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A Research on the Use of Machine Learning on Building Facades

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Abstract

Artificial intelligence and its sub-branch, machine learning technologies, have developed rapidly in recent years and their use for various purposes has seemed to be increased in various sectors from automotive to medicine, from law to marketing. Similarly, these technologies have begun to be used in the building sector and in the field of architecture. These technologies are being used in many fields in architecture such as feasibility studies, building design, project control, occupational safety, earthquake resistant building design and applications, energy efficient system design, construction with smart construction equipment, smart building design, and smart facade design. Despite this increasing use in the field, it has been determined by the literature review that the number of studies focusing on the use of machine learning in architecture, especially on building facades, is low. In this sense in the study, it is aimed to examine the relationship between artificial intelligence and machine learning technologies with architecture in the context of building facades. Initially in the study the topics and the historical process related to artificial intelligence and machine learning were explained, subsequently the use of technologies on the building facades was examined through examples. In this way, a guiding resource has been created for those who want to work on this subject in the future.

Keywords: Artificial Intelligence, Machine Learning, Future Architecture, AI for Building Construction, AI for Facades.

1. Introduction

Artificial intelligence and machine learning technologies, which have been the subject of numerous research in many fields over the years, have started to be used to increase human capabilities in almost every sector today with their development that accelerates at an exponential rate. In the last few years, it has been seen that artificial intelligence and machine learning have started to be used in the architecture and building sector as well with quite a variety of purposes and methods. However, the number of studies in the literature is relatively low despite the increasing use of these technologies in the sector.

Two supervised machine learning-based models that predict fuzzy criteria to be used in facade design decision analysis have been proposed in Moghtadernejad et al. [20]. Abediniangerabi et al. investigated the feasibility of a deep learning model that predicts the energy savings of different facade alternatives during the early design phase of the building in their study [1]. Bhamare et al. developed a machine learning and deep learning-based model in their study for the thermal performance prediction of a structure with a phase change material integrated into its shell [5]. Han et al. proposed a model for affinity propagation-based new radial basis function (RBF) of an energy-efficient building envelope using neural network-integrated affinity propagation in their study [13]. Meanwhile, Cha et al. worked on a random forest-based machine learning model that predicts the generation of construction and demolition waste and monitors the waste management efficiency of facilities in their study [7].

On the other hand, Bingöl et al. proposed a deep learning-based machine learning model that evaluates the structural systems of structures in the context of earthquake resistance in their study [6]. Zhou et al. worked on a machine learning-based facade model to reduce the cooling load of buildings in their study [30]. Masiero and Costantino proposed a model in their study for detecting submillimeter damage to the brick surfaces of a sample university building using machine learning [18]. Peng et al. worked on a model that develops HVAC systems in real-time according to users' habits and makes them efficient in their study [24]. Apart from that, MacKnight developed and tested a machine learning model based on artificial neural networks that enable movable smart facades to adapt to various environmental factors in his study [17]. The thermal behavior of an outer wall of the facade using deep learning techniques has been modeled in Aznar et al. [3] as Kim et al. proposed a method in their study to optimize the double-storey perforated facade of a building using machine learning according to various factors (Kim et al., 2018). On the

other hand, Dhariwal and Banerjee proposed an empirical methodology design in their study to optimize the building design for natural ventilation under external influences in a reasonable time [9]. The use of artificial neural networks to predict energy consumption has been investigated by Melo et al. [19].

Considering the literature research, the lack of research on artificial intelligence and machine learning technologies, mainly on building facades, is noticed. In this context, global technological developments and applications on the use of artificial intelligence and machine learning in building production and facades, literature studies are addressed through the literature review method and examples in this study. Furthermore, in the study, explanations for understanding the concepts of artificial intelligence and machine learning are given, and the development of the subject in the historical process is conveyed. Afterwards, focusing on the usage areas of these technologies on building facades has aimed to create a guiding resource for researchers who want to work on these subjects in the future.

2. Artificial Intelligence and Machine Learning

In this part of the study, artificial intelligence and machine learning topics are explained, concepts and sub-fields are described; the developments on the subject are examined in the context of their historical processes.

Even though there is no definite definition in the literature for artificial intelligence, which was theorised conceptually in the 1950s, today artificial intelligence is a branch of computer sciences that aims to develop machines that have human behaviors [6].

Nabiyev defines artificial intelligence as "The ability of a computer or a computer-controlled machine to perform tasks related to a higher mental processes, such as reasoning, inference, generalization and learning from past experiences, which are often assumed to be human traits" [21]. In this context, it is possible to see the main usage area of artificial intelligence as "The work of getting machines to perform tasks that require intellectual ability by introducing some data to computers" and the artificial intelligence may be described as "The technology for development of machines that exhibit human behavior and movements, created entirely by artificial means, without using of any kind of living organism" [2].

Likewise the concept of machine learning, which was introduced in the 1980s, describes an artificial intelligence system that works based on certain data and statistical inferences and may be described as 'gaining the ability for computers to think and make decisions without a need for explicit orders and instructions from the human' [12, 15].

During the process which brought machine learning and artificial intelligence technologies to their current state today, many developments have occurred from the past to the present. Some of the most significant of these developments may be listed as follows [28, Moor, 2016; 25, 37]:

- At the age of 25, Leibniz developed the first machine that could do all four operations, with the idea that " it is not worth the hours working like slaves for perfect people for calculations which even the simplest person is able to do with help of a machine". He presented his machine to the Royal Academy of London in 1673.
- In 1943, Warren McCulloch and Walter Pitts proposed the first artificial neuron named "Threshold Logic Unit (TLU)", or "Linear Threshold Unit".
- The concept of "artificial intelligence" was mentioned for the first time in an official application letter submitted to the Rockefeller Foundation in USA in 1955 by John McCarthy, Claude Shannon, Ray Solomonoff, Nathaniel Rochester and Marvin Minsky.
- Between the years of 1952 - 1969, a major information technology company wrote the first chess-playing program, while Joseph Weizenbaum wrote an early natural language processing program called Eliza in 1965.
- While artificial intelligence was becoming an industry in 1980, 1986 was the year that artificial neural networks came to the fore. Hereafter in 1987, artificial intelligence became a science.
- In 1997, a software named ‘Deep Blue’ defeated the Russian chess master Garry Kasparov.
- With the proliferation of the internet in 1988, many artificial intelligence programs began to reach the masses.
- Between 2000 and 2005, robot toys were put on the market.
- In 2007, Fei Fei Li and her team started to create a large database called ImageNet.
- In 2009, the first self-driving vehicle was developed.
- In 2011 a question-answering computer system named ‘Watson’ was developed and the machine beat two champions.
- In 2012, Siri, an artificial intelligence virtual assistant, was introduced.
- In 2014, Amelia, the virtual assistant that is able to detect the feelings of the person in front of it, was developed.

Artificial intelligence has taken its advanced form today with great efforts, thanks to the discoveries and studies complementing each other of numerous scientists over the years.

Today, thinking machines which are able to understand people, think like people, imitate people and human-like robots have started to take an active role in every aspect of life.

Machine learning is considered a sub-branch of the artificial intelligence research field. Machine learning algorithms create a statistical-based logical system based on predictions even though they are not defined by explicit commands to complete the task expected of them. This logical system is established with the help of a mathematical model, which is based on chunks of data defined by the user and called 'training data'. Extracting useful and clean information from the large chunks of data is another field of machine learning called 'data mining' [11, 15]. Machine learning can be examined under three titles as fuzzy logic, artificial neural networks, and deep learning [6].

2.1.Fuzzy Logic

Fuzzy logic was developed by Azeri mathematician Lotfi Zadeh in 1965. In fuzzy logic, unlike Aristotelian logic, there are no exact results such as 100% true and 100% false. Instead of black and white, there are grays. There are partial truths and partial falses. There are certain degrees of cluster memberships. For instance, a 30-year-old person may be a member of the youth group by 60%, meanwhile 20% member of the seniors group. And a 70-year-old person may be a member of the youth group by 10%, while 90% member of the seniors group. Fuzzy logic is considered to be a better solution for decision making in real life situations [6].

2.2.Artificial Neural Networks

Artificial neural networks are interconnected artificial neurons inspired by human nerve cells in a structural and conceptual context. They are non-linear and contain a single output versus a set of inputs. In 1943, McCulloch and Pitts laid the foundations for artificial intelligence and machine learning by mathematically simulating the complex learning and interpretation ability of the human brain. Artificial neural networks are used in areas such as control and system identification, image and sound identification, prediction and fault detection [6, 10, 25, 29]

2.3.Deep Learning

Deep learning or hierarchical sequential learning is a new machine learning method based on artificial neural networks which started to be used in the 2010s. It covers sound and image recognition/classification, text reading and vocalization near human level precision. Deep learning, which is a field of where research and studies are still intense, is briefly mentioned in the literature as 'multi-layered artificial neural networks' [4, 6, 8].

3. Use of Machine Learning in Architecture

In architecture, machine learning is used as expert systems, genetic programming and fuzzy systems. In the field of architecture, machine learning is used in the early stages of the building design process such as pricing estimation, schema design, plan design optimization, project supervision, occupational safety control, building subsystems design, energy efficient system designs, earthquake resistant building design.

3.1.Use of Machine Learning in Building Processes

Machine learning is used in the design phase, construction phase, usage phase, demolition phase and post demolition waste management phase in the building production process.

3.1.1. Designing Process

A software called Spacemaker AI, a machine learning-based artificial intelligence product, analyzes, evaluates and compares multiple plan alternatives up to 100 criteria at the same time, and iterates all of these works quickly and uninterruptedly. In Figure 1 different alternatives of the same area is shown [40].

Figure 1. Spacemaker AI [40]

3.1.2. Construction Process

Working through an artificially intelligent robot, Open Space is a photo and video-based software that creates a street view of the area and associates them with the project plans, by taking 360-degree photographs of the construction area where the robot roams freely every half second. Images of the same spots from robot and human eyes may be seen in Figure 2 [38].

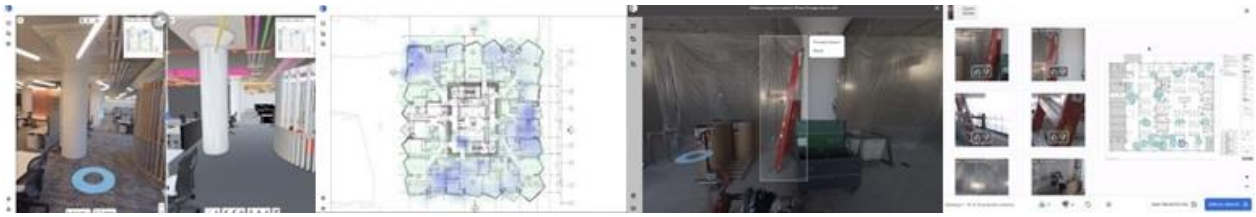

Figure 2. Open Space [38]

In Builtrobotics project, whose aim is to build robots that build the world, heavy construction equipment which are completely managed by machine learning-based systems are being produced. Figure 3 shows the robots and the user interface of the project [34].

Figure 3. Built Robotics [34]

AirWorks is a mapping software that can independently identify high-resolution aerial photographs utilizing machine learning and artificial intelligence algorithms and categorizes them into categories such as land, road, building, walking track, train track, green area, lake/sea, manhole cover and pavement and it converts 2D and 3D data into CAD models. Figure 4 shows the three phases of the working principle of Airworks [32].

Figure 4. AirWorks [32]

3.1.3. Building Using Process

In 2018, a machine learning-based system called Energis.Cloud, which monitors temperature, water and energy consumption remotely, was implemented at The Hotel

Brussels in order to prevent waste. The hotel has determined a plan to reduce resource consumption and waste in the 5 years that will pass from the time it was built until 2023; It aims to reduce water consumption by 20%, electricity consumption by 35%, gas consumption by 25% and CO_2 emissions by 20%. At Hotel Brussels, data is collected automatically from meters and devices (chillers, HVAC systems, boilers and fiber optic sensors) and water, gas, electricity, temperature, humidity and CO_2 values are being monitored in real-time. The system, in which data from previous years and thermal principles are introduced, can predict appropriate consumption through the behavioral models verified by aggregated data. In this way, anomalies are detected and the fastest response is being made. Necessary reporting and interventions are made in possible deviations and the system operates with high efficiency [36].

3.1.4. Demolition Process

DAPS, an expert system written for the assessment of building damage and demolition decision, which are ambiguous issues due to subjective opinions and the use of imprecise numerical data, is based on both numerical and non-numerical data. Non-numerical, ambiguous expert opinions are defined to the system by fuzzy sets and together with numerical data, they form the knowledge base of the system. The system synthesizes the input data by filtering the rule base and acts as a decision mechanism on the demolition decision [26]. Figure 5 shows working system of DAPS.

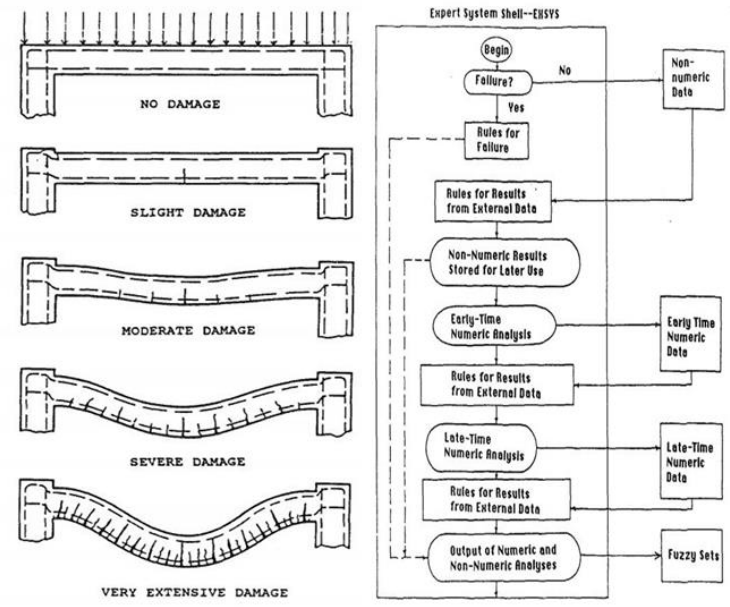

Figure 5. DAPS [26]

3.1.5. Post Demolition Waste Management Process

A machine learning based robot named Heavy Picker, separates structural wastes up to 30 kg in categories suitable for recycling and reuse such as "metals, stone, concrete, wood, plastics" with its one to three robot arms, each of which can separate 2000 objects per hour. Heavy Picker is shown in Figure 6 [41].

Figure 6 Heavy Picker[41]

3.2.Use of Machine Learning in Building Facades

Machine learning is used in various fields in architecture on building facades.

3.2.1. Automatic Creating Facade Design Alternatives

In the building design phase, there are some genetic algorithms that produce different facade and shell alternatives by providing the conditions demanded by users and designers. The demand here may be visual aesthetics, as well as reducing the negative consequences of factors such as energy efficiency or shadows falling on each other with the surrounding buildings, or providing the highest benefit from a similar situation. In the analyzed case study, different shell proposals have been produced for a high-rise building according to the environmental effects of solar radiation and shade by using genetic algorithms [27]. Figure 7 shows the visualisation of the algorithm in the study.

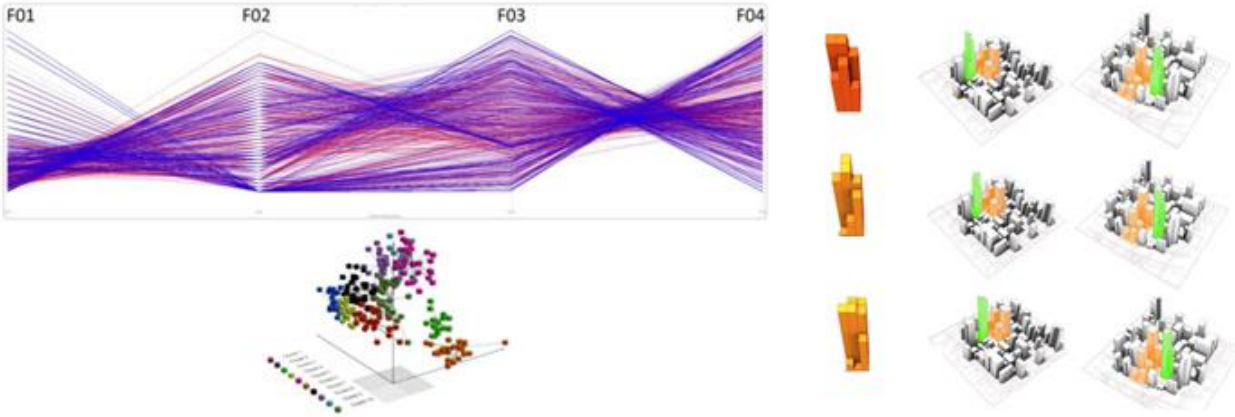

Figure 7 Automatic Creating of a Facade Design Alternative [27]

3.2.2. Facade Design Optimization

The building envelope has a great effect on the operating and maintenance costs during the using process of the building. These costs can be reduced by considering various performance factors. However, optimizing a large number of factors, especially in complex geometry and situations, requires a lot of time and cost with a limited manpower. Machine learning algorithms generate an infinite number of alternatives and make an infinite number of analysis in this optimization phase. In fact, this process can be made much faster by applying experimental techniques learned through experimentation and experience, rather than a direct analysis of all alternatives [14].

In a case study presented by Kim et al (2018), a model which is able to handle the optimization process of a sample building envelope with complex geometry made with perforated panels is proposed. Figure 8 and Figure 9 exhibits the scheme of the optimization process.

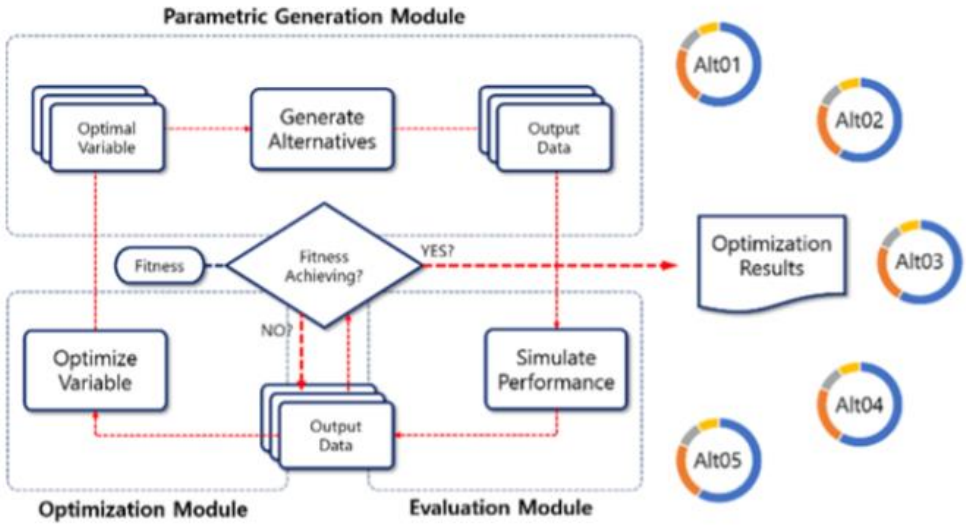

Figure 8. Optimization Process [14]

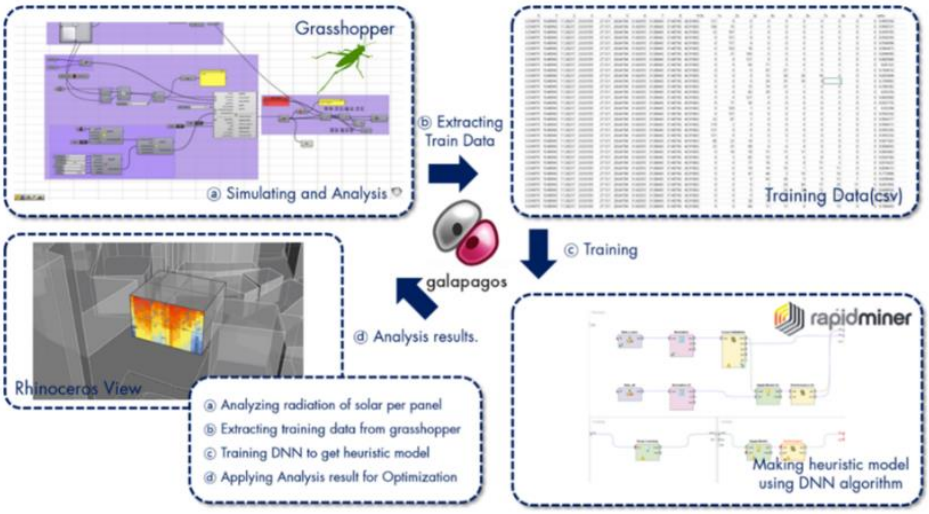

Figure 9. Optimization Process [14]

3.2.3. Creating 3D Models of The Existing Buildings

Today, virtual cities may need to be created for various purposes such as computer games, movies, urban planning, and pre/post-disaster studies. However, accurate procedural modeling of large numbers of 3D buildings is time consuming and expensive. Modeling of the buildings by machine learning based computer systems is possible to be completed much cheaper and in a shorter time compared to manpower [22, 23].

In the two studies reviewed, two different machine learning-based tools which make it possible to create 3D models from a single photograph of sample building facades have been proposed. The user selects a photo of the building facade and introduces it as an input to the system. The algorithm defines the positions of the architectural elements of the facade (wall, windows, doors, etc.) at the pixel and text level. When the layout of the elements is defined with this method, it acts as a grammar input and is ultimately used in the reconstruction and modeling of the facade [22, 23]. Figure 10 shows the process of creating a 3D model from a picture of an existing building.

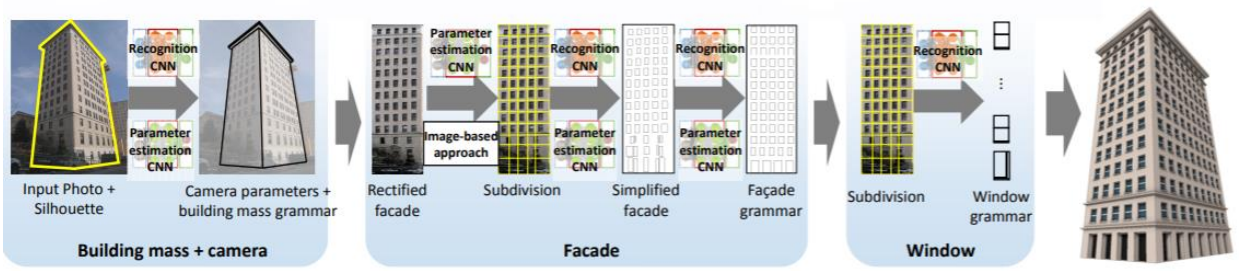

Figure 10. Modeling process [22]

3.2.4. Intelligent Facades

In order to improve energy performance and indoor comfort, studies are continuing to transform the facade design from static to dynamic in contemporary architecture. In order to increase the energy efficiency of buildings, dynamic system design is given importance to ensure the development of materials, concepts and technology [16].

Dynamically controlled adaptive facade is a concept used for dynamic facades that can adapt to changing environmental conditions. The design of dynamic facades has become a serious research subject in recent years. One of the building elements that make the most important contribution to the adaptability of the architectural structure is the facades. Buildings need their facades to be able to adapt to climatic changes.

In this part of the study, Al-Bahr Towers in Dubai and Central Place Sydney in Sydney are presented as two examples of machine learning-based facades.

The machine learning-based, inspired by a traditional wooden lattice shading shell system called 'Mashrabiya' of Al-Bahr Towers wraps the building 2 meters from the outside like a second skin to protect it against daily weather conditions such as above 50 degrees heat and sandstorms. The system both protects the building from structural deterioration and offers the user a comfortable experience thanks to these 2098 independently opening and closing dynamic flowers shown in Figure 11 [31, 33, 35].

Figure 11. Mashrabiya [35]

In the project called Central Place Sydney, which will have the world's first facade system that produces 100% artificial intelligence-controlled smart shading solutions against real weather conditions when completed in 2028, it is planned to use completely renewable energy in two towers of 37 and 39 floors and 165 meters grand high. Through these automatic facades that control the air flow and daylight, it is planned to make the most

efficient use of both natural lighting and natural ventilation in the interior areas of the building. The designers of the project also state that they aim to create the most contemporary, sustainable and modern designed workplace in the world by imitating nature and combining biophilic design elements such as smart shading and large terraces [39].

As can be seen in these two examples examined, the use of machine learning on building facades not only provides an energy efficient and sustainable structure, but also increases user comfort at the maximum rate without leaving it to human decisions. Furthermore, it provides an economic advantage by reducing the maintenance costs and the need for labor during the usage phase of the building. In this way, it is beneficial both in terms of resource use in the global context and in creating a comfortable living space in the individual context.

4. Results and Suggestions

It is known that machine learning is used in building sector due to the benefits and convenience it brings. However when the literature studies and the projects that are still being developed or used are examined, it is seen that machine learning-based systems are used in the design production and building usage process, especially for the purpose of saving time and labor.

It has been seen that there are more examples of dynamic and smart facades both in the literature and in the projects in the field; moreover the machine learning algorithms used in these examples, which can also be called 'learning facades', are mostly based on artificial neural networks. Fuzzy logic and deep learning are frequently used while evaluating daylight, heat and other factors in facade systems.

As a result of the researches, it has been seen that the number of projects that are using the machine learning technology is not very high because it is very expensive and recently developed technology. Machine learning has began to be used much more recently, especially in building facades, and this use is mostly concentrated in the fields of design, energy efficiency, optimizations and 3D modeling of existing structures. It has been observed that machine learning is mostly used for energy efficiency and user comfort in building facades. It has been determined that this technology is used the least in the field of automated design on building facades.

In the light of the information obtained, as a result of the research it is possible to state that the machine learning-based facade systems, which can provide an important solution to the global resource problem experienced in the world today in the context of

energy efficiency and sustainability for the construction sector. Machine learning is a very new subject, open to research and development, both in the literature and in the field.

In conclusion, it has been seen that machine learning is mostly used in new building facades in the examined examples. However, considering the excess of the building stock, the use of this technology in existing buildings may be expected to be beneficial both for the user in the buildings intended for use and in terms of minimizing labor and human failures in historical buildings that require restoration. In this context, the use of machine learning technology on existing building facades for future studies is clearly a subject which is to be suggested for researching. In this field, subjects such as energy conservation, labor saving, smart materials that extend the life of the facade or a model that can be used to detect various problems may be researched. This case shows that the projects, such as intelligent facade materials or movable facade elements using machine learning technology which are possible to apply to the existing buildings as well as the new or a perfectly automated real-time 3D scanner, are open to research and development.

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