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A systematic review on artificial intelligence applications in architecture

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Abstract

Since the advent and usage of artificial intelligence approaches in architecture, a significant number of studies have focused on integrating technological solutions to architectural issues. Artificial intelligence applications in architectural design range from intelligent material design to architectural plan solutions. The ubiquity and distribution of research in this field, as well as the rising use of artificial intelligence techniques to solve design challenges, require an analytical classification of the essential literature review. This article presents a descriptive and analytical review of the work on artificial intelligence applications in architecture. A strong review has been made that identifies and addresses the gaps in artificial intelligence and architecture; and the literature review is transformed into statistical plots. The study's findings indicate a growing interest in artificial intelligence in the field of architecture. There is a need for novel research to be conducted in these areas using advanced technology and techniques.

Keywords: algorithm, architectural design, architecture, artificial intelligence, computational design

1. Introduction

Architecture is one of the oldest known professions, and its historical formation is based on a long process. Throughout this process, there have been different definitions of what architecture is. Despite the presence of architecture, these theoretical definitions were developed somewhat belatedly. In terms of the presentation of definitions, all socio-cultural trends have influenced architecture. Therefore, there are numerous refined, elaborate, and poetic definitions of architecture throughout history. According to Vitruvius, architecture is the design of spaces that are safe, adequate for their function, comfortable, give people the pleasure of living, and evoke a sense of the sublime (Vitruvius, 2005). The definition of Le Corbusier is masterful, accurate, and majestic plays of the masses brought together under the illumination of architecture (Corbusier, 2007). Additionally, Ludwig Mies Van der Rohe defines it as the spatial manifestation of the era (Conrads & Bullock, 1976). This transition from ancient architecture to modernism and then to postmodernism resulted in changes in the definitions of architecture, which have left their mark on architecture.

The theoretical and existential evolution of the concept of architecture has led to a variety of architectural design tools. In the architectural literature, artificial intelligence is one of the most recent techniques. The fact that artificial intelligence contains iterative processes and design procedures that include problem definition, concept generation, and evaluations creates an overlap between the two disciplines. Thus, parallel to technological advancements, artificial intelligence,

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which is present in nearly every aspect of our lives and is used to solve multilayered and difficult design challenges, has begun to emerge in the discipline of architecture. Initially, artificial intelligence was used in the fields of imitating the thinking and learning processes; however, now it is also used in the fields of building relationships with new advances, analyzing the methods of forming relationships, and replicating relationships. Approaches in the field of architecture that utilize artificial intelligence offer the opportunity to take problem inputs and to discover multiple optimal solutions in a reasonable amount of time. Distinct subfields of artificial intelligence employ various technological developments, including computational, iterative, reproductive, and developmental methods. As a result of these advancements, the artificial intelligence models produce the most appropriate output possible. Due to the fact that these methods are applicable not only as problem-solving techniques but also as simplified mathematical models that resemble the architect's perspective, artificial intelligence can be used to create a wide range of architectural products. These developments have led to the addition of inventive, smart, and productive elements to the field of artificial intelligence architecture. Architecture, is an art form (like sculpture and painting), but the most significant distinction is that the architect's art is functional and focuses on finding practical answers to issues (Rasmussen, 1964). The concept of functionality, which is of considerable importance in the field of architecture, is one of the most crucial variables in the complexity of design issues. Functionality can be spatial; it also plays a prominent role in the processes of obtaining solutions, such as discovering a form based on performance. With the development of technology, the use of artificial intelligence in the problem-solving process can yield major benefits.

Artificial intelligence is the broad category for the technology that enables a computing system with a non-biological structure to demonstrate all of the cognitive capacities of logic, self-awareness, comprehension, reasoning, problem solving, and creativity (Artut, 2009). This technology is based on the outputs produced through learning by adopting rules, reasoning, benefitting from cognitive disciplines, and self-correction (Bingöl, et al., 2020). In 1956, the phrase “artificial intelligence” was first used in a Dartmouth, United States, symposium attended by the leading scholars (Gülşen, 2019). Therefore, it has been possible to discuss the existence of artificial intelligence for over fifty years. In recent years, however, the usage of artificial intelligence has become widespread due to advancements in processing power, the availability of huge amounts of data, and the creation of new algorithms (Atalay & Çelik, 2020). The interdisciplinary approach provided by artificial intelligence to architectural problems can provide a highly expansive perspective. Artificial intelligence is used in a variety of architectural design domains, such as obtaining multiple proposals in a short period of time, obtaining variations of existing designs quickly, obtaining materials with optimal properties, obtaining quick results with decision support systems, and developing environmentally conscious approaches. While artificial intelligence can handle the pragmatic portion of design challenges in architecture and AI studies, the architect retains authority over the contextual, socio-cultural, and historical linkages of the design. The integration of artificial intelligence and architecture will reach a point that will be debated in the future during architectural periods thanks to inter-disciplinary approaches.

There have been numerous proposals and developments in the literature pertaining to the use of artificial intelligence in architectural design. While the studies concentrate on a particular problem and serve as design support mechanisms, they also employ multiobjective methodologies that manage numerous design inputs simultaneously. This study was conducted to categorize all of these approaches and assess the scope of artificial intelligence's influence in the field of architecture. Since the emergence of artificial intelligence, a wide field of work has emerged in the process of solving architectural design problems, and these are performance based, form finding, spatial programming, multi objective optimization, restoration works, and design tool development.

Artificial intelligence, which is prevalent in practically every part of our lives today, has begun to be implemented in architecture for a variety of purposes (Table 1). Within the scope of the

investigation, the research in the literature was classified under six primary categories. Some research serves several purposes, despite the fact that these broad categories permit the achievement of various more particular aims. For instance, while trying to optimize thermal loads and ventilation in skyscrapers, this approach has been developed so that it can give correct suggestions in various climatic conditions (Zhao, et al., 2020; Chen & Yang, 2017).

Table 1 The initial and sub-purposes of architecture's usage of artificial intelligence.

Initial Purposes	Sub-Purposes
Performance based	Energy-saving Maximum benefit from daylight Passive design solutions Facade design
Form Finding	Building envelope design Parametric designs Modular architecture Facade design
Spatial Programming	Site plan suggestions Plan solution suggestions Mass settlement proposals on an urban scale
Multi-objective	Applications of active and passive systems Mass and facade recommendations for maximum benefit from daylight
Restoration	Completing the missing parts of the structures Transferring important structures to digital platforms
Design Tool Development	Developing algorithms that solve various design problems

By developing performance-based designs using artificial intelligence-based methodologies, optimal solution ideas for energy sources, such as saving from diverse energy sources and maximizing the usage of non-renewable energy sources, are generated. Using utilitarian approaches such as facade solutions, mass orientations, and good design for passive systems, studies have been conducted to determine the optimal solution suggestions based on the building's location. In addition to being one of the sub-goals in the process of achieving these solutions, achieving the optimal form can also be one of the primary objectives of this integrated work area. This demonstrates that most design challenges entail multi-objective methods. In form-finding procedures, artificial intelligence enables the use of context-based design parameters to approach the most suitable outcome. It is used to optimize forms based on several contextual inputs, particularly in parametric designs (Caetano, et al., 2020).

Renovation projects are one of the most significant areas of study in architecture. Since the entire built environment leaves a significant carbon imprint, maximizing the lifespan of a structure contributes to environmental solutions. For these reasons, applications of artificial intelligence are used in building rehabilitation projects and for estimating the missing elements of ancient buildings. The fourth strategy involves the creation of design development tools. These tools offer outputs or recommendations in particular problem-solving domains. It is essential to create these tools in order to get closer to viable architectural solutions (Gallo, et al., 2020).

This study presents a detailed review of the works on artificial intelligence in architecture to determine where we are in the process of integrating AI into architecture by classifying them according to their inferences to the parameters. The research methodology part of the paper defines the study field and performs a literature-based keyword analysis to clarify prospective keyword discovery. Findings' second part comprises the statistical data of the papers in accordance with the established research framework, according to the publishing years, the countries in which they were published, their objectives, the algorithmic technique, and the programming languages used. In the conclusion part, the evaluation of the collected research and the architectural applications of artificial intelligence are described.

2. Research Methodology

This article identifies interpretable patterns and gaps in academically published journals using descriptive statistics and knowledge-based representations. The literature search is carried out using the cross-content reading method (Aslan, 2016). Furthermore, the acquired data were

categorized using the parameter extraction technique. Using this strategy, the most discussed research-related categories were identified, while the insignificant ones were eliminated. This classification evaluates research under six main categories for a more structured presentation (Figure 1). In the initiation phase, the most relevant keywords are identified based on the literature research. Scopus, Sciencedirect, ProQuest, Thesis Center (Council of Higher Education - Türkiye), and/or Google Scholar indexed, preferably highly cited, in English between 2012 and 2022, and based on the keywords "artificial intelligence", "machine learning", "deep learning", "expert systems", and "evolutionary" were chosen as the key terms for this study. In the second phase, to widen the search area, the keywords "form finding", "spatial programming", "site plan optimization", "shape grammar", and "architectural optimization" were added, and the research scope was selected. In the third phase, the present state of the relationship between artificial intelligence and architectural studies was investigated. In the fourth phase, 214 articles and 28 theses were chosen among 1700 articles and 87 theses relevant to the subject. In the fifth phase, the research was categorized by publication year, country, objective, algorithmic technique, and programming language. Finally, based on the achieved analysis and categorization results, a research model for the classification of studies in the field of architecture with artificial intelligence was developed.

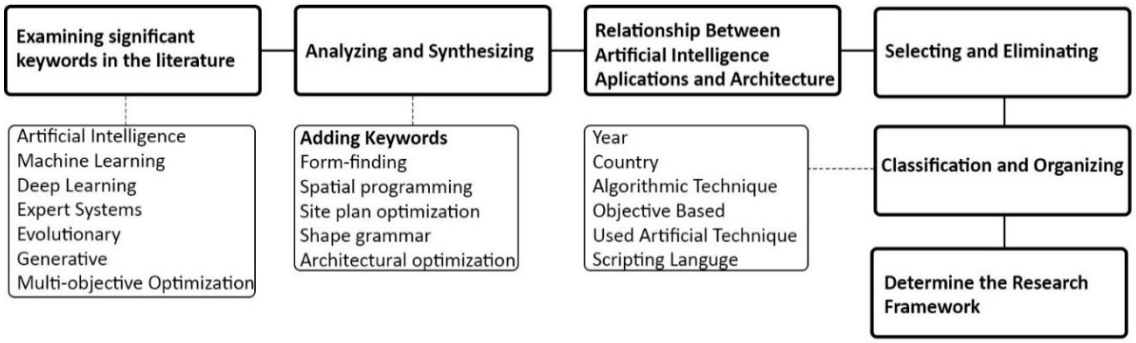

Figure 1 Research Flowchart

The number of studies in the literature connected to productions made with architecture and artificial intelligence has been determined as a result of the literature search and classification of the studies that were discovered as a consequence of these searches. Stun charts are used to display this data. In conclusion, assessments of the area were made based on these statistical findings.

2.1. Background Research

Within the scope of the research, the studies' keywords are one of the essential factors that serve to categorize them. An analysis was carried out on the keywords identified in the 242 studies that were included in the research. As a result of this study, the VOSviewer software was used to generate a network map of the terms in the literature (Figure 2). This analysis yielded the results of studies conducted on artificial intelligence in the subject of architecture, revealing which subfields of artificial intelligence are most prevalent. Based on this conclusion, it has been determined that there are more studies in the literature on six major issues in the field of architecture: expert systems, machine learning, evolutionary design, generative design, multi-objective optimization, and deep learning.

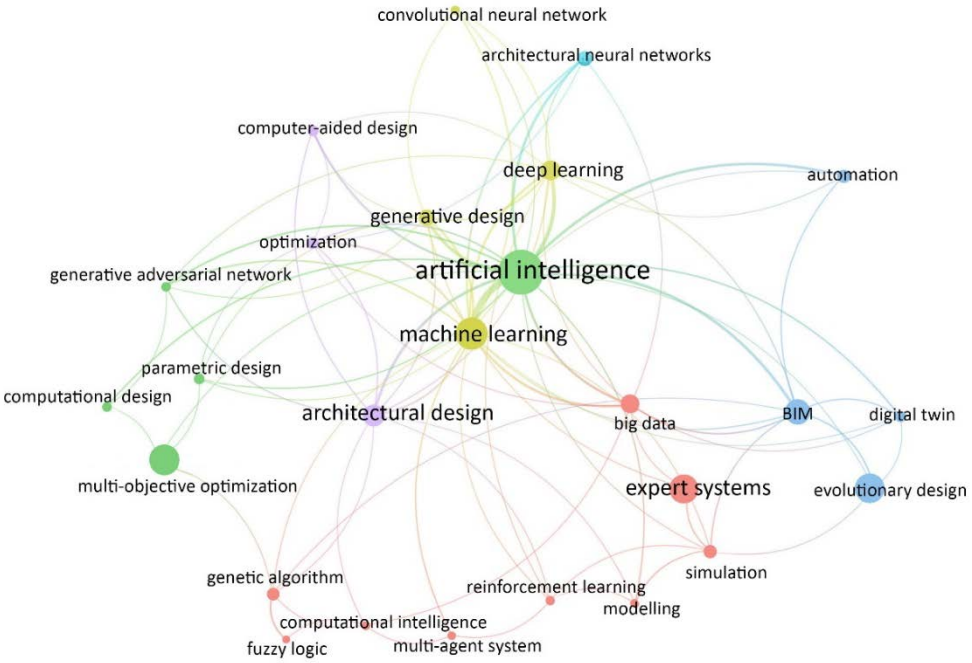

Figure 2 Keyword network analysis of the studies on artificial intelligence and architecture

In the literature on artificial intelligence, it is defined as the capacity to comprehend and learn from vast quantities of data in order to accomplish certain goals and tasks (Kaplan & Haenlein, 2019). In 1943, McCulloch and Pitts introduced their Boolean circuit model of the brain, in which artificial intelligence initially appeared as an abstract idea. In 1950, Turing's research into "information processing machines and intelligence" laid the theoretical groundwork for computer science (Pirim, 2006). These foundations have spawned numerous artificial intelligence methodologies and subdisciplines (Table 2).

Table 2 Definitions of concepts in the literature related to artificial intelligence subcategories, definitions and history

ARTIFICIAL INTELLIGENCE SUBCATEGORIES	GENERAL DEFINITION
Expert systems	Expert systems are intelligent computer systems that provide solutions to a given problem at the expert level (Bohanec & Rajkovič, 1990).
Machine Learning	Machine learning is a field of study that seeks to comprehend and build methods that use data to improve performance on specific tasks (Wang, et al., 2009).
Evolutionary Algorithms	In artificial intelligence, an evolutionary algorithm is evolutionary computation, which is a population-based metaheuristic optimization technique. An evolutionary algorithm uses evolutionary-inspired mechanisms including reproduction, mutation, recombination, and selection (Link-1).
Generative Algorithms	A generative algorithm classifies data by imitating its production. Enables the rapid development of new ideas (Link-2).
Multi-objective Optimization	Multi-objective optimization provides concurrent, conflict-free resolution of competing objectives (Toffolo & Benini, 2003).
Deep Learning	Deep learning is a strategy for artificial intelligence based on artificial neural networks that employs multiple processing layers to gradually extract higher-level data features. It learns data representations rather than specialized problem-solving methodologies (Zhang, et al., 2018).

These disciplines have also enabled numerous developments in the field of architecture. Expert systems, one of the earliest forms of artificial intelligence, have been utilized in the design process to produce the optimal outcome from the combination of various inputs. Expert systems have aided in the production of solutions to multi-layered design issues in this area. Within the scope of expert systems, life cycle assessment in architectural studies, holistic analyses of environmental performance (Sartori, 2021), building energy-saving designs based on real-time simulations (Mirarchi, et al., 2020), various emergency situations in building renovation systems to the building portfolio designing building envelopes that adapt to the climate (Kim & Clayton, 2020), and energy

performance analysis of various facade systems (Abediniangerabi, et al., 2020) are all used in the process of obtaining utilitarian solutions.

Machine learning, a subfield of artificial intelligence, is a technical strategy with transformative potential in architecture, as well as in numerous other fields. Due to its ability to change, it has been used in many fields, such as estimating energy savings (Banihashemi & Wang, 2017), predicting the growth of city plans (Xia & Tong, 2020), and coming up with architectural aesthetic variations (Zhou & Park, 2021).

Significant contributions have been made by evolutionary algorithms to the realization of computational principles in architectural design. In continuation of the concept of evolutionary algorithms, generative algorithm approaches were used to find the most effective solution. In architecture, these algorithms are used for parametric design optimization (ElBatran & Ismaeel, 2021), sustainable architectural approaches (Chatzikonstantinou & Sariyildiz, 2017), and form finding (Yan, et al., 2022).

In addition, the evolution of artificial intelligence techniques has led to the emergence of multi-objective optimization methodologies, which have enabled the simultaneous resolution of multilayer problems. This method has been effective in the majority of simulations. Finally, deep learning techniques which are among the most recent approaches, are used in the production and classification of urban textures, as well as providing solutions in the field of architecture that other approaches cannot.

3. Findings

After reviewing 1700 articles and 28 theses, it was determined that 242 studies demonstrated artificial intelligence and production methods in the field of architecture. These studies were organized according to six primary categories, which were as follows: the year in which they were published; the country in which they were created; the objective of the study; the algorithmic technique used in the publication; the programming language employed in this study; and the artificial intelligence technique.

It has been seen that as artificial intelligence methods have improved (Table 1), the total quantity of publications in the field has increased (Figure 3). At least in part, this rise can be explained by the fact that the architects are now able to write code in a more straightforward way thanks to the visual scripting languages (Boshernitsan & Downes, 2004).

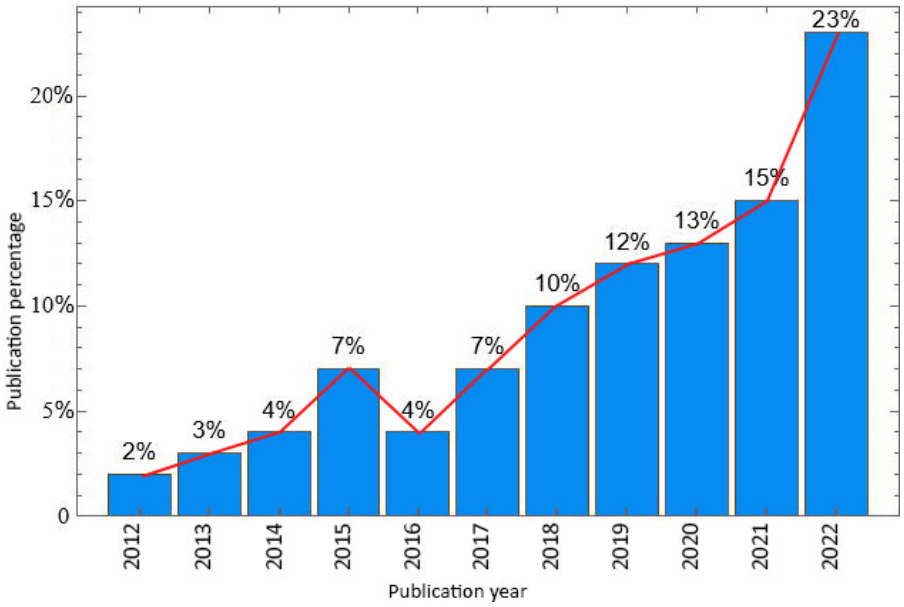

Figure 3 The quantity of articles classified by publication year

China has a significant number of publications compared to other nations whose authors contributed to these surveys' collections during that time (Figure 4). Examining the research from China reveals that the reasons for this are to provide optimal solutions and energy efficiency in skyscraper designs, as China has a large population. It has been noted that Italy and the United States are two other countries with the highest publication rates (Kong, et al., (2012).

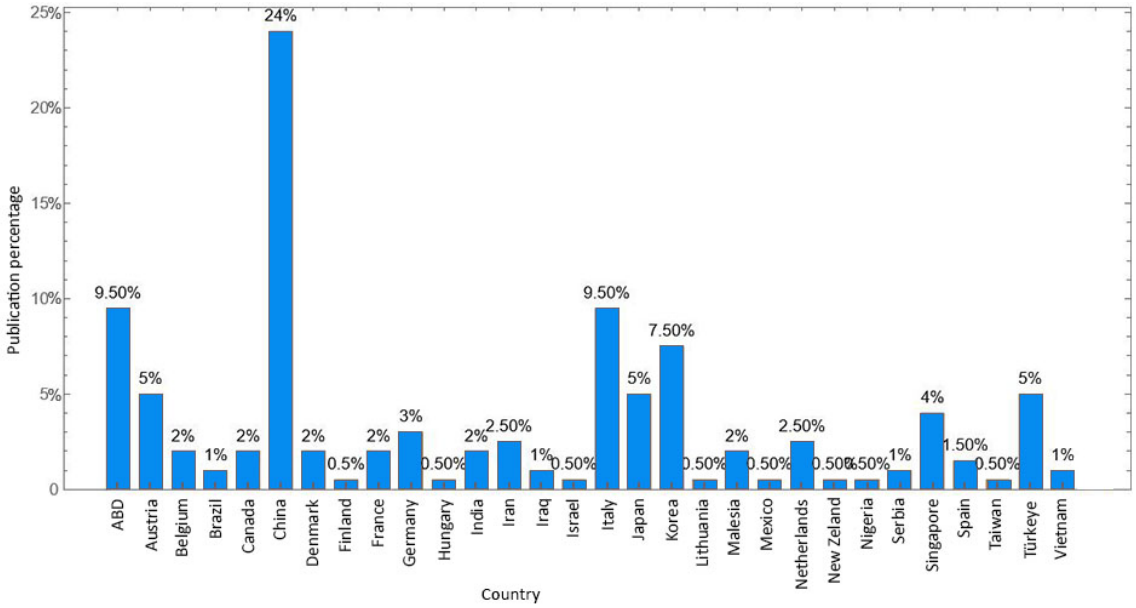

Figure 4 The quantity of articles classified by country

The analyzed studies cover a range of disciplines, including architecture and artificial intelligence applications. Based on their research objectives, these study disciplines can be grouped into six categories (Figure 5). With 43% of 242 studies, performance-based studies represent a significant portion of the literature. Table 3 lists some of the studies from which we acquired this substantial numerical ratio (Table 3). The performance-based category includes studies that focus on the energy performance of buildings. On the other hand, the multi-objective optimization category comprises studies that aim to optimize both energy performance and other design requirements simultaneously. Therefore, some of the performance-based research falls under the multi-objective optimization category.

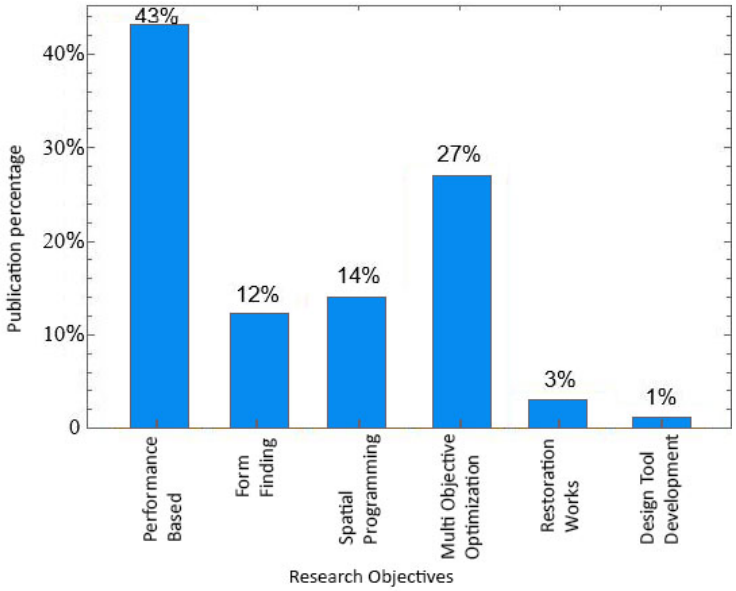

Figure 5 The quantity of articles categorized based on their research objectives

Table 3 The significant studies that based on their research objectives

Category	References
Performance based	(Rahimian, 2022), (Han, 2022), (Xu, 2022), (Jia, 2021), (Singh & Geyer, 2022), (Paterson, et al., 2017), (Baghdadi, et al., 2020), (Wang, et al., 2019), (Li, et al., 2018), (He, et al., 2021), (Singaravel, et al., 2018), (Lin, et al., 2021), (Chokwitthaya, et al., 2019), (Gan, et al., 2019), (Olu-Ajayi, et al., 2022), (Zou, et al., 2021), (Li, et al., 2019), (Chou, Bui, 2014), (Wortmann, 2019), (Schwartz, et al., 2021), (Scherz, et al., 2022), (Sun, et al., 2015), (Mangan, 2021), (Ruiz, et al., 2017), (Singaravel, et al., 2018), (Toniolo, Leon, 2017),
Multi objective optimization	(Singaravel, et al, 2018), (Chardon, et al., 2016), (Natephra, et al., 2018), (Yousif & Bolojan, 2021), (Chardon, et al., 2015), (Liu, 2022), (Zhuang, et al., 2021), (Zhang, et al., 2021), (Baydoğan & Şener, 2014), (Chen & Pan, 2015), (Chen & Yang, 2017), (Si, et al., 2019), (Razmi, et al., 2022), (Carbonari, et al., 2019), (Kim & Clayton, 2020), (Yi, 2019), (Pilechiha, et al., 2020), (Mukkavaara & Shadram, 2021), (Marcolino, et al., 2015), (Seghier, et al., 2022)
Spatial programming	(Nisztuk & Myszkowski, 2019), (Ng, et al., 2019), (Buruzs, et al., 2022), (Karadoğan, 2021), (Doukari & Greenwood, 2020), (Raman & D'Souza, 2019), (Xia, et al., 2020), (Wang, et al., 2022), (Xiong, et al., 2022), (Liu & Lee, 2022), (Zheng, et al., 2020), (Shen, et al., 2020), (Yong & Chibiao, 2022), (Guo & Li, 2017), (Bei, et al., 2019), (Uzun, 2020), (Güleç, 2014), (Şen, 2022)
Form finding	(Yan, et al., 2022), (Guo, 2022), (Cai & Li, 2021), (Radziszewski, 2017), (Bao, et al., 2022), (Zheng & Yuan, 2021), (Yan, et al., 2022), (Müezzinoğlu, 2022), (Aldemir, 2014), (Zheng, 2022)
Restoration works	(Gade, et al., 2018), (Mulero-Palencia, et al., 2021), (Morbidoni, et al., 2020), (Kamari, et al., 2018), (Jiang, et al., et al., 2022)
Design tool development	(Jalaei, et al., 2015), (Cichocka,et al., 2017), (Gade, et al., 2018)

According to the algorithmic methodologies employed in their research, 242 studies have been categorized. The results of these studies suggest that genetic algorithm-based techniques are extensively employed in the published works (Figure 6). Although evolutionary algorithms were developed earlier than genetic algorithms, the reason behind the prevalence of the latter in architecture is the discipline's versatility in applying generative algorithms to various contexts such as form diversification, facade suggestions, plan proposals, and site plan layouts (Su & Yan, 2015). Other techniques include machine learning techniques such as CNN (Płoszaj-Mazurek, et al., 2020; Ng, et al., 2019) and ANN (Naji, et al., 2016), in addition to genetic and evolutionary algorithms, which are extensively employed.

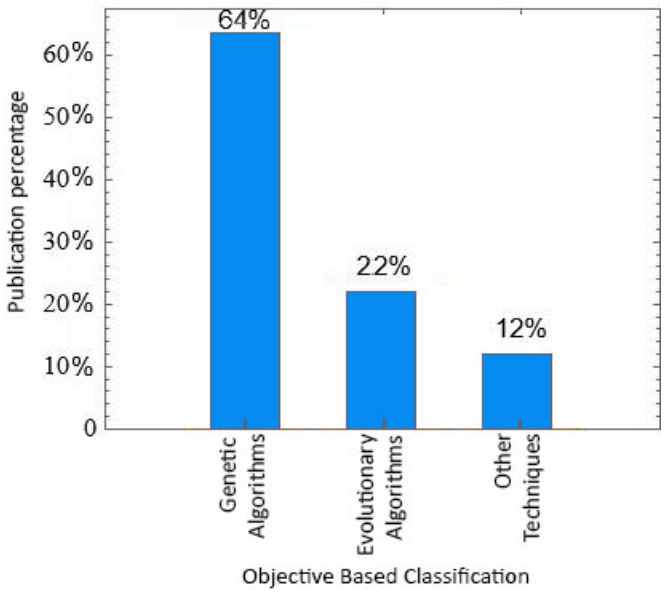

Figure 6 The quantity of articles classified by algorithmic technique

Studies in the literature that are related to architecture and artificial intelligence typically employ visual programming languages (Figure 7). Even an architect who is not familiar with the

process of putting together any code can use visual programming languages since they enable the mixing of different instructions through the use of a drag-and-drop interface. Rapid optimization was accomplished by the utilization of technologies for artificial intelligence that are accessible through these programming languages. As a result, a large number of studies have been completed with the indirect use of artificial intelligence as a ready-made tool rather than employing it directly.

Grasshopper and Dynamo are two examples of commonly used visual programming languages. These two interfaces accomplish their functionality by integrating with a variety of drawing applications. When comparing the two visual programming languages, Dynamo appears to be more advantageous to Grasshopper. This is due to its unique characteristics, which facilitate a greater level of engagement with diverse stakeholders, particularly in the context of BIM-based initiatives.

In general, open source programming languages are more accessible than visual scripting languages. Open source programming languages can be acquired and used without cost or licensing restrictions, whereas visual scripting languages are typically only accessible via licensed programs that utilize their interfaces. Therefore, not all works created with visual scripting languages are readily accessible or usable by individuals who lack access to these licensed programs.

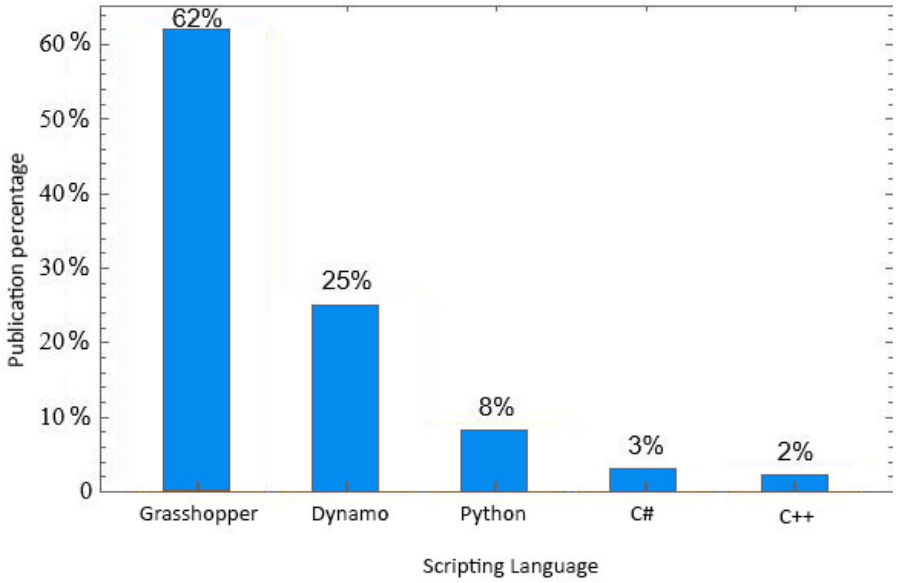

Figure 7 The quantity of articles classified by programming language

4. Concluding Remarks

The studies that used artificial intelligence in the field of architecture were searched on the Scopus, Sciencedirect, ProQuest, Thesis Center (Council of Higher Education – Türkiye), and Google Scholar directories. An iterative technique was utilized to identify the appropriate keywords for this study. This approach was executed in accordance with the research design outlined in the methodology part (Figure 1). 87 theses were analyzed using the cross-reading technique, and 1700 articles were gathered through the research. As a result of the evaluation, 214 articles and 28 theses were evaluated as works that involve architecture and artificial intelligence. The evaluation outcomes were categorized into six primary groups and given as statistical data. The outcomes of the collected data are listed below.

- The investigations in this area tend to utilize pre-existing frameworks. The focus of research is on the applications of artificial intelligence rather than its development. Therefore, it is suggested that future studies direct their attention towards the innovation of artificial intelligence in order to further advance the field

- Recent research using artificial intelligence optimization algorithms has not favored modern algorithms, despite the fact that the research was conducted in recent years. This circumstance affects optimization results.
- Significantly more architectural and artificial intelligence disciplines have been synthesized in China than it is done in other nations (Figure 4).
- Autodesk's Revit-Dynamo and Robert McNeel & Associates' Rhinoceros-3d-Grasshopper pairs dominated artificial intelligence research. It has been determined that no (reachable) free and open-source development platform exists.
- The authors of remarkable research are those who employ the disciplines of architecture and engineering together (Piira, et al., 2022; Liang, et al., 2022; Olu-Ajayi, et al., 2022; Pilechiha, et al., 2020).
- Architects have focused considerable attention on energy efficiency, which has been a significant issue in recent years. (Aksoy & Çağdaş, 2014; Kerdan & Gálvez, 2022; Seyedzadeh, et al., 2019; Li, et al., 2019).
- The incorporation of AI-based approaches has enabled architects to analyze and optimize previously difficult-to-solve complex design problems, thereby facilitating the emergence of interdisciplinary studies in the field. Also, the increase in interdisciplinary research follows an exponential growth trend (Figure 3). This trend reflects the increasing potential of advanced technologies and computational methodologies to revolutionize architectural research and practice and open up new avenues for architectural innovation and creativity.

In recent years, as interdisciplinary research on this topic has increased the use of artificial intelligence approaches to solve architectural problems has become more prevalent. These interdisciplinary collaboration strategies are expected to accelerate progress.

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Resume

Buse Bölek, who graduated with first place honors from the Architecture Department at ESOGU (Eskisehir Osmangazi University), has subsequently obtained two years of significant professional experience as an architect in an office environment. Presently, she is pursuing doctoral studies as a TUBITAK 2211 scholarship recipient, with a specific emphasis on augmenting her proficiency in a variety of artificial intelligence and software skills that are indispensable to the field of architecture.

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