Vartanian et al. (2015) noted aesthetic processing activation in response to curvilinear architectural forms, while Coburn et al. (2020) delineated cortical sensitivity to psychological dimensions within architectural settings.

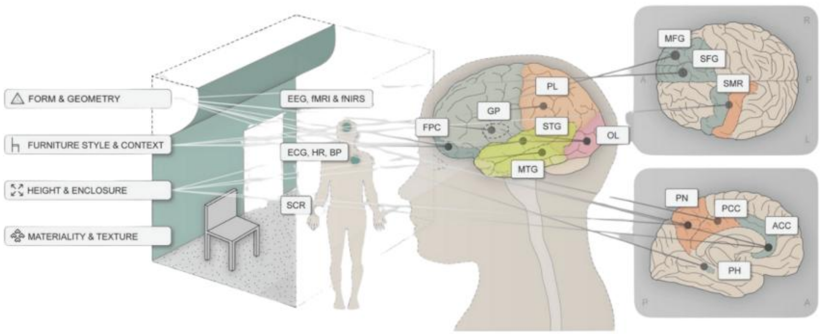

Figure 5. The independent variables, tools used, and relationships among activated brain regions (Bower, Tucker, & Enticott, 2019).

Research in neuroarchitecture has extensively explored the impact of architectural attributes on human stress levels, yielding compelling evidence of their interconnectedness. Studies investigating stress reduction through architectural interventions, such as biophilic and biomorphic design (Yin et al., 2020), optimal window placement and dimensions (Fich et al., 2014), and effective signage (Ergan, Radwan, Zou, Tseng, & Han, 2019), have emphasized the beneficial effects of these interventions on human health. Conversely, studies examining stress-inducing architectural features, including room proportions (Shemesh et al., 2021), wall curvatures (Vartanian et al., 2015), lighting conditions (Ergan et al., 2019), and window configurations (Fich et al., 2014), have underscored their potential to evoke unconscious perceptual responses and trigger stress reactions in individuals.

Although neuroarchitecture is a multifaceted discipline and the number of experimental studies conducted on the subject has increased significantly, there is still no holistic review of the analysis of the current state of neuroarchitecture literature and the changes in the concepts in this field that emerged over time. Despite the advances in experimental studies, neuroarchitecture lacks an integrated analysis of its literature and emerging concepts. This study aims to create a robust evidence foundation for designing spaces that provide positive human experiences, guiding researchers in understanding architectural stimuli's effects. The main research question addressed in this study was: "What is the current status, progression, and development of the scientific literature on neuroarchitecture, which is a multidisciplinary field of study? "The research hypotheses formed for understanding the conceptual infrastructure of the neuroarchitecture discipline, of its developmental process, and of its location in the future have been given below:

H0: To create a convincing evidence foundation for the design of places and areas, which provides a positive context to human experiences of *neuroarchitecture studies, based on the correlation of architecture and neuroscience.*

H1: Studies have been conducted that determine the brain activations and physiological changes in individuals within the scope of neuroarchitecture studies.

H2: Neuroarchitecture studies have adressed different environmental and experimental conditions.

H3: The variables of neuroarchitecture design have different effects on human health.

2. Research Method

This study was based on a bibliometric analysis and was conducted with the aid of a bibliometric map obtained with the RStudio Bibliometrix software. The software, with its free of charge use policy and its broad compatibility with the databases, such as Scopus and Web of Science (WoS), was selected as the main tool for analysis.

First, a database was formed containing studies on neuroarchitecture. Multivarious literature scanning series were used which were formed of the keywords related to neuroscience and physical environment. When designing the search system, it was also kept in mind that different term variants could be used in the literature. The search strategy, as seen in Figure 6, was as follows: subject = ("architecture" OR "built environment" OR "architectural space" OR "interior" OR "environmental design" OR "physical environment") AND ("neuroscience" OR "neuroarchitecture"). The search results were limited with subject sections for determining the publications that focused on the neuroarchitecture study area and the conceptual infrastructure of neuroarchitecture. The research was conducted between 1-15 January 2024 without using any filter for limiting the search. It was selected based on the abstracts, keywords, and titles of the studies, and publications were selected about neuroscience, architecture, and physical built environment for the bibliometric analysis.

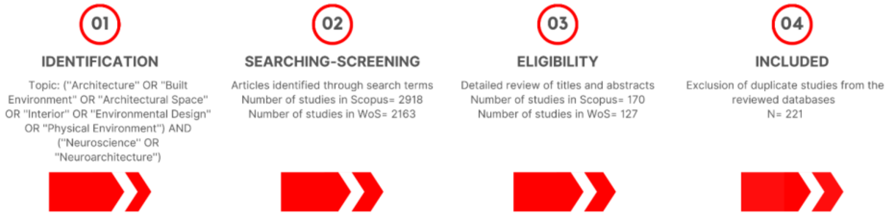

Figure 6. Scanning flow chart (Authors' own illustration).

The scanning flow chart of the bibliometric analysis was given in Figure 6. The research fields of the first scanning findings include some publications related to electrical engineering, robotics, and computer science systems, since they share terminology. After carefully examining the abstracts, keywords, and titles by the authors of 4,784 publications, the publications with no relationship to neuroarchitecture were removed from the database and not included in the bibliometric analysis. Accordingly, 170 studies taken from the Scopus database and 127 studies taken from the WoS database were included in the bibliometric analysis. The final database contains a total of 221 publications, which were published from 1984 up until 2024.

3. Research Findings

This section presents the findings of neuroarchitecture studies that were included in the bibliometric analysis and those focusing on the various effects of built environment design on individuals.

3.1.Bibliometric Analysis for the Neuroarchitecture Studies

The scanning results determined 221 studies which were published from 1984 up until 2024. Of these studies included in the bibliometric analysis research, 494 authors realized them from 145 organizations in 19 countries (Figure 7).

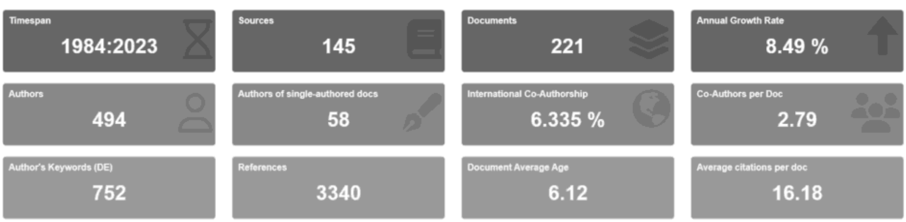

Figure 7. General information related to the studies included in the bibliometric analysis (obtained from RStudio).

Figure 7 shows that research in the field of neuroarchitecture has developed rapidly in recent years with the use of machine learning and digital technologies. Thus, it has become easier to investigate more accurately the effects of neuroarchitecture on design and humans. The fact that the number of studies carried out in the field of neuroarchitecture increased as of 2013, shows that the use of technological equipment in research had become widespread (Figure 8). Thanks to this, the effects on humans of the built environment, which were researched in neuroarchitecture studies, started to be determined in a more effective and intensive manner through experiments.

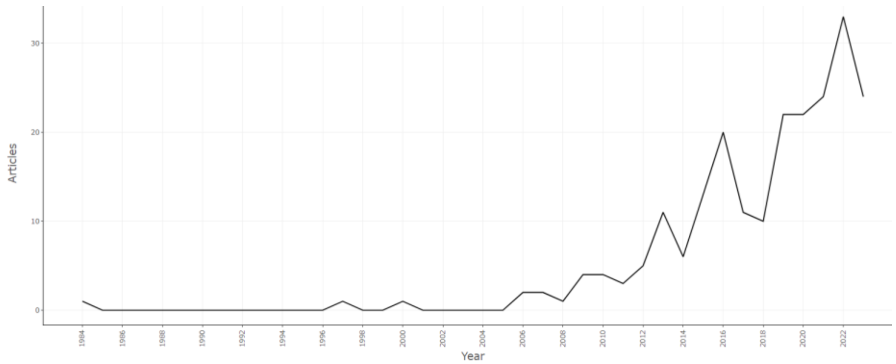

Figure 8. Total publication graph of the annual neuroarchitecture studies (obtained from RStudio).

3.1.1. Co-occurrence Analysis of Keywords Included in the Studies

The co-occurrence analysis of the terms included in articles, by determining the focus fields and the subjects that appear together more frequently, or by determining the sub-subjects, is a bibliographic analysis method formed of thematic groups (Van Eck & Waltman, 2010). All the keywords within the publications included in this study were included in the analysis and those that were determined as keywords for a minimum of two times in the publications were shown in a network diagram.

According to the analysis study conducted, in the 39-year time period from 1984 up until 2024, it was observed that terms, such as “architectural design”, “neuro-architecture”, “built environment”, “brain”, “human”, “EEG”, “cognitive neuroscience”, “attention”, “perception”, “ergonomy”, and “human experiments” had higher occurrence values and connection strengths (Figure 9). This situation showed that the terms mentioned were preferred and related to other terms. The high values of the “fMRI” and “EEG” terms show the significant role of these neuroimaging techniques in neuroscience studies. According to the analysis conducted, the “fMRI” and “EEG” terms are perceived as the techniques used the most prevalently in the field of neuroarchitecture studies.

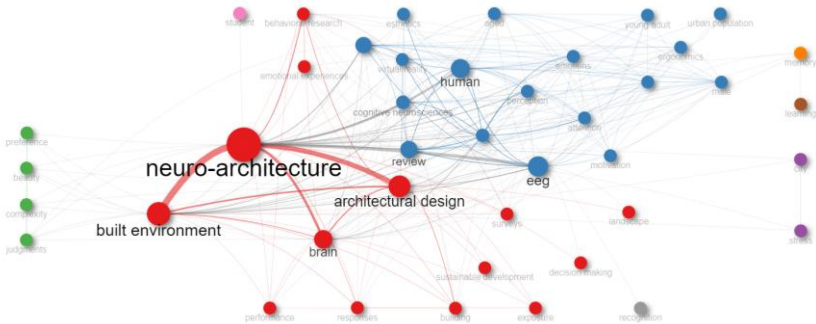

Figure 9. Network diagram of the keywords used in the period from 1984 to 2024 (obtained from RStudio).

Figure 9 illustrates two prominent clusters identified through co-occurrence analysis, marked by distinct colors. The larger red cluster includes keywords central to the neuroarchitecture concept, such as architectural design functions, brain activity, performance, decision-making, and emotional and behavioral responses. This grouping highlights the complex interplay between architectural design, the built environment, and neuroscience, affirming their interconnection.

In contrast, the smaller blue cluster comprises keywords related to neuroscientific methodologies like EEG, fMRI, and VR, along with terms such as perception, emotions, human experiments, aesthetics, attention, and cognitive neuroscience. This cluster reflects the growing trend of using neuroscientific approaches to explore human experiences in architectural settings, emphasizing behavioral, emotional, sensory, and cognitive responses across conscious, unconscious, and subconscious levels. The frequent occurrence of the keyword "EEG" further underscores its central role in neuroarchitecture research. Moreover, the blue cluster encompasses experimental and environmental conditions commonly examined in neuroarchitecture studies, revealing a strong psychological association with human experience.

3.1.2. Thematic Map: “Neuroarchitecture”

A thematic map was constituted for obtaining a deeper impression about the research field. “Work Trap” was selected as the grouping algorithm. Centrality is the X axis on the thematic maps. The Y axis was defined as the density axis and the themes about the field were defined in four different areas (Xiao, Qin, Xu, & Skare, 2023).

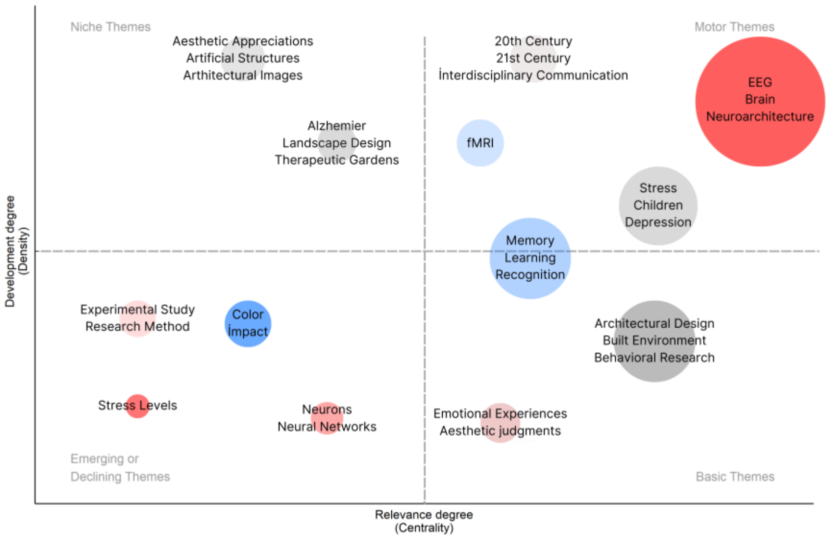

Figure 10. Thematic map of neuroarchitecture studies in the period from 1984 to 2024 (obtained from RStudio).

Figure 10 presents a thematic map analysis of neuroarchitecture studies spanning from 1984 up until 2024. Thirteen distinct themes were identified, showcasing the diverse thematic focus within the neuroarchitecture field. Key themes such as "Neuroarchitecture," "brain," "EEG," "fMRI," "stress," "depression," "children," "interdisciplinary communication," "twenty-first century," "memory," and "learning" emerge as prominent motifs, indicating a significant shift in thematic emphasis towards understanding the influence of environmental factors on human health. In the upper left quadrant, general architectural terms like "aesthetic appreciations," "architectural images," "artificial structures," "Alzheimer," "landscape design," and "therapeutic gardens" are observed. Meanwhile, the lower left quadrant reveals emerging themes such as "experimental study," "research method," "neurons," "neural networks," "stress levels," "color," and "effect," underscoring evolving research trends and the intricate neural networks within the nervous system shaped by the development of the neuroarchitecture field.

3.1.3. Countries with the Highest Contributions Most Related to the Subject

A bibliographic analysis was performed to identify the countries with the greatest contribution to the field of neuroarchitecture. Bibliographic connection refers to the correlation between two elements citing the same document (Van Eck & Waltman, 2010). Based on data from the RStudio Bibliometrix database, authors from 19 different countries contributed to the publication of 221 studies.

Figure 11 presents the primary countries, and the outcomes of the bibliographic analysis conducted to identify the countries with the highest citation rates.

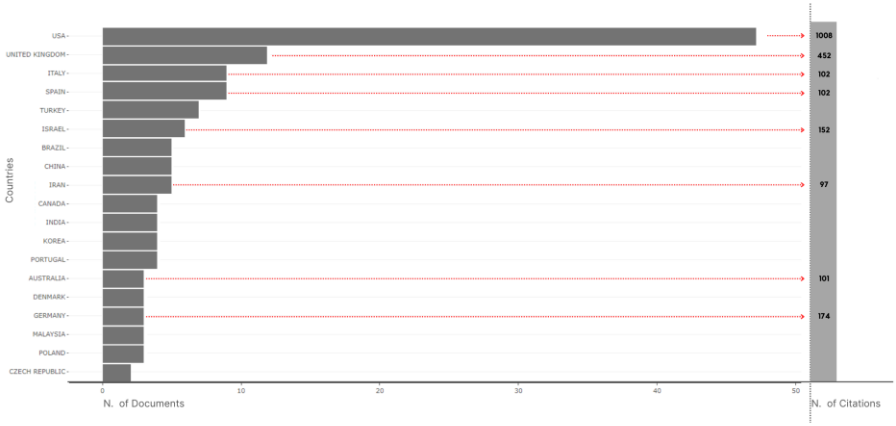

Figure 11. The most related countries in neuroarchitecture studies and the top referencing countries (obtained from RStudio).

The analysis results indicate that the United States leads the field with 125 studies, followed by other developed countries such as the United Kingdom, Italy, and Spain. When the studies in the literature are considered, then it is also understood that cultural differences also affect the neural activation of humans.

3.1.4. Authors with the Highest References Most Related to the Subject

The foremost authors in the field of neuroarchitecture and their relationships with each other were shown in Figure 12. The co-occurrence diagram according to the research field of authors was given in three main groups of green, red, and blue. The studies of authors in the red group were shaped around the effect of environmental behavior and the built environment on the level of cognition and emotions of humans (Bar & Neta, 2007; Fich et al., 2014; Ghamari et al., 2021). Shemesh, Grobman, Bar, and Vartanian were included in many joint studies with other researchers. Talmon and Karp also conducted studies together with Shemesh.

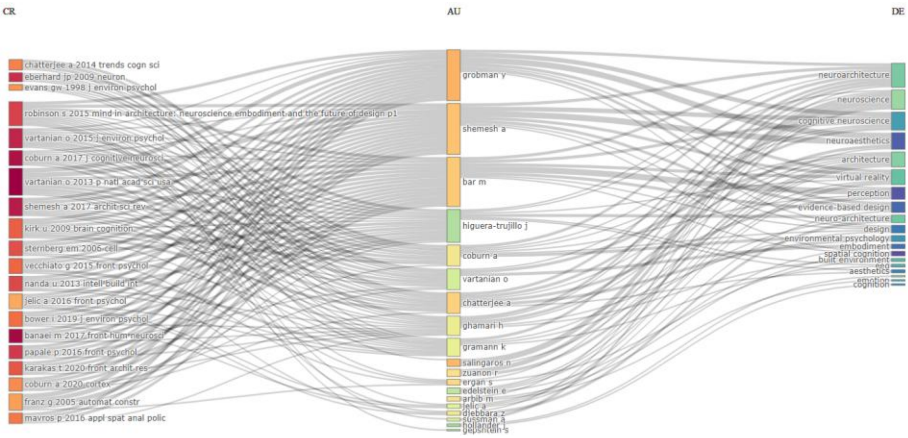

Figure 12. Three-field graph for the field of neuroarchitecture studies. (obtained from RStudio).

3.1.5. The Number of Publications of the Most Active Institutions and Universities

Bradford's Law of Scattering analysis (2010) was used for determining the most effective journals in the field. The H-Indices (an author-level metric that measures both the productivity and citation impact of publications, initially used for an individual scientist/scholar), and the number of articles of the foremost journals have been given in figure 13.

Journal	H-Index	Articles
Architectural Science Review	6	9
Frontiers in Psychology	6	8
Frontiers of Architectural Research	5	8
Intelligent Buildings International	5	7
Urban Science	4	5
Frontiers in Human Neuroscience	3	5
Journal of Environmental Psychology	3	5
Proceedings of the National Academy of Sciences of the United States of America	3	4
Advanced Engineering Informatics	2	4
Archnet-Ijar	2	4
Buildings	2	4
Cognitive Processing	2	3
Frontiers in Neuroscience	2	3
Health Environments Research and Design Journal	2	3

Figure 13. The H-indices and the number of articles of the most active institutions (Authors' own compilation based on outputs obtained from RStudio).

The results showed that there are four main journals in this field: *Architectural Science Review*, *Frontiers in Psychology*, *Frontiers of Architectural Research*, and *Intelligent Buildings International*. When the number of publications of the most active universities engaged in research in neuroarchitecture studies were evaluated, then it is understood that Technion – Israel Institute of Technology and University of California at San Diego with 8 publications each, Independent Bilkent University, Nanyang Technological University, University of Maryland, and University of Pennsylvania with 6 publications each, Aalborg University, University of Lisbon, Valencia Polytechnic University, and University of Southern California with 5 publications each are considered among the most active universities (Figure 14).

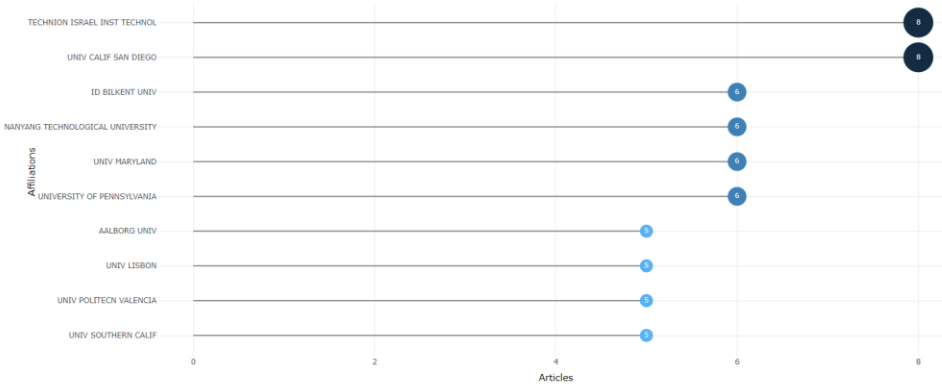

Figure 14. Number of publications on neuroarchitecture of the most active universities (obtained from RStudio).

3.2. Analysis of Neuroarchitecture Studies Conducted for the Different Effects on Individuals of the Built Environment Design

Many experimental studies on neuroarchitecture exist in the literature. These studies, conducted between 2007 and 2024, focused on experiences in the built environment using neurological methods (EEG, fMRI) and physiological methods (HRV, GSR, ECG, ET, and salivary cortisol [SC]). The experiments were carried out in two-dimensional environments presented through real settings, virtual reality (VR), and visual representations.

3.2.1. Research that Determined Brain Activation of Individuals

Experimental studies on brain activations in individuals are compiled in Table 1, explaining neuroarchitectural research methods, experimental methods, independent variables, and detailed effects on humans. It has been understood that the study topics in the literature vary for independent variables. In addition, fMRI and EEG have been frequently used as measurement tools among studies.

Table 1. Research that determined the brain activations of individuals.

Experimental Studies	Experimental Method	Experimental Space	Independent Variable
Epstein, Higgins, Jablonski, & Feiler, (2007)	fMRI	fMRI image	Familiar and unfamiliar location
Martínez-Soto, Gonzales-Santos, Pasaye, & Barrios. (2013)	fMRI	fMRI image	Built and natural environment
Vecchiato et al. (2015)	EEG	VR	Interior space furnishings
Vartanian et al. (2015)	fMRI	fMRI image	Ceiling height
Shin et al. (2015)	EEG	Real space	Direct and indirect illumination
Banaei et al. (2017)	EEG	VR	Geometric shapes
Tang et al. (2017)	fMRI	fMRI image	City, mountain, forest, etc.
Guan et al. (2020)	EEG	Real space	Comfortable and uncomfortable milieu
Llinares et al. (2021)	EEG / HRV	VR	Color element
Zur, Shamay-Tsoory, Sterkin, & Fisher-Gewirtzman. (2023)	EEG	VR	Entrance and window dimensions
Bower et al. (2023)	EEG	VR	Interior scale and color

**Note. Source: Authors' own compilation based on the literature. fMRI=Functional Magnetic Resonance Imaging; EEG=Electroencephalogram; ECG: Electrocardiogram; VR=Virtual Reality.*

As indicated in Table 1, various studies have utilized neuroimaging techniques to explore the neural responses to environmental stimuli. Epstein et al. (2007) conducted a comparative fMRI analysis on brain activity in reaction to familiar and unfamiliar surroundings. Tang et al. (2017) investigated the neural correlates of urban versus natural environments using fMRI, revealing distinct activation patterns across brain regions. Martínez-Soto et al. (2013) utilized fMRI to explore neural responses to rehabilitative environments. Guan et al. (2020) examined the correlations between thermal, acoustic, visual comfort, and overall comfort with neural responses. Total EEG energy was found to be higher in a disturbing environment, meaning that the brain receives more external stimuli in a disturbing situation. Shin et al. (2015) utilized EEG to assess the impact of illumination on emotions and brain activation. Theta oscillations at electrodes F4, F8, T4 and F8 increased more in the direct/indirect illumination environment. Banaei et al. (2017) studied the relationship between emotions and EEG activity during VR navigation. The results revealed a strong influence of curvature geometries on the activity of the anterior cingulate cortex (ACC). Vecchiato et al. (2015) measured EEG responses during the perception of three-dimensional interior spaces, revealing associations with familiarity, comfort, and stimulation. Llinares et al. (2021) investigated the effects of cool color categories on physiological measures using EEG and HRV, showing improvements in attention and memory. Vartanian et al. (2015) examined psychological and neural responses to aesthetic judgments in interior design using fMRI. The study concluded that a room with a high ceiling is more beautiful and that the area that processes visual information becomes more active. Zur et al. (2023) utilized EEG to investigate the effects of wider wall positioning and window size in trapezoidal-shaped apartments, within the context of perceived density and its positive impact. Bower et al. (2023) employed EEG to investigate the modulation of brain network communications by scale and color design elements, revealing increased theta connectivity in specific brain regions in response to design changes. The results of the study show that both increasing and decreasing the scale increased theta connectivity across the left temporoparietal region and the right frontal region. These findings suggest an interplay between environmental attributes and neural oscillations, impacting cognitive processes and mental well-being.

3.2.2. Research that Determined Physiological Changes in Individuals

Experimental studies, experimental methods, independent variables, and by explaining the detailed effects on humans of the physiological changes determined in humans through neuroarchitecture methods has been collected in Table 2. It is understood that HRV, SC, GSR, and ET tools are preferred frequently. In some of these studies (Castilla, Higuera-Trujillo, & Llinares, 2023; Higuera-Trujillo, Llinares Millán, Montañana i Aviñó, & Rojas, 2020; Llinares et al., 2021; Shemesh et al., 2021), besides the physiological effects, analyses for effects in the brain were conducted and the EEG equipment was also used in the research. More than one tool was used together in some studies (Table 2).

Table 2. *Research that determined the physiological changes in individuals.*

Experimental Studies	Experimental Method	Experimental Space	Independent Variable
Selander et al. (2009)	SC	Real space	Noise
Valtchanov, Barton, & Ellard (2010)	ECG / GSR	VR	Natural environment
Fich et al. (2014)	SC / ECG	VR	Open and closed areas
Gidlow et al. (2016)	SC / ECG	Real space	House
Higuera-Trujillo et al. (2020)	GSR / HRV / EEG	VR	Environmental pleasure
Llinares et al. (2021)	EEG / HRV	VR	Classroom width
Shemesh et al. (2021)	EEG / GSR / ET	VR	Space geometry
Castilla et al. (2023)	EEG / HRV / GSR	VR	Illumination levels
Sirvent et al. (2023)	ET	VR	Color and illumination
Shaaban, Kamel, & Khodeir, (2023)	HRV	VR	Environmental factors

**Note. Source: Authors' own compilation based on the literature. SC=Skin Conductance; ECG=Electrocardiogram; EEG= Electroencephalogram; GSR = Galvanic Skin Response; HRV=Heart Rate Variability; ET=Eye Tracking; VR=Virtual Reality.*

Experimental studies outlined in Table 2 examined various aspects of neuroarchitecture. Castilla et al. (2023) analyzed the psychological and neurophysiological responses to different illumination levels. In their research, as the level of illumination increased, performance on memory tests and neurophysiological activation decreased. Llinares et al. (2021) found that broader classrooms were associated with lower performance and emotional stimulation, with significant differences observed in HRV, particularly in Heart Rate Variability-Low Frequency (HRV-LF) and Heart Rate Variability-High Frequency (HRV-HF). Gidlow et al. (2016) compared responses to urban, natural, and water+natural environments after a 30-minute walk, noting decreased cognitive function and recovery experiences in urban settings. Shemesh et al. (2021) investigated the impact of spatial geometry changes using EEG, GSR, and ET tools. The study found that cramped spaces were associated with higher levels of emotional response and discomfort. Higuera-Trujillo et al. (2020) studied stress levels in hospital environments using GSR, HRV, and EEG. The research results show that a combination of environmental sources of pleasure in the simulation produces a significant synergistic effect at the psychological and neurophysiological levels, emphasizing the importance of auditory and olfactory stimuli. Fich et al. (2014) explored the relationship between psychosocial stress and architectural design, observing slower recovery in closed rooms. Valtchanov et al. (2010) assessed the restorative effects of artificial natural environments created with VR using ECG and GSR. Selander et al. (2009) evaluated SC concentration in response to airplane noise. The study found that exposure to aircraft noise increased morning SC levels in women. Sirvent et al. (2023) studied the impact of musicians playing instruments in built environments using ET. The lack of daylight and outside visibility significantly increased twitching eye movements, which are associated with higher levels of anxiety. Shaaban et al. (2023) examined the physiological and psychological effects of distinctive design decisions on children's brain development, observing sympathetic nervous system activation, heart rate increase, and brain activation changes in specific areas in response to environmental elements.

3.2.3. Research that Determined the Experimantal Condition Differences in Neuroarchitecture Studies

Neuroarchitecture studies employ experimental spaces of varied configurations, including real spaces, virtual reality (VR) setups such as Cave Automatic Virtual Environment (CAVE), and functional magnetic resonance imaging (fMRI) environments. Table 3 encompasses studies utilizing VR (CAVE or VR earphones) and physical interior spaces, alongside those conducted in Magnetic Resonance Imaging (MRI) rooms using 2-dimensional images. VR setups typically consist of CAVE systems with three walls of screens and a ground, or virtual environments accessed via head-mounted equipment. This advancement allows researchers to measure physiological and brain responses in controlled environments, including simulations of walking and immersion in water, which are crucial for understanding movement's impact on perception and emotion. In fMRI experiments, subjects remain motionless while exposed to 2-dimensional images projected onto a mirror positioned above their eyes, providing visual stimulation.

Table 3. *Research that determined experimental condition differences in neuroarchitecture studies.*

Experimental Studies	Experimental Method	Experimental Space	Independent Variable
Martínez-Soto et al. (2013)	fMRI	fMRI image	Built and natural environment
Shin et al. (2015)	EEG	Real space	Direct and indirect illumination
Vecchiato et al. (2015)	EEG	VR	Interior space furnishings
Vartanian et al. (2015)	fMRI	fMRI image	Ceiling height
Zhang, Lian, & Wu, (2017)	ECG	Real space	Wood and non-wood environments
Banaei et al. (2017)	Mobil EEG	VR	Interior space forms
Guan et al. (2020)	EEG	Real space	Visual, thermal, and acoustic comfort
Llinares et al. (2021)	EEG / HRV	VR	Color factor
Shemesh et al. (2021)	EEG / GSR / ET	VR	Geometry of the space
Castilla et al. (2023)	EEG / HRV / GSR	VR	Illumination levels

**Note. Source: Authors' own compilation based on the literature. fMRI=Functional Magnetic Resonance Imaging; EEG=Electroencephalogram; ECG= Electrocardiogram; Mobil EEG=Mobile Brain Body Imaging Electroencephalogram; GSR=The Galvanic Skin Response; ET=Eye Tracking; HRV=Heart Rate Variability; VR=Virtual Reality.*

In the experimental studies summarized in Table 3, Zhang et al. (2017) investigated the impact of wooden structures in office environments by comparing rooms constructed with steel and concrete, a fully white-painted room, and rooms with varying percentages of light and dark wooden panels. Martínez-Soto et al. (2013) examined the neural correlates of exposure to restorative environments using fMRI and 2-dimensional images. Guan et al. (2020) explored neural responses to thermal, acoustic, visual, and overall comfort in physical spaces. Shin et al. (2015) studied the effects of direct and indirect illumination on emotions and brain activation in enclosed real spaces. Banaei et al. (2017) analyzed group formation tendencies based on different interior space images and constructed 3D room models representing various shapes. Vecchiato et al. (2015) designed three virtual bedrooms with different furnishing styles in VR, measuring EEG signals from 12 participants. Llinares et al. (2021) evaluated attention and memory performance in a virtual classroom with warm and cool color tones on the walls, involving 160 participants. Vartanian et al. (2015) investigated height perception using fMRI with 2-dimensional stimuli. Castilla et al. (2023) conducted a comprehensive analysis of students' psychological and neurophysiological responses to varying illumination levels using EEG, HRV, and EDA. Shemesh et al. (2021) explored the effects of space geometry changes on EEG, GSR, and ET measures in a laboratory setting. They presented VR scenes with 27 areas of different proportions, curvature, and scale, finding narrow spaces evoked stronger emotional responses and discomfort, excessive proportions were more pleasurable, and simplicity attracted less attention.

4. Results

This study is based on a bibliometric analysis and explores the trends in neuroarchitecture studies recorded in the Scopus and WoS databases, published from 1984 up until 2024. It aims to evaluate the main areas of interest in neuroarchitecture and related research. The bibliometric map analyzed in the research was composed of 221 studies transferred from the Scopus and WoS databases. The bibliometric analysis showed an increase in the number of studies conducted in the field of neuroarchitecture as of 2013. Thanks to the widespread availability of technological equipment, the effects of the built environment on humans have started to be explored more actively and intensively through experiments in the scope of neuroarchitecture research.

When the co-occurrence analysis of keywords (included in the bibliometric analysis results) was examined, it was found that between 1984 and 2024, terms such as “architectural design,” “neuro-architecture,” “built environment,” “brain,” “human,” “EEG,” “cognitive neuroscience,” “attention,” “perception,” “ergonomics,” and “human experiments” had higher occurrence values and strong interconnections. This indicates that these subject terms attracted greater attention and were closely related to each other.

The analysis of country contributions revealed that developed countries predominantly contributed to the field, with the United States leading with 125 studies. Notable authors in this field include Y. Jacon Grobman, Avishag Shemesh, Ofer Karp, Ronen Talmon, Moshe Bar, Maryam Banaei, Klaus Gramann, Javad Hatami, Abbas Yazdanfar, and Amir, each with at least 10 contributions. Most of the studies focused on examining the relationship between architectural form, shape, and emotion.

In terms of leading journals publishing neuroarchitecture research, Architectural Science Review, Frontiers in Psychology, Frontiers of Architectural Research, and Intelligent Buildings International stand out. Regarding active institutions in the field, the Technion – Israel Institute of

Technology and the University of California at San Diego emerged as the most prolific, each contributing 8 publications.

When the analysis results of neuroarchitecture studies investigating the effects of built environment design on individuals were examined, many experimental studies were found in the literature. These studies, conducted between 2007 and 2024, employed neurological methods (EEG, fMRI) and physiological methods (HRV, GSR, ECG, ET, and SC). In most cases, more than one measurement tool was used simultaneously to assess user experience in the built environment. It supports the H1 hypothesis proposed in the research: *Studies have been conducted that determine the brain activations and physiological changes in individuals within the scope of neuroarchitecture studies.* According to these results, it can be suggested that physical environmental conditions affect individuals either positively or negatively by causing brain activations and physiological changes.

Another result in neuroarchitecture studies indicated that experimental spaces were represented in various forms, including real spaces, VR environments, and 2-dimensional images, and these were examined through fMRI equipment. As a result of the comprehensive literature review conducted, it was found that the reviewed studies included research on interior spaces experienced both virtually (through Cave Automatic Virtual Environment [CAVE] or virtual reality headsets) and physically (real space). It supports the H2 hypothesis proposed in the research: *Neuroarchitecture studies have adressed different environmental and experimental conditions*. Even though most neuroarchitecture studies are conducted in virtual spaces, experiments are also possible that are designed in real spaces.

The results of neuroarchitecture studies analyzed through literature research indicate that the research topics focus on various aspects related to the built environment. These aspects include health, performance, attention and memory, stress, aesthetics and emotion, experiential spaces, and human responses; the studies also encompass environmental factors influencing these areas. It supports the H3 hypothesis proposed in the research: *The variables of neuroarchitecture design have different effects on human health.* In this context, it can be stated that architectural designs with positive interventions on environmental variables have the potential to preserve and positively influence human health.

When the results given above are considered in general, the experimental method applications of neuroarchitecture studies are in the forefront, they are considered as a new multidisciplinary approach, and the integration of neuroarchitecture to architectural designs could provide for human prosperity by positively affecting humans. Although the developing neuroarchitecture field still appears to be very untapped, most of the neuroarchitecture studies were carried out abroad, whereas in Türkiye, sufficient experimental studies on neuroarchitecture have not been conducted. The fact that the effects of conducted neuroarchitectural studies are verifiable makes the field of neuroarchitecture research noteworthy and preferable.

5. Proposals

The effects of architecture on people's emotional and behavioral states are clearly seen as a result of the studies. Therefore, the design of spaces that will positively affect human health and well-being should be developed in the context of neuroarchitecture. The application of neuroarchitecture, especially in health and education structures that are of public interest, will increase the level of spatial quality and the performance of users. However, considering the emergence of neuroarchitecture, most of the literature is currently limited to inconsistent measurements for architectural characterization, small sample sizes, single sensory measurements, and evaluation of non-contextual architectural interactions (Valentine & Mitcheltree, 2024). In addition, high funding values emerge due to the experimental methods used in neuroarchitecture. Some policies are needed to financially support these studies. Consequently, it is seen that the possibilities related to this new theoretical field need to be carefully interpreted. In addition, it is suggested that the strategic application of neuroarchitecture to contemporary architecture should be examined and guidelines that integrate neuroarchitectural principles should be designed according to the effects detected on people.

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LIST OF ABBREVIATIONS

ACC: Anterior Cingulate Cortex

ANFA: The Academy of Neuroscience for Architecture

BP: Blood Pressure

CAVE: Cave Automatic Virtual Environment

CIAM: International Congresses of Modern Architecture

ECG: Electrocardiogram

EEG: Electroencephalogram

ET: Eye Tracking

fMRI: Functional Magnetic Resonance Imaging fNIRS: Functional Near-Infrared Spectroscopy

FPC: Frontopolar Cortex

GP: Globus Pallidus

GSR: The Galvanic Skin Response

HR: Heart Rate

HRV: Heart Rate Variability

HRV-HF: Heart Rate Variability-High Frequency

HRV-LF: Heart Rate Variability-Low Frequency

MEG: Magnetoencephalography

MFG: Middle Frontal Gyrus

MoBI EEG: Mobile Brain Body Imaging Electroencephalogram

MRI: Magnetic Resonance Imaging

MTG: Middle Temporal Gyrus

OL: Occipital Lobe

PCC: Posterior Cingulate Cortex

PH: Parahippocampus

PL: Parietal Lobe

PN: Precuneus

SC: Salivary Cortisol

SCR : Skin Conductance Resonance

SFG: Superior Frontal Gyrus

SMR: Sensorimotor Cortex

STG: Superior Temporal Gyrus

TMS: Transcranial Magnetic Stimulation

VR: Virtual Reality

WoS: Web of Science

CHAPTER 2

The Role of Artificial Intelligence Applications in the Protection of Cultural Heritage Elements

İbrahim Batuhan Doğan [1]

INTRODUCTION

The combination of advancing technology and humanity's instinct to discover the unknown led to the invention of machines in historical processes, and subsequently, the aim was to make these invented machines more intelligent. The first machines were designed as tools intended to provide a gain in muscle power for humanity. As time progressed, these machines were developed to calculate in addition to physical strength, bringing them to a level that facilitates human life. The rapid advancement of science and technology today, through the mediation of experts, aims for machines to possess intelligence (AI), enabling the production of programs and applications that allow the machine itself to execute and control the necessary software and processes.

In light of these developments, cultural heritage elements are tangible or intangible resources that allow us to gather information about the lifestyles, habits, and histories of a specific region, society, or individual. These elements exist physically as writings, inscriptions, structures, and artifacts, as well as intangibly as songs, folk songs, sayings, and customs. The protection, preservation, and transmission of these elements to future generations, which illuminate the history of societies, nations, and even humanity and serve as documentary evidence, are crucial for the preservation of history and culture.

Considered one of the great revolutions of our age and expected to shape future periods, artificial intelligence programs and applications have also begun to be used for the protection of cultural heritage elements. With the developed methods and techniques, studies are being carried out using AI programs and applications specific to the operations required for the protection of cultural heritage elements. The number of AI programs produced and the studies conducted with them for the preservation and transmission of tangible and intangible cultural heritage elements to future generations are increasing day by day.

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This study examines the AI-supported applications and efforts carried out for the preservation of tangible and intangible cultural heritage elements and investigates the methods and techniques that can be followed in the protection of architectural heritage elements, which are a part of cultural heritage and shed light on individuals' lifestyles.

Artificial Intelligence Concept

When examining the definitions of the Artificial Intelligence (AI) concept, it can be generally described as machines that think and act like humans. AI is defined as a collection of systems that, by taking in information, mimic human intelligence instead of natural intelligence, process, and improve the acquired data (Kasap et al., 2025). The appearance of studies in this field in the literature took place in the 1950s. The article titled "Computing Machinery and Intelligence" written by Alan Turing is considered the foundation of these studies. This work, which questions the thinking ability of machines, also introduced the concept of the Turing Test to the literature (Powell, 2019).

The Darthmouth Conference, organized in 1956 by John McCarthy, known as the father of artificial intelligence, led to the scientific definition of the artificial intelligence concept (Nilsson, 2009; Kasap et al., 2025). Since its initial use in 1955, AI has branched into several sub-disciplines depending on the nature of the problem, including Artificial Neural Networks (ANN), Fuzzy Logic, Expert Systems, Computer Vision, and Genetic Algorithms (Kasap et al., 2025).

As an umbrella concept containing different methods and specialized techniques for various functions, artificial intelligence has several sub-branches and areas of expertise. Ünal and Kılınç (2020) classified artificial intelligence as narrow AI, general AI, strong AI, and weak AI.

Artificial intelligence encompasses multiple methods and working principles. These methods and principles, which can be defined as sub-components, are customized for different processes to achieve the best result in the conducted studies. It includes sub-branches such as "Machine Learning" and "Deep Learning."

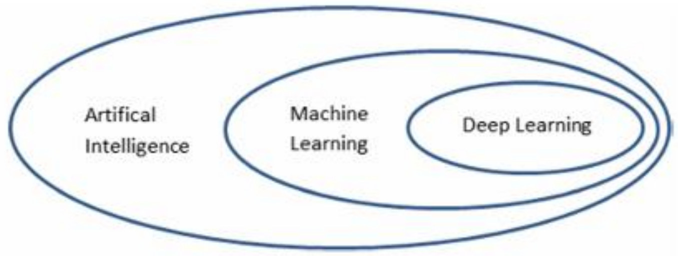

Figure 1 The relationship between artificial intelligence, machine learning, and deep learning. (Cantemir ve Kandemir, 2024)

Machine Learning (ML)

Machine learning is fundamentally defined as giving computers the ability to learn (Samuel, 1959). This working principle is based on data, and the computer works on the given inputs to generate predictions for future data (Russell and Norvig, 2016).

Machine learning has more than one method. These methods differ depending on whether the machine learns by itself or if there is a supervisor (Cantemir and Kandemir, 2024). In supervised learning, the machine is trained with data consisting of labeled inputs and outputs by a supervisor. Zhou (2021) also defined reinforcement learning and semi-supervised learning models alongside supervised and unsupervised learning.

Deep Learning (DL)

Deep learning can be described as a more detailed version of machine learning. In this system, learning results from the sequential operation of multiple layers. The working principle in these layers is arranged so that the output of one layer becomes the input of the next (Deng and Yu, 2014). It has different sub-branches such as CNN, RNN, and GAN.

Convolutional Neural Network (CNN)

CNN, a type of multilayer perceptron, gives good results in studies involving visual data and was developed inspired by the visual cortex of animals (Şeker et al. 2017). These algorithms learn from data and classify visuals, therefore they do not require human intervention (Albawi et al., 2017). The working principle of CNN is based on processing the given image by turning it into smaller images (Şeker et al., 2017).

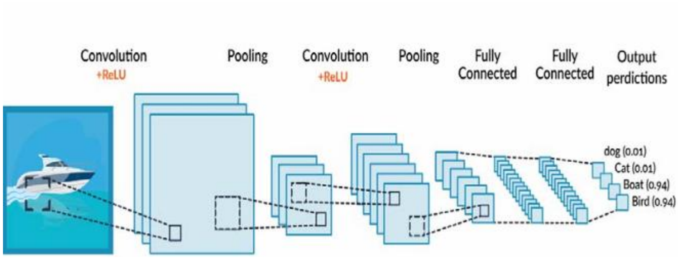

Figure 2 Operating principle of Convolutional Neural Networks (Lee et al., 2021)

Generative Adversarial Networks (GAN)

In this system, unlike CNN, there are generator and discriminator algorithms (Balcı et al., 2020). The two algorithms work in relation to each other, producing outputs similar to the given input while also questioning the reality of these outputs, thereby improving itself (Balcı et al., 2020).

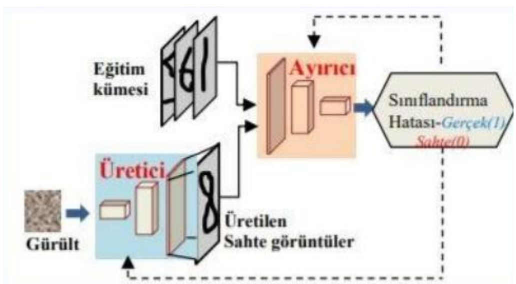

Figure 3 Operating principle of Generative Adversarial Networks (Çelik and Talu, 2019)

Definition and Conservation Values of Architectural Heritage

A significant portion of cultural heritage elements consists of structures and spaces built throughout history. These structures and areas can be damaged over time due to natural or human-made reasons, resulting in the loss of cultural heritage elements. Conservation and restoration applications are of great importance in transmitting these structures to future generations.

Definition of Immovable Cultural Heritage

Cultural heritage first entered a scientific field with the UNESCO "Convention Concerning the Protection of the World Cultural and Natural Heritage" in 1972 (Kasap, 2022). Immovable cultural heritage or cultural property is defined by the International Council on Monuments and Sites (ICOMOS) in the statute created in 2008 as: "An area, natural appearance, architectural complex-space legally protected due to its historical and cultural importance" (Kasap, 2022). This definition shows that cultural assets are discussed in three different dimensions: time, space, and quality. The idea of conservation should include the past, present, and future; the goal of conservation is not to freeze the past but, on the contrary, to keep it alive (Güleç, 2019 cited in Kasap, 2022).

Values Attributed to Heritage

In determining the main idea involving the conservation of architectural heritage, it is essential to define, conserve, and ensure the sustainability of the original values of the cultural property (ICOMOS Turkey, 2013, Article 4.1.3). Understanding these values, which are the subject of the conservation process, is critical for the success of Artificial Intelligence applications aimed at protecting architectural heritage. The 2013 "Architectural Heritage Conservation Declaration" of the ICOMOS Turkey National Committee states that cultural heritage includes historical, artistic, documentary, aesthetic, social, and spiritual values. Some of the core elements of these values, important for conservation science, are (Kasap, 2022):

- Authenticity: Refers to the preservation of design, workmanship, material, and environmental characteristics.

- Integrity and Continuity Value: The wholeness of the features originating from the structure's type, form, material, spirit, and location.

- Historical Value: Associated with the heritage's relationship with its important historical past or its age.

- Technical and Technological Value: Shows the level of technology and techniques used during the construction period of the structure.

- Multi-Layeredness Value: Arises from the relationship that cultural assets, hosting multiple periods and cultures, establish with other periods, adopting a holistic conservation approach.

Artificial Intelligence Applications in the Protection of Cultural Heritage

With technological developments, the determination of the current condition of structures, the performance of analyses, and the implementation of appropriate interventions have become easier. In architecture and design disciplines, technology, initially limited to two-dimensional drawing software, later advanced design processes with Three-Dimensional Modeling (3D) and Building Information Modeling (BIM) applications (Kasap et al., 2025). Following these processes, Artificial Intelligence technologies also began to be integrated into architectural design processes. AI systems automate repetitive and time-consuming tasks, allowing designers to save time and resources (Gaber et al., 2023; Kasap et al., 2025). It stands out not only for facilitating mathematical operations such as visualization and cost calculations but also for its abilities to solve complex problems, quickly generate design alternatives, and improve existing options (Kasap et al., 2025).

The artificial intelligence techniques used in the protection of cultural heritage elements are applied in many different areas, from reconstruction to restoration. Visual scanning systems, professional equipment, and artificial intelligence tools are currently used in the conservation field. AI techniques used in conservation applications are utilized in many different areas, from the restoration of paintings and frescoes to the period analysis of structures. Gaber et al. (2023) point out that manual techniques in visual restoration applications are subjective, high-cost, and time-consuming, while artificial intelligence is more useful in data analysis, processing, and digitization processes.

Some examples from field studies include:

- Dunhuang Caves (China): In a study by Yu et al. (2022), artificial intelligence was used for the restoration of caves dating back to the 4th century. AI analyses were performed to detect artifacts from different periods within the cave.

- Hera Temple (Italy): Pepe et al. (2022) performed a 3D re-dimensioning of the temple using unmanned aerial vehicles and machine learning algorithms (Random Forest). The obtained point cloud data (973,125 points) was classified by AI into structure, environment, and vegetative elements, which was used for current status detection.

- Architectural Style Determination: Cantemir and Kandemir (2024) aimed to determine the periods (Gothic, Modern, Deconstructivist) of built structures using Convolutional Neural Networks (CNN). An accuracy rate of 84.66% was achieved with a dataset consisting of 1043 images.

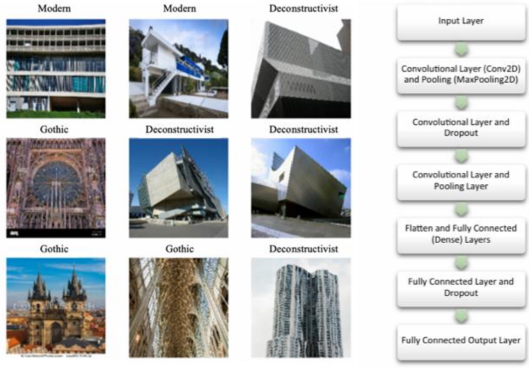

Figure 4 Sample images belonging to the dataset and the operating principle of artificial intelligence (Cantemir and Kandemir, 2024)

- Pagoda Image Search: Lee et al. (2021) trained an AI algorithm using images of Pagoda structures to prevent subjective approaches of experts in restoration applications. After 20,000 cycles with the revised 1000-data set, the accuracy rate was determined to be 98%.

Figure 5 A result image showing the correct and incorrect outputs produced by artificial intelligence (Lee et al., 2021)

CONCLUSION

Artificial intelligence technologies are present in every area of life today, and their effects are increasing day by day. AI applications are also used in the protection and transmission of cultural heritage elements—which act as a bridge between the past and the present, appearing in tangible and intangible forms—to future generations, and their usage areas are increasing with ongoing studies.

In the field of conservation and restoration, one of the specialization areas of architecture, the number of applications performed with artificial intelligence is increasing daily. AI provides time, manpower, and resource savings, while also preventing authorities from developing personal approaches and preventing the work from becoming subjective. AI is positioned not as a threat to the architectural discipline but as a powerful opportunity that transforms production methods, broadens the designer's vision, and augments their capabilities (Bernstein cited in Kasap et al., 2025).

In applications carried out with machine learning and deep learning systems, which are sub-branches of artificial intelligence, increasing the accuracy rate and selecting the appropriate method for the study ensure that AI usage yields more accurate and objective results. The size, definitions, and repetition counts of the data set during the training process affect the accuracy rate of the outputs.

These methods, effective in the digital archiving, exhibition, and conservation applications of cultural heritage elements, enable the determination of architectural style, the prediction of the structure's state before deterioration, and the recognition of the period or structural features of the buildings when trained with a data set belonging to specific typologies. Especially in the process of protecting the values of immovable cultural heritage such as authenticity, integrity, historical, and multi-layeredness, AI programs can ensure the creation of survey (rölöve), restitution, and restoration data required in the conservation and restoration process, contributing to the faster and more accurate completion of studies.

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CHAPTER 3

Comparative Analysis of AI-Based Floor Plan Generators in Architectural Design Process

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1. Introduction

The advancement of architectural design has been characterised by significant transformations driven by the development of various digital tools throughout history. The advent of computer-aided design systems in the architecture has precipitated a paradigm shift, transitioning from analog drawing environments to digital ones. This transition has resulted in enabling architects to process geometric information with greater efficiency, precision, and reproducibility. While CAD systems have significantly accelerated architectural representation and documentation processes, they do not automate the design process. Consequently, the evolution of design alternatives frequently arises from designers repeatedly revising their plans and exploring a range of possibilities.

Unlike traditional CAD tools, which focus primarily on drawing and representation processes, parametric design tools allow for the systematic generation of different design variations through parameters and relationships. The process of parametric modelling is predicated on the delineation of geometric relationships through the establishment of specific parameters and the implementation of associated rules (Jabi, 2013). The advent of visual programming tools such as Grasshopper has profoundly impacted the field of architecture, enabling practitioners to define geometric relationships algorithmically and swiftly generate numerous design alternatives by adjusting parameters. However, while parametric design offers a powerful approach to expanding the design space, it still requires the designer to explicitly define the fundamental rules and relationships of the design.

In recent years, generative approaches to architectural design based on machine learning and artificial intelligence have become an increasingly significant research topic. Especially, the utilisation of artificial intelligence has emerged as a notable tool for architects in recent times, particularly during the architectural design process. In contradistinction to parametric design approaches, these approaches engender new design proposals through patterns learned from large datasets, as opposed to directly programming design rules. In particular, Generative Adversarial Networks (GANs), diffusion models, and Large Language Models (LLMs) have begun to be used in various fields,

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including architectural plan generation, urban morphology analysis, facade design, and spatial planning. The potential inherent in this technological application enables a statistical approach to the design process (Chaillou, 2020).

2. AI Based Generative Models in Architectural Design Process

Generative Adversarial Network (GAN) models, which are frequently employed in architectural floor plan production (Chaillou, 2020; Nauata, 2020; Wang, 2021), are predicated on a learning mechanism in which discriminator and generator operate in a competitive manner (Godfellow, 2020). In these structures, one network generates new data, while the other network attempts to evaluate how closely this data resembles the actual data distribution. Consequently, the model is capable of generating novel design outputs that bear a resemblance to the patterns present within the training dataset. In the domain of architecture, GANs have become a prevalent approach, particularly in the realm of image-to-image translation, including the generation of floor plans, facade design (Yu, 2020), and urban morphology generation (Zhang, 2022).

In recent years, diffusion models have gained significant attention as an alternative approach in the field generative artificial intelligence. The fundamental principle underpinning these models is the progressive degradation and reconstruction of data. During the training process, the model learn to produce meaningful data samples from random noise by gradually adding noise to the data, and then reversing this process (Ho, 2020). This methodology has been instrumental in attaining superior outcomes, particularly in the realm of intricate visual structures. In the domain of architecture, diffusion-based models are being utilized with increasing frequency in areas such as the generation of floor plans, the formulation of urban layout proposals, and the generation of architectural variations.

Moreover, large language models (LLMs), as they are recently termed, have introduced a novel form of interaction to the design field. LLMs are models that have the capacity to comprehend and interpret natural language inputs (Arcas, 2022). This feature enables designers to utilize natural language to guide design systems, thereby obviating the necessity for the definition of complex parametric rules. This facilitates a paradigm shift in human-machine interaction within the design process.

These developments have also given rise to a significant research agenda in the field of floor plan generation in architecture. Floor plans represent a pivotal component within the architectural design process, wherein pivotal decisions concerning spatial organisation, circulation relationships, and functional distribution are made. While conventionally, such decisions were primarily based on the designer's experience and intuitive assessments, artificial intelligence-based methods have the capacity to generate novel spatial arrangement alternatives by analysing a multitude of existing plans. This has the potential to accelerate alternative generation, especially in the early design stages, and expand the design space.

Nevertheless, the role of AI-based plan generation tools in the architectural design process remains a subject of debate. While these systems have the capacity to generate a multitude of plan alternatives, it is acknowledged that architectural design encompasses numerous cultural, functional and contextual factors in addition to geometric arrangements. Moreover, the extent to which these systems provide the designer with control, and the manner in which design decisions are shaped, are also significant topics of discussion in the literature.

Therefore, an examination of the functionality of disparate AI approaches in floor plan generation, the datasets and methods on which they are based, and the decision-making possibilities they offer to designers is considered important for understanding the potential and limitations of these tools in the field of architecture. Such an examination will contribute to a more critical and comprehensive evaluation of how generative AI tools can be positioned in architectural design processes. These tools' ability to solve different spatial typologies and their potentials have recently been a frequent topic of discussion in the literature.

3. Methodology

This research's methodology is founded upon an analysis to examine and compare AI-based floor plan generation tools. The objective of the research is to discuss the possibilities and limitations of generative AI models used in the architectural design process in the scope of generation of floor plans.

In the context of this study, a selection of five tools representing different AI approaches to floor plan generation was undertaken as case studies. The following tools are employed: ArchiGAN, HouseGAN, PlanFinder, ChatHouseDiffusion, and ActFloor-GAN. The selection process was informed by a comprehensive review of frequently referenced processes in the literature, the utilisation of diverse AI architectures and design options, and the potential for intervention in various sections, thereby establishing units that embody the methodological diversity of the field.

The data utilised in this research was obtained from literature review and selected case project documentation in their web pages or github if available. The selected tools were analysed based on a set of criteria to facilitate a comparison of artificial intelligence methods used in architectural plan production. The following criteria are to be considered: (i) dataset, (ii) generative method, (iii) designer interaction, and (iv) output quality. The study does not involve the training of a model or its experimental application; rather, it is a theoretical evaluation based on a systematic examination of extant studies.

The dataset utilised by each instrument examined in this study was analysed. Consequently, the datasets utilised for model training, their content, and the number of samples employed were evaluated in accordance with the information reported in the extant literature. The type of generative model employed in plan generation models (Generative Adversarial Networks, diffusion models, hybrid approaches, etc.) were also examined for each AI based floorplan tool. The analysis also examined the decision-making options offered by each ai tool during the design process and evaluated the extent to which the models provided the designer with control over design constraints, including spatial program, room relationships, plan boundaries, and usage scenarios. In the study, the readability and the quality of the images that were generated by these tools were examined in addition to the designer intervention after the first iteration.

In the analysis, each tool was examined according to the aforementioned criteria, and the findings were evaluated on a comparative basis. The objective of this approach is to elucidate the advantages and limitations of diverse AI architectures in architectural plan production. This study provides a framework for understanding how generative AI tools are positioned in architectural design processes and how they transform the designer's role (see Figure 1 and Figure 2).

4. Case studies

4.1 Archigan

ArchiGAN is an adversarial deep learning network that automates the design of floor plans through three distinct steps: “program repartitioning, building footprint massing, and furniture placement”. A Pix2Pix GAN model has been trained to perform each of these three tasks, and each step corresponds to a specific model. The placement of these models in a sequential manner enables user input at each step, thereby facilitating a hands-on approach (Chaillou, 2020). ArchiGAN has the capacity to generate images for all three stages of the process. At each stage of the process, users have the capacity to edit the generated images, with the option of modifying the inputs. However, it doesn't have more advanced features such as measuring room sizes or setting technical needs (Zeytin et al, 2024). ArchiGAN uses generative adversarial networks which consists of two neural networks that are trained concurrently: a generator and a discriminator. The generator enables creating plans based on user input, while the discriminator is tasked with evaluating the realism and feasibility of these generated plans (Andreou et al, 2023).

ArchiGAN has been utilised more than 800 house floor plan in the training process (Chaillou, 2020). The data was extracted from a comprehensive database of apartments. The spaces are typically entered into the model in raster image format, and different space types such as bedroom, kitchen, living room, bathroom are semantically labelled.

The plans generated by ArchiGAN have been found to demonstrate consistency in terms of spatial organisation, and have been shown to offer layouts that bear a strong resemblance to real residential plans. The model has the capacity to generate a range of layout alternatives by adapting to the given building boundary and core elements. The GAN-based generation mechanism facilitates the generation of diverse plan variations under consistent input conditions, thereby supporting alternative generation in the early design phase. However, it should be noted that certain outputs may present architecturally problematic arrangements in terms of circulation relationships, spatial proportions, or topological connections. Furthermore, the model's exclusion of more intricate design criteria, such as structural systems and regulatory requirements, is identified as a factor that restricts the architectural applicability of the output.

Like many GAN-based image generation models, the outputs produced by ArchiGAN are raster-based and pixel-level plan sketches. Therefore, the boundaries of spaces in the generated plans may not always be clearly and sharply defined. In some cases, blurry transitions may be visible between walls and space boundaries, and the resolution of the plans may be relatively low. This makes the plan geometry appear more like a sketch representing spatial organisation than a detailed, directly applicable architectural drawing. However, the model's outputs can offer alternatives that provide insight into the general layout and spatial relationships of spaces. They can also provide designers with quick visual references for different plan layouts, especially in the early design stages.

4.2 HouseGAN

HouseGAN is a generative model based on a generative adversarial network (GAN) that generates different house plans based on the spatial relationships revealed in a bubble diagram. The nodes present rooms, and the edges represent the spatial relationships between rooms in the diagram (Nauta et al, 2020). This approach allows the designer to decide the number of the rooms and the spatial relationship between them as a design constraint. HouseGAN generates a sequence of axis-aligned bounding boxes for rooms, in accordance with a series of architectural principles. In the literature, the generated houseplans by the demo version of HouseGAN, have been evaluated according to criteria of feasibility, diversity, and compliance with input graph constraints (Zeytin et al, 2024).

The HouseGAN model was trained using the validated LIFULL HOME database, which contains residential floor plans. This database contains around five million floor plans, of which 117,587 were selected for training the model (Nauta et al, 2020). The floor plans in the dataset were converted into graphical representations showing room types, adjacencies between spaces and the position of each space within the plan, which is indicated by bounding boxes.

This representation method enables users to define design constraints using bubble diagrams that illustrate the number of rooms and their relationships. The model then generates spatial layouts that conform to this graphic structure, creating floor plan alternatives that satisfy the given relationships. It can also offer multiple plan proposals based on the same input. However, unlike some other plan generation models, the plan boundary is not given as a direct input or design constraint in the HouseGAN approach. Consequently, while the model generates topological relationships between spaces, its ability to create the overall geometric boundaries of the plan within a user-defined framework is limited.

The plan outputs produced by HouseGAN offer more clearly defined spatial boundaries than those produced by ArchiGAN. In particular, the examples in the demo version of the model show clearer definitions of the boundaries between rooms and a more legible representation of spatial organisation. However, these outputs are still primarily raster-based and the plans are mostly presented as diagrammatic raster images. Therefore, the generated plans are visual sketches representing spatial organisation, rather than vector drawings that can be used directly in a CAD environment.

4.3 ActFloor-GAN

ActFloor-GAN is a generative adversarial network model that facilitates the generation of floor plans by providing external wall boundaries as an input. Furthermore, it facilitates the generation of diverse floor plans derived from a human activity map. In the initial phase, an activity map is generated based on human-environment interaction. Subsequently, a vectorized floor plan is generated using the GAN model (Wang, Zeng et al, 2023). The ActFloorGAN model is not constrained by rigid criteria; rather, it employs a pioneering methodology grounded in human activity (Yang, 2025).

The RPLAN dataset was used to train the model (Wang, Zeng et al, 2023). The system accepts the user-defined building boundary as the main input for generating plans. Additionally, the model uses a representation known as a human-activity map to display information about space usage and human movement. This activity map is a probabilistic representation of room layouts and furniture placements, showing the intensity of human movement within a space. Changes to furniture placement made via the user interface can generate different activity maps, which serve as crucial design inputs that guide the model's plan generation process (Wang, Zeng et al, 2023). This enables users to obtain alternative plans corresponding to different human activity scenarios for the same building boundary.

The generated plans are obtained as raster-based images, using a representation similar to that of many other deep learning-based plan generation approaches. However, the outputs provide plans with clear spatial boundaries and room layouts, offering a level of visual clarity comparable to that achieved with other raster-based models, such as HouseGAN. The article reports that errors can sometimes occur, such as confusing spaces like kitchens and bathrooms, or misclassifying similar room types (Wang, Zeng et al, 2023).

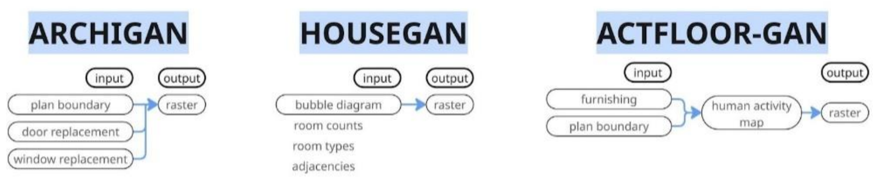

Figure 1. ArchiGAN, HouseGAN and ActFloor-GAN designer interaction

4.4 Planfinder

PlanFinder is a plug-in that generates plans with alternatives through the entry of specific parameters such as the size, form, entrance, facade, and the number of rooms as inputs (Naseri, 2024). PlanFinder facilitates the rapid generation of these plans within existing CAD and BIM software environments and speeds up architectural design processes by facilitating the creation of models and reducing the time taken to produce them. (Dwiananda et al, 2025).

PlanFinder is a tool for generating floor plans, but unlike ArchiGAN, HouseGAN and ChatHouseDiffusion, it has not been reported in detail in academic studies. Consequently, comprehensive technical details regarding the dataset employed by the system, its training process, and the generative model architecture are not accessible in publicly available scientific sources. However, the system produces vector plan geometries instead of raster images. The generated plans consist of readable, editable drawings that are ready to use in design environments. The system can be used as an add-on for design tools such as Revit, Rhino and Grasshopper. Rather than offering a single solution, it generates different spatial arrangement alternatives, enabling design options to be compared.

4.5 Chathouse Diffusion

Chathouse Diffusion is a diffusion model that relies on the automatic generation and modification of floor plans through the utilisation of textual prompts (Qin et al, 2024). The designer delineates the boundaries of the plan and provides a description of the spatial needs by using prompts. It allows editing by textual prompts on the generated floorplans. In this respect, ChatHouseDiffusion aims to establish an interactive design environment between the designer and the artificial intelligence system. The model has been trained on datasets consisting of residential plans, learning patterns such as spatial organisation, room types, and spatial relationships, and is capable of generating new plan alternatives based on these patterns.

ChatHouseDiffusion facilitates more flexible interaction possibilities through natural language inputs. The designer is able to define various design requirements, such as the number of rooms, spatial relationships, or usage scenarios, through textual expressions. The model can then take this information into account in the planning and production process, creating new layout alternatives. This demonstrates that AI-based design tools can be positioned not just as automated production systems, but as interactive design tools that work alongside the designer.

The training dataset employed by the model is derived from the RPLAN dataset. RPLAN is a large-scale dataset consisting of 80,788 floor plans manually compiled from real buildings, thereby enabling the model to learn spatial organisation patterns. The performance of the method was evaluated using the Tell2Design dataset. The Tell2Design dataset comprises approximately 80,000 floor plan designs accompanied by natural language commands, thus enabling the testing of the relationship between textual design inputs and plan generation (Qin et al, 2024). The amalgamation of these datasets facilitates the model's capacity to discern the spatial configuration of plans and to assimilate design imperatives articulated in natural language into the plan generation process. However, given the model's substantial reliance on plan patterns present within the training dataset, the diversity of generated plans and their alignment with the architectural context are contingent upon the extent of the dataset.

The diffusion-based production approach offers certain advantages in terms of the visual quality and spatial integrity of the plans. It has been demonstrated that, due to the model's progressive construction of the plan layout from a state of random noise, the resulting plans frequently manifest geometric continuity and visual consistency. Moreover, the capacity to formulate numerous plan alternatives for a given set of textual instructions enables the expeditious evaluation of diverse spatial organisation options during the preliminary design phase. However, since the interpretation of natural language inputs does not always produce definitive results, in some cases the generated plans only partially meet the textual instructions or fail to fully establish certain spatial relationships.

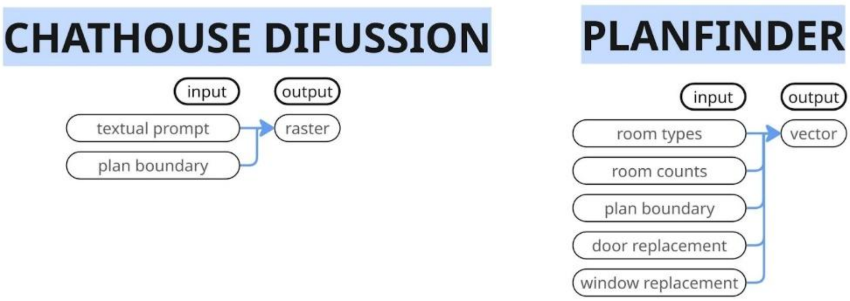

Figure 2. Planfinder and Chathouse Diffusion designer interaction

5. Findings

A comparison of the architectural plan generation tools examined in this research reveals that each tool has its own advantages and limitations in terms of dataset, production method, designer interaction, and output quality (see Table 1).

Table1: Comparison of AI-based floor plan generation approaches

	Dataset	**Generative method**	**Designer interaction**	**Output quality**
ArchiGAN	800+ house plans	GAN	plan boundary, door and windows replacement	pixel based, blurry
HouseGAN	117,587 house plans, LIFULL HOME	GAN	Room types, Adjacencies, and Room count	pixel based, clear
PlanFinder	NA	NA	plan boundary, door and windows replacement, room types and room count	vector based, clear
ChatHouseDiffusion	80,000 house plans, RPLAN and Tell2Design	Difusion and LLM	plan boundary, textual prompt	pixel based, clear
ActFloor-GAN	80,000 house plans, RPLAN1	GAN	plan boundary, furnishing	pixel based, clear

5.1 Dateset

On examining the datasets of all these tools, the first notable aspect is the size of the datasets utilised. The size and diversity of the dataset are of crucial importance, as they directly impact the capacity of generative models to learn and diversify spatial patterns. The ArchiGAN model was trained on a relatively small dataset of approximately 800 house plans. HouseGAN utilises a substantially larger database, comprising approximately 120,000 plans. ChatHouseDiffusion and ActFloor-GAN utilise datasets comprising approximately 80,000 plans. The substantial size of the dataset enables these models to learn larger spatial patterns. In contrast, PlanFinder functions as a software-dependent plug-in rather than a dataset-based learning model. Consequently, the performance of PlanFinder is more dependent on the adjustments made by the designer than on the size of the dataset on which it is trained. This distinguishes PlanFinder from generative model-based approaches, positioning it more as a design-supported tool.

5.2 Generative method

ArchiGAN, HouseGAN and ActFloor-GAN generate plans through the utilisation of GAN-based models. GAN-based models are predominantly founded upon pixel-based representation, which may consequently impose certain constraints on their capacity to accurately represent architectural drawings and to accurately depict spatial relationships. In contrast, ChatHouseDiffusion integrates diffusion models with large language models (LLMs) into the generative process, generating plans based on textual inputs provided by users. Conversely, PlanFinder does not utilize a generative model; instead, it can be regarded as a software plugin.

5.3 Designer interaction

The intervention options offered to the designer by all these models are at different levels, as will be demonstrated in the following discussion. In the ArchiGAN and ActFloor-GAN models, the capacity for designer intervention is constrained to the definition of parameters associated with plan boundaries, door and window positions, and furniture placement. HouseGAN, conversely, facilitates the definition of parameters associated with room types, the number of rooms, and spatial adjacency relationships. ChatHouseDiffusion, conversely, facilitates the designer's involvement in plan creation through text-based inputs. Differently, PlanFinder functions as a plugin for software, in contrast to generative systems. Consequently, the designer's control is constrained by the limitations imposed by the software interface.

5.4 Output quality

Generative models such as ArchiGAN, HouseGAN, ActFloor-GAN, and ChatHouseDiffusion are able to produce pixel-based plan outputs. However, it should be noted that these outputs are subject to certain limitations with regard to clarity and accuracy, although they do demonstrate considerable potential. In contrast, PlanFinder produces vector-based outputs. The components of the plan, including walls, windows, and doors, facilitate more precise and quantifiable outcomes.

6. Conclusion

The present study is constrained to a particular focus on AI tools that are specifically designed for the purpose of floor plan production. While the selected examples represent important approaches in the field, it should be noted that they do not encompass all models found in the literature. Moreover, the analysis is based on results reported in extant studies and does not involve a direct experimental model comparison. Nevertheless, the study aims to initiate a conceptual discussion of the potential and limitations of generative AI methods employed in architectural plan production.

This study methodically examines five distinct AI-based floor plan generators. While these tools demonstrate their potential to accelerate the architectural design process and offer diverse alternatives, they also exhibit limitations, such as producing output based on specific datasets and failing to adequately respond to diverse contexts. Moreover, plan generation models have been shown to be effective in creating spatial organisation, they may be limited in their ability to directly represent more complex aspects of architectural design, such as structural systems, regulatory requirements, or detailed technical design criteria.

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CHAPTER 4

What Does Plastic Furniture Production Offer in Terms of Resource Efficiency? An Environmental Assessment of Moulding Methods

***Gamze Özcan*[1] & *Gamze Demirci*[2]**

INTRODUCTION

The furniture manufacturing sector has a complex industrial structure involving the use of various materials and production techniques. This diversity, providing flexibility in design and production, also raises significant environmental concerns regarding the management of waste generated during the production process and the efficiency of resource use. In the literature on sustainable production, it is emphasised that environmental performance should be assessed not merely on the basis of the type of material used, but through the holistic structure of production processes (Güneş & Demirarslan, 2020).

The literature on resource efficiency considers the reduction of material losses arising during the production process and the reintroduction of in-process waste back into the system to be key indicators of sustainable production (Demir & Yılmaz, 2018, pp. 1127–1129). This approach necessitates the redesign of material flows in accordance with closed-loop principles, particularly in sectors engaged in high-volume production. Similarly, the circular economy paradigm aims to keep products and materials within the economic system for as long as possible and to minimise value loss (Geissdoerfer et al., 2017, p. 759). The furniture sector is considered one of the most critical areas for this transformation due to its use of multiple materials and complex production processes. In particular, the synthetic resins used in the production of wood-based panels, along with pressing processes and surface coating techniques, impose significant environmental burdens in terms of energy consumption and chemical emissions (Özdemir & Tutus, 2013).

In the furniture industry, wood-based and plastic-based production methods are frequently compared. However, these comparisons often focus on the

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materials themselves, while the structural characteristics of the production process are not sufficiently examined. In particular, the capacity to reintroduce in-process waste back into the system emerges as a decisive factor in terms of resource efficiency.

The aim of this study is to assess the quantity, types and recycling potential of waste generated during the production process of polypropylene-based plastic furniture manufactured using the moulding method, and to analyse these results in comparison with wooden furniture produced using CNC machines and moulded wooden furniture. In this way, the effects of different production methods on waste management and resource efficiency are systematically demonstrated. In wood-based production processes, the fact that panel optimisation depends on the design, coupled with inefficiencies in cutting planning, can lead to increased wastage rates in production. A significant proportion of the shavings and scrap generated in CNC-based production systems cannot be directly reused in panel production due to their composite structure and binder content. Furthermore, the environmental and health impacts of formaldehyde-based resins used in MDF and particleboard have been discussed in detail in the literature (Gültekin, 2011, p. 112).

Conversely, the ability to convert in-process waste generated during the production of thermoplastic materials back into raw material through mechanical recycling offers a significant advantage. The literature on plastic recycling indicates that recovery rates are particularly high for clean production-sourced waste and that this practice enhances material efficiency (Hopewell et al., 2009, p. 2118). The remeltable nature of thermoplastics such as polypropylene (PP) enables the implementation of production models that are close to a closed-loop system in compression and injection moulding processes.

However, the sustainability performance of plastic production should not be assessed solely on the basis of recycling capacity. Polypropylene production relies on fossil-based raw materials and is an energy-intensive process during the primary production stage (PlasticsEurope, 2018). Therefore, the environmental performance of plastic furniture production must be analysed by considering the in-process recycling rate, product durability, service life and post-use recovery potential together.

This study is a case study designed within the framework of a qualitative research approach. A case study enables an in-depth examination of the contextual characteristics of a specific production process. The research focuses on the production process of a medium-sized firm operating in Turkiye that manufactures polypropylene-based plastic furniture. The firm has been anonymised for ethical reasons.

Data:

- *On-site observations carried out on the production line*
- *A comprehensive review of the production process from start to finish*
- *Process explanations provided by technical staff*
- *The researcher's two years of industry experience in the production of wood-based furniture*

were obtained through these means.

The data were evaluated using descriptive analysis methods; the plastic moulding production process was interpreted in a comparative manner with CNC-based wood production and pressed wood production methods. The analysis is a process-based evaluation rather than a quantitative performance measurement.

The research question can be defined as follows:

"*How does the moulding method in plastic furniture production offer an advantage in terms of waste management and recycling compared to wood-based production methods*?"

In seeking an answer to this question, the fundamental problem of the study also comes to light: the uncertainty regarding the environmental impacts and efficiency of different methods used in furniture production, particularly in terms of waste management. The literature indicates that wooden furniture produced using CNC machines has a high scrap rate and that recycling is difficult due to the complex material structure (Bekar, 2023). While pressed wood furniture offers a low scrap rate, its efficiency is limited due to long production times (Ceyhan, 2021). In contrast, when polypropylene-based plastic furniture is produced using the moulding method, the resulting burrs, transition material and shim waste can be converted back into raw material using shredding machines (Purde, 2019; Çalışkan, 2024). This finding demonstrates that plastic furniture represents a significant alternative in terms of environmental sustainability and resource efficiency with regard to waste management (Özel & Ürük, 2019). Furthermore, the high recycling rates in the production processes of plastic furniture serve as a guiding principle for the sector to align with the principles of the circular economy. Consequently, this study both fills a gap in the literature and contributes to the development of more environmentally friendly production practices within the furniture sector.

THEORETICAL FRAMEWORK

The furniture manufacturing sector ranks among industries with significant environmental impacts in terms of the materials used and production techniques; consequently, issues such as waste management, resource efficiency and sustainability are gaining increasing prominence in the literature. Particularly with the growing prevalence of the circular economy approach in recent years, the nature, quantity and recycling potential of waste generated in furniture production processes have become key criteria in the evaluation of production methods (Güneş & Demirarslan, 2020). A review of the literature reveals that wood-based and plastic-based production methods are frequently compared in this context; however, it is observed that the opportunities offered by plastic furniture produced using the moulding method in terms of resource efficiency have so far been addressed in only a limited number of studies.

Resource efficiency is based on the principle of converting the inputs used in the production process into the highest possible added value and minimising waste generation. Similarly, the circular economy approach aims to keep materials within the system for as long as possible. In this context, in-process recycling practices are regarded as one of the key indicators of sustainable production. The reintroduction of waste generated during production back into the production process, without it leaving the system, reduces material loss and enhances resource efficiency. Although wood is widely used in the furniture industry as a traditional and aesthetically pleasing material, it poses significant challenges in terms of environmental sustainability due to the high waste rates generated during the production process and limited recycling capacity. In particular, the production of wooden furniture using CNC machines generates large quantities of sawdust and waste during the cutting and shaping stages; a significant portion of this waste cannot be reintroduced into production due to components such as panel structure, adhesive and veneer (Bekar, 2023). Although pressed wood furniture offers a lower waste rate compared to CNC production, it is considered a limited alternative in terms of efficiency due to long production times and energy-intensive processes (Ceyhan, 2021). This situation highlights the need to assess the environmental impacts of wood-based production methods not only in terms of waste volume but also in conjunction with the energy and resources consumed during production.

Plastic materials, in particular, are attracting increasing attention in the literature due to their recyclability, which is largely attributable to their thermoplastic properties. When polypropylene-based plastics are produced using methods such as compression moulding and injection moulding, a significant portion of the waste generated during the production process, such as flash, sprues and shanks, can be converted back into raw material using shredders (Purde, 2019; Çalışkan, 2024). The plastics fed into the machine melt and take on the shape of the mould inside the machine (Figure 1). Previous studies have shown that such in-process recycling applications significantly reduce material losses and bring plastic production processes closer to a closed-loop structure (Garg & Ateeq, 2025). This feature makes plastic furniture production a strong alternative not only from an economic perspective but also in terms of environmental sustainability.

Comparative studies in the literature have shown that plastic furniture offers greater advantages than wooden furniture in terms of recyclability. Özel and Ürük (2019) highlight the formal flexibility and ease of production that plastic materials offer in furniture design; while Molano Gómez et al. (2025) note that plastic-based furniture products make an indirect contribution to the conservation of forest resources and hold significant potential from a circular economy perspective. However, it is observed that plastic waste is not only utilised in furniture production but also in alternative applications such as eco-bricks for urban furniture and construction materials; these approaches are increasingly gaining prominence in the waste management literature (Kumar et al., 2024).

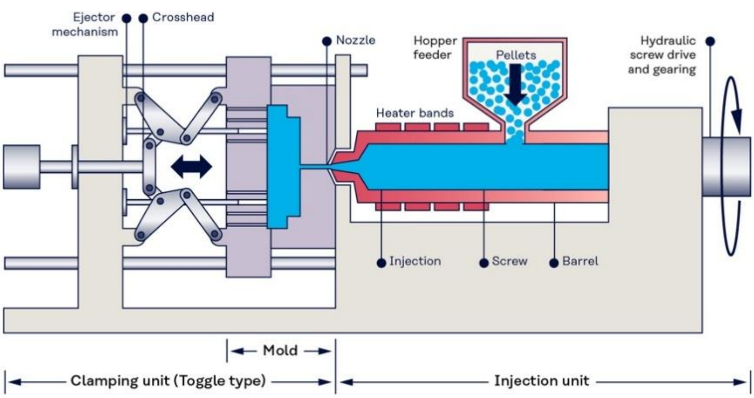

Figure 1: Plastic furniture production process, injection moulding machine diagram (Kuraray Elastomer / Blog)

From the perspective of resource efficiency, plastic furniture produced using the moulding method offers a production model that extends the life cycle of raw materials, as the majority of waste generated during the production process can be reintroduced into the production cycle. While the circular economy approach aims to keep materials within the system for as long as possible, the recycling practices applied in plastic furniture production align closely with this objective (Güneş & Demirarslan, 2020). Çalışkan (2024) emphasises that reintroducing plastic waste into production reduces the environmental burden and supports industrial sustainability; meanwhile, Garg and Ateeq (2025) demonstrate that reprocessing plastic and polyethylene waste using appropriate methods significantly reduces resource consumption.

The wood shavings and scrap material generated during the CNC cutting and shaping stages of wood-based production processes have limited recyclability due to their composite structure and binder content. Although pressed wood production methods offer a lower waste rate, they present different limitations in terms of energy intensity and production time.

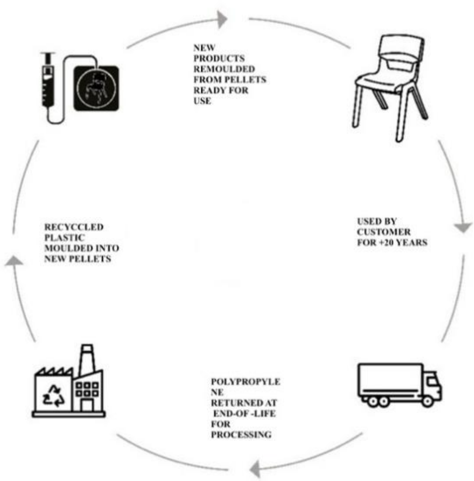

Figure 2: Circular plastic waste management (Krueger International, Inc.)

In thermoplastic-based plastic production processes, it is known that the scrap and off-cuts generated during production can be re-granulated and reintroduced into the production process. This characteristic makes plastic production systems more suitable for in-house closed-loop applications. The reprocessing of plastic material after its use and its reintroduction into the production system constitutes one of the fundamental principles of the circular production model (Figure 2).

METHODOLOGY

This study is based on a qualitative research approach. The aim is to highlight the advantages offered by the moulding method in plastic furniture production in terms of waste management, recycling capacity and resource efficiency, and to compare these findings with wood-based production methods. The qualitative approach was chosen as it allows for an in-depth evaluation of the contextual aspects of the subject under investigation (Yıldırım & Şimşek, 2018). However, some of the data obtained were supported by quantitative indicators (e.g., scrap rate, recycling rate), thereby grounding the research findings on a more concrete basis (Creswell & Creswell, 2018).

The methodological process of the study is structured as a sequence comprising the research design, data collection and analysis stages. The research methodology and the general framework of the data analysis process are illustrated in the flowchart presented below (Figure 3)

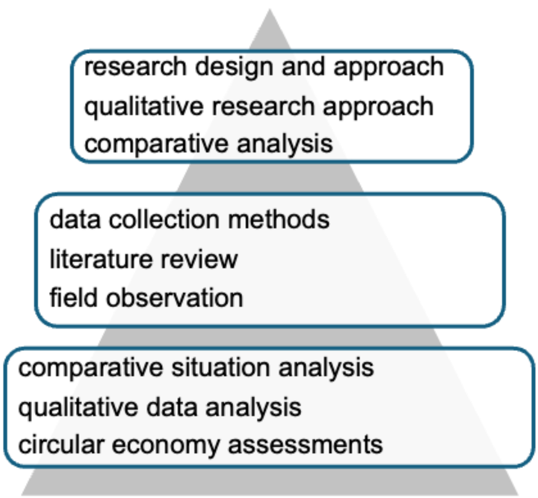

Figure 3: Research Methodology Diagram (Gamze Özcan, 2025)

The study utilised both secondary and primary data. In this context;

• As part of the literature review, national and international studies published in the context of plastic furniture production, the moulding method, waste management and the circular economy were examined (Geissdoerfer et al., 2017).

• Through field observation, the machinery, production lines and waste management practices used in the plastic furniture production process were directly observed. These observations enabled a concrete assessment of the production efficiency and waste management practices associated with furniture produced using the moulding method (Yin, 2018).

The findings obtained from these two methods were considered in conjunction with the theoretical framework of the study and formed the basis for a comparative analysis.

The data obtained were evaluated using comparative situation analysis and qualitative data analysis methods. The plastic furniture production process was analysed by comparing it with wooden furniture produced using CNC machines and pressed wood furniture, based on criteria such as waste volume, recycling capacity and production efficiency (ISO 14040, 2006).

During the analysis process, the characteristics and recycling potential of the waste generated by each production method were first identified. These findings were then evaluated from the perspectives of the circular economy and resource efficiency. The reliability of the study was enhanced by supporting the qualitative analysis findings with existing quantitative data, where available (Creswell & Creswell, 2018).

RESULTS AND DISCUSSION

AN ASSESSMENT OF THE POTENTIAL OF PLASTİC FURNITURE PRODUCTION IN TERMS OF RESOURCE EFFICIENCY

The title of this study, “What Does Plastic Furniture Production offer in Terms of Resource Efficiency? An Environmental Assessment Based on Moulding Methods”, aims to reopen the debate on the generalised environmental judgements frequently encountered in the literature on plastic materials. Research conducted in Turkiye in the fields of sustainable production and environmental management emphasises that the environmental impacts of production processes cannot be reduced solely to the nature of the materials used; rather, process design, energy consumption and waste recovery capacity must be assessed collectively (Yılmaz, 2014; Demir & Yılmaz, 2018). In this context, the question posed in the title, “What does it offer?”, provides an analytical framework that questions the opportunities offered by the production process, rather than subjecting plastic furniture production to a categorical environmental judgement.

The concept of resource efficiency is based on the principles of the effective use of inputs and the reduction of waste generation in industrial production.

Studies on clean production and eco-efficiency in Turkiye demonstrate that in-process recycling practices can simultaneously improve economic and environmental performance by reducing material losses (TÜBİTAK MAM, 2015; Aksoy & Polat, 2020). This perspective necessitates that the various production techniques used in furniture manufacturing be evaluated not only in terms of aesthetics or cost, but also in terms of waste management and recovery capacity.

The emphasis on the moulding method in the title indicates that the study focuses on production technology rather than the type of material. Technical studies on plastic processing technologies indicate that flash and scrap material generated during the production process of thermoplastic materials can be re-granulated and reintroduced into production (Köse & Şahin, 2016). This enhances the feasibility of closed-loop systems within production and represents a significant advantage in terms of resource efficiency.

On the other hand, research conducted on the forest products industry in Turkiye has shown that cutting planning and panel optimisation in sheet production are decisive factors in determining efficiency; it has also been demonstrated that scrap rates increase when there is a lack of integration between design and production (Eroğlu & Usta, 2000; Karakuş, 2012). These findings are significant in that they demonstrate a direct relationship between the production method and the amount of waste generated.

Consequently, the concept of 'offer' in the title does not refer to the aesthetic or economic superiority of plastic furniture, but rather to the performance of the production process in terms of resource efficiency, in-process recovery capacity and waste minimisation. Studies on sustainable industrial policies in Turkiye also emphasise that the restructuring of production processes is a key element in improving environmental performance (Ministry of Industry and Technology, 2021). Within this framework, the study goes beyond the normative and one-dimensional assessments frequently encountered in discussions of environmental sustainability regarding plastic furniture production, and instead examines, in a comparative manner, the potential offered by the moulding method in terms of resource efficiency. The title positions this assessment not as a definitive judgement but as an analytical research question; it explores under what conditions plastic production could offer a more efficient model.

FINDINGS AND DISCUSSION

The findings of this study indicate that, in assessing the environmental impact of furniture production, production methods and waste management practices are more decisive factors than the type of material used. In the literature, resource efficiency is associated with retaining raw materials within the system as much as possible throughout the production process and reintroducing waste into production (Güneş & Demirarslan, 2020). The assessments carried out within the scope of this study reveal that this approach can be effectively implemented in practice for plastic furniture produced using the moulding method. According to the findings, the flash, sprues and production blocks generated during the moulding process in plastic furniture production can be converted back into raw material through in-house recycling practices. Previous studies have also highlighted that such waste generated in plastic production processes can be reintroduced into the production cycle through crushing and reprocessing (Purde, 2019; Çalışkan, 2024). Similarly, in this study, the revaluation of waste generated in plastic furniture production without it leaving the system demonstrates that the recycling potential described in the literature is also valid in practice.

A comparison with wood-based production methods clearly demonstrates why plastic furniture production is an area worthy of scrutiny in terms of resource efficiency. It is noted in the literature that CNC-produced wooden furniture has high waste rates and that a significant portion of this waste is not suitable for recycling (Bekar, 2023). In the comparative assessment conducted in this study, it was also observed that the shavings and offcuts generated in CNC wood production cannot be reintroduced into production due to the material's composite structure and binding agents. Although pressed wood furniture offers a lower waste rate compared to CNC production, it remains limited in terms of resource efficiency due to long production times and energy-intensive processes (Ceyhan, 2021). Although the production of plastic furniture is often associated with environmental issues in the literature, the findings of this study demonstrate that, when the production method is properly designed, plastic holds significant potential in terms of resource efficiency. While previous studies have highlighted the production ease and formal flexibility offered by plastic materials in furniture design (Özel & Ürük, 2019), it has also been demonstrated that recycling practices in plastic-based production reduce resource consumption (Garg & Ateeq, 2025). The results obtained in this study, in line with the relevant literature, demonstrate that plastic furniture produced using the moulding method minimises material loss through in-process recycling.

The results of the comparative assessment indicate that the environmental performance of plastic furniture production is linked to the structure of the production process rather than the negative perceptions attributed to plastic itself. Findings in the literature suggesting that plastic-based products can reduce pressure on forest resources (Molano Gómez et al., 2025) are consistent with the assessments obtained in this study. In this context, it is concluded that the production of plastic furniture should be evaluated in terms of resource efficiency as an alternative to wood-based production methods.

Table 1: Comparison of Furniture Production Methods, Gamze Özcan 2025

production method	rate of fire	recycling capacity	the production time	environmental impact
CNC-machined wooden furniture	high	limited	average	negative
pressed wood furniture	low	low	long	average
moulded plastic furniture	average	high	short	positive

Field observations, as shown in Table 1, demonstrate that burrs and offcuts generated during the production of plastic furniture manufactured using the moulding method can be converted back into raw material using shredders (Table 1). This process enables in-house waste to be reintroduced into the production cycle without leaving the system.

In CNC-based wood production, it has been observed that a significant proportion of the wood shavings and scrap material generated during cutting and shaping processes cannot be directly reused in the production of new boards. While the waste ratio is relatively low in pressed wood production methods, there are various limitations in terms of process continuity and energy consumption. This comparative assessment demonstrates that in-process recycling capacity offers a more significant advantage in plastic moulding production. However, this advantage does not imply that plastic is environmentally superior throughout its entire life cycle.

The findings of the study suggest that environmental assessment in furniture production should be based on the structural characteristics of the production process rather than the type of material. Plastic moulding production offers a model that is closer to a closed-loop system in terms of in-process recycling capacity.

However, factors such as the reliance of plastic production on fossil-based raw materials and post-use waste management fall outside the scope of this study. Consequently, the study does not declare plastic materials to be environmentally superior; it merely presents an assessment focused on the production process.

This study is based on a short-term field observation conducted at a single company. No quantitative measurements were taken, and scrap rates and energy consumption were not calculated. Furthermore, the post-use environmental impacts of plastic products and carbon footprint analysis are outside the scope of this study. Consequently, the findings do not provide generalisable quantitative results, but rather contextual qualitative assessments.

RESULTS AND RECOMMENDATIONS

This study aims to highlight the potential of plastic furniture production, specifically focusing on the moulding method, in terms of resource efficiency and waste management. The findings indicate that, when supported by appropriate production techniques and in-process recycling practices, plastic furniture production can offer a production model that is close to a closed-loop system. In this respect, the study makes a significant contribution to the literature by highlighting that environmental assessment in furniture production should be based not only on the type of material but also on production methods and processes.

This study occupies a unique position in that it evaluates the discussions on plastics, wood, waste and sustainability, which are often addressed in a fragmented manner in the literatüre, within a holistic framework centred on production methods. The question of what plastic furniture production 'offers' has been addressed in this study not through normative judgements, but in terms of resource efficiency and recycling capacity. This approach highlights the need to rethink generalised environmental judgements regarding plastic materials.

Future research following this study could examine plastic furniture production within the framework of a life cycle assessment, evaluating both the use and post-use phases. The effects of different types of plastic on moulding efficiency and the use of recycled raw materials on product durability could be investigated. Furthermore, a quantitative comparison of plastic and wooden furniture production methods in terms of energy consumption and carbon footprint will fill a significant gap in the literature. This study provides a theoretical and conceptual foundation for such research; it contributes to the discussion of sustainability in furniture production by focusing on the production process.

This study demonstrates that the moulding method used in plastic furniture production holds potential for resource efficiency in terms of in-process waste management. The findings suggest that, when the production process is properly designed, plastic-based manufacturing can exhibit a structure more suited to closed-loop applications.

However, these results do not imply that plastic materials are environmentally superior throughout their entire life cycle. It is recommended that future studies expand this assessment through quantitative performance measurements, energy consumption analyses and carbon footprint assessments.

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