

Artificial Intelligence Techniques to Support Design and Construction

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Abstract –

In recent years, researchers have relied heavily on data (historical and real-time) and digital solutions to support informed decisions. Consequently, data analysis has become an integral part of the design and construction process. Researchers spend a tremendous amount of time cleaning, organizing, and understanding the data. Artificial Intelligence (AI) can be used to help overcome human limitations in processing and enriching large volumes of data from a variety of sources. AI can encompass millions of alternatives for various design and project delivery solutions and ultimately improve project planning, construction, and maintenance and operation process. AI can be a solution to the severely under-digitized Architecture, Engineering, and Construction (AEC) industry, however, there are two challenges with respect to creating intelligent agents in AEC; (1) finding appropriate ways of gathering information from the environment and transforming them into internal context, and (2) selecting an appropriate AI technique to succeed in decision-making based on the relevant knowledge about the environment. This study focuses primarily on the second challenge by looking at potential applications of AI in AEC. The AI techniques in AEC can generally be classified into two main areas: (1) decision making methods and algorithms, and (2) learning methods. Regarding the first area, search methods and optimization theories are used when there is enough information to tackle decision-making and the problem is solved by the selection of the best action (with regard to some constraints and criteria) from a set of alternatives. The learning methods, on the other hand, are further classified into knowledge-based, reasoning, and planning methods (to learn how to adapt to changing conditions), learning probabilistic methods (e.g. Bayesian learning), and machine learning (e.g. supervised learning, reinforcement learning).

Keywords –

Artificial Intelligence Techniques; Artificial Intelligence Applications; Architecture, Engineering, and Construction Industry

1 Introduction

Artificial Intelligence (AI) is no longer a science fiction. AI is used advantageously in different industries such as healthcare, agriculture, finance, and banking industries. AI is already embedded in our lives in a wide range of applications such as Siri, Google search, smartphone, and Amazon recommendations. People might even not realize that they are using AI in their daily life. AI uses computer processing techniques to complete tasks that need human intelligence for learning or problem solving to make human-like decisions [1]. As a result, AI performs tasks faster and with a higher level of accuracy [2]. AI is transforming all segments of numerous industries. For example, in the agriculture industry, AI can help farmers know when to plant, water, harvest, or to produce more food and less waste [3]. In the healthcare industry, AI can analyze complex medical data and also help in real-time decision-making [4]. In the banking and finance industry, AI can enhance financial cyber-security to a higher level and prevent potential fraud [5].

Architecture/Engineering/Construction (AEC) is moving toward increased automation to enhance productivity and safety. Like many other industries, the AEC industry is struggling to find analysts who can make informed decisions that require computationally intensive data processing fast enough or in real-time. AI can offer exceptional benefits to increase automation in the construction industry and can be integrated into different phases of a project during its lifecycle. It is important to note that AEC is behind other industries in advancing new technologies and implementing AI solutions [6]. Forward-thinking project managers consider AI applications to enhance productivity,

increase profits, and advance safety in their construction projects [7]. Data is the fuel of AI techniques which is produced and collected throughout the life cycle of construction projects. The collected data in each phase of a construction project, including feasibility, planning and design, construction, and operation and maintenance, can be used to feed AI techniques. Construction data are the documentation that every project collects in different forms such as requests for information, drawings, photos of the job site, change orders, contracts, list of stakeholders, communications among stakeholders, and safety issue logs [8].

AI can be used to help overcome human limitations in processing and enriching large volumes of data from a variety of sources. AI can encompass millions of alternatives for various design and project delivery solutions and ultimately improve project planning. The ultimate aim of this study is to make AI part of the AEC's digital journey. AI is basically any device (or system) that perceives its environment and takes actions that maximize its chance of successfully achieving its goals. After gathering information from the environment and transforming them into an internal context (perception), we should select an appropriate AI technique to succeed in decision-making based on the relevant knowledge about the environment (action). The information presented in this study will be used to understand potential applications of decision making and learning methods in the AI domain and thus to select the AI technique best suited to the problem at hand.

After this introduction, an overview of AI and related techniques is presented. This is followed by the applications of AI in AEC, particularly in order to support design and construction. The next section presents new opportunities and challenges for the use of AI in AEC. Finally, conclusions and recommendations are presented.

2 Overview of AI Techniques

Although it may not be scientifically accurate to classify AI techniques and algorithms into two main areas of decision making, i.e. methods/algorithms and learning methods, such classification enables researchers and practitioners, without a lot of AI and machine learning knowledge, to apply these techniques to their problems. The following sections will discuss each area separately. Search methods and optimization theories are used when we have enough information to tackle decision-making and the problem is solved by the selection of the best action (with regard to some constraints and criteria) from a set of alternatives. Examples include linear programming, genetic algorithms, and ant colony optimization.

Ant colony optimization algorithm is a simple mathematical procedure and probabilistic technique that simulate the shortest and most efficient route for solving computational problems through graphs in a way that is also used within an ant colony [9]. Artificial bee colony algorithm is also a nature-inspired optimization technique that mimics and simulates intelligent behavior of honey bees [10].

Genetic algorithm is inspired by the natural theory of evolution that can be used to solve large optimization problems such as a pre-processing technique to select the best function/attribute subsequent to trying iteration after iteration under a given set of requirements [11].

Linear programming techniques involve optimizing a quantity with a mathematical method to determine the best feasible solution with a set of constraints presented in the form of linear programming problems [12].

Teaching-learning based optimization is an efficient optimization method which is a population-based method. The population includes a cluster of learners and the quality of the instructors influence the outcome of the students based on their performances or grades [13].

Local search algorithms are a heuristic approach to solve a problem by using a number of solutions while applying local changes to find an optimal solution [14].

Game theory is the study of human being in a strategic setting that can be used to solve more difficult problems when there are at least two or more players collaborating or competing to accomplish a task. To have a game, the outcome of players might depend on how they play based on the rules and solution concepts [15].

Stochastic models have a probability-based approach and are used when the environment is not perfectly predictable and decisions are partly influenced by the user's feedback and the regulations, standards, and guidelines. The random variations used in stochastic models are observed and collected through historical data for a specified period of time by using time-series techniques [16].

Bayesian networks gain an understanding of a problem and anticipate the results of intervention when some data are missing. Bayesian networks are considered when using some data in combination with prior knowledge [17].

Meanwhile, hidden Markov models are similar to statistical Markov models with hidden or unobserved states. When decision making can be modeled as sequential decision problems in uncertain environments, decision-making algorithms such as Markov decision processes can be used [18].

The learning methods, on the other hand, are further classified into knowledge-based, reasoning, and planning methods (to learn how to adapt to changing

conditions), learning probabilistic methods (e.g. Bayesian learning), and machine learning (e.g. supervised learning, reinforcement learning, and unsupervised learning).

A knowledge-based system (KBS) is a form of AI which is based upon reasoning that uses a knowledge-base to support decision-making and solving problems more efficiently. KBS includes seizing the knowledge and problem-solving methodology with relation to real world problems with a particular domain of knowledge [19]. In another approach, case-based reasoning (CBR) substitutes cases for rules. Cases are solutions to existing problems that a case-based system would apply to new problems. [19] described the CBR as a cycle including the four REs: 1) RETRIEVE the most similar case(s); 2) REUSE the case(s) to attempt to solve the problem; 3) REVISE the proposed solution if necessary; 4) RETAIN the solution as part of a new case.

Machine learning is the study of mathematical and statistical models, algorithms, and applications of artificial intelligence that machines use to improve their performance by learning and improving from their experience. Machine learning and deep learning are subsets and core of AI (shown in Figure 1).

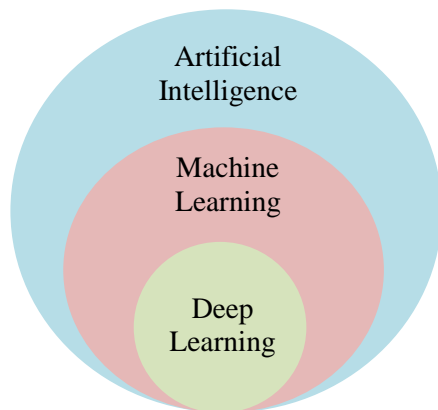


Figure 1. AI, Machine Learning, and Deep Learning

Machine learning technologies are helping computers to learn from data while thinking like a human and imitating the human brain. This became possible because of very powerful computers, availability of online data, large investment of businesses in AI, smarter algorithms, and revolution in programming. Deep learning covers a broader spectrum of machine learning methods using supervised, semi-supervised, and unsupervised techniques. In a supervised machine learning method, a machine learns from known quantities as an input that then maps an output as a future judgment. In an unsupervised technique, a machine learns from using data that is not

labeled, classified, or categorized. The machine learns through the process without guidance.

3 AI Applications in AEC

In about 50% of the time, typical construction projects are behind schedule or over budget with many ongoing issues, many conflicts, numerous RFIs (Request for information), and frequent change orders [20]. Imagine having an intelligent assistant to provide help during building construction. AI has already started to change the conventional construction industry compared to the way that buildings used to be designed, constructed, and operated. AI applications can be used for many purposes, including those which have not yet been devised. Imagine the role of AI when machines provide assistance to a construction team by using algorithms. Alternatively, AI systems can collect and organize data related to projects for a project team to be used during all phases of a project like the job Watson did. Watson provides patient information to doctors in a new way to help them make better decisions related to their diagnosis.

AI can provide extra insights into data that a construction team cannot or that will take a longer time and might be processed with lower accuracy because of human errors. Construction robots can perform routine tasks that are performed by construction workers, such as a mason's job of bricklaying for a masonry project. Utilization of robots in the construction industry can be beneficial to accomplishing the job faster without the need for a break during the work or going for vacations which significantly increase productivity and efficiency. These robots enhance quality, precision, and safety while also reducing waste. Construction projects are unique in nature and can be complicated. Meanwhile, the construction industry struggles with skilled workers shortages, and the emergence of new technologies provides tremendous benefits to enhance productivity in construction and to bridge the gaps and helps the construction team with their tasks. AI works well with automation and does not get tired or make mistakes, unlike workers.

Most importantly, AI helps with projects' records. In the past, all of the construction team used paper records to save project data or used a blackboard to record information during a meeting, keep notes or create to-do lists. With all of this existing information, it was still hard to keep track of information properly and to stay on the same page with other co-workers. The use of the data being collected through mobile devices in combination with AI makes the information available, reliable, accessible, and consistent. It helps the project team to mine the information and see patterns in data that are not otherwise evident. The following examples

discuss various ways in which AI can help construction with automation through access to resources such as data.

3.1 Drones

Drones are one type of mobile robots that became a powerful innovation for the construction industry by being employed in surveying, inspection, aerial images and photography, and project monitoring and controlling. Each type of drone can be equipped with a variety of technologies and equipment, and more importantly, offers the opportunity to include AI. Drones can be controlled remotely or equipped with AI techniques to provide solutions for image detection and processing. Drones can be used for monitoring and maintaining purposes as they can provide views from a different vantage point and provide on-demand support to construction workers in their daily activities.

A drone can also be used as a first-responder at a job site for construction hazards as well as search and rescue operations including finding safety violations [21]. Project monitoring and controlling is another important area in which drones are transforming construction projects to the next level. Not only they can monitor projects, report progress, and spot problems, drones can also work together, exchange information, and collaborate in a real-time manner to complete their tasks. They can provide pictures with high resolutions to monitor projects in real-time. Drones can become the eyes of project engineers and project managers by providing vision in situations that are costly, require travel, and are challenging or hazardous. Finally, drones can determine different kinds of damage during any disaster.

3.2 Construction 3-D Printing

Construction 3-D printing includes the applications of different technologies that use 3-D printing to fabricate buildings or components of construction projects with different materials, such as cement, concrete, foam, and polymer. Construction 3-D printing has a variety of applications in the construction industry including residential, commercial, and industrial buildings, bridges, and infrastructure. 3-D printing of construction-scale projects offers design-driven construction process where the design determines the final product with a lower labor cost, shorter project duration, and making possible complex designs with the required functionality [22].

This technology has gained popularity in recent years within the construction industry. Adding AI to construction 3-D printing lets the printer create an object and then learns from the process to improve it. In addition, the use of 3-D printing was further promoted

after NASA announced 3D-printed habitat competition for Mars.

3.3 Safety 4.0

With the trend of automation in construction, the internet of things (IoT), and cloud computing and cloud-based data exchange, it is necessary to take construction safety to the next level to be compatible with the new work environment. Safety 4.0 refers to conducting safety in a smart work environment or the way future safety will be practiced. With the merging of AI applications into the construction industry and shifts from conventional safety methods, safety management systems and inspections are used by project team members through using new technology, and field personnel becomes part of the decentralized safety program.

With real-time access to all of the safety information, there is no need to look for paper-based blueprints or going back to the office to look for a report. Safety 4.0 enhances communication among the project team members, specialty contractors, and stakeholders. Safety 4.0 enables team members to have access to real-time safety data. This can enhance the quality of data that can be used for AI techniques offering for the use of reporting accidents, forecasting potential incidents, or near misses. By having all the safety data, information, and report in hand, conducting regular safety meetings at the job site is made easier.

Smart wearable equipment or personal protective equipment (PPE) are developed in a way that is connected to the internet or other devices to provide real-time data while decreasing the exposure to construction safety hazards and sending automatic notifications [23]. Smart PPE can provide unlimited opportunities for field workers. For example, smart communication devices that can be connected to safety hard hats or face shields to facilitate communication in a noisy work environment can minimize hazard exposure. With all of these new technologies and AI applications, data can be transformed and adapted for safety to industry 4.0.

3.4 Autonomous Vehicles

Autonomous vehicles or self-driving cars can play an important role in construction projects. For example, some manufacturing companies have already developed heavy equipment for dozing and hauling for earthmoving projects that are able to provide 3-D pictures of the earth. As automation in construction becomes more practical, the use of autonomous vehicles that can be equipped with AI technology, robotic solutions, and sensors, enable construction equipment to operate without drivers and with better communication.

The equipment can be operated remotely and with all of the advancement in technology, it has the potential to increase productivity, efficiency, and safety and to be more cost-effective.

3.5 Generative Design

Generative design refers to a design process that employs AI techniques that generate several numbers of iterative designs according to the possibilities and constraints provided. Generative design can be used in AEC during the design process to empower the architects and designers particularly throughout the conceptual design process. Employing AI techniques by using algorithms to formulate project requirements generates design solutions and navigates them into the detailed design process. Recently, Autodesk [24] used the same approach as conceptual research and conducted the generative design approach to perform space planning. For space planning, several constraints such as building orientation, area, size of windows, daylight, and HVAC design criteria were considered in the developed algorithm.

Generative design augments architects and designers' capability and combines it with the cloud computations and machine learning to provide new solutions for clients. It enhances the ability of architects and designers to exceed current challenges during the design phase.

3.6 Risk Mitigation and Control

The use of AI applications for risk mitigation and control in construction projects is useful even with unstructured data. Cognitive analytics such as natural language processing (NLP), offers advanced algorithms to process unstructured data. Most of the generated data related to risk identifications are unstructured and it is beneficial to use cognitive analytics to leverage proactive risk identification in projects. With cognitive analytics, known and unknown risk identification can become more accurate.

3.7 Smart Sensor

In construction projects, smart sensors provide a unique role in facilitating IoT. Installing smart sensors at the job site creates continuous data collection that can be used for different purposes. For example, if there are any toxic substances or physical agents such as chemical substances or high-level noise above the permissible exposure limit in the environment, the sensors can sound an alarm and inform workers for evacuation. The sensors will be helpful for measuring air quality at the job site or in confined spaces. The real-time data collection and alarm can be shared with other

people in the office such as the project manager, superintendent, or safety manager. The report can be developed automatically based on the data if AI techniques are used. Sensors can mitigate risks and issues and keep the job site safer.

To understand how the AI can be used in AEC, some of the AI applications during different phases of construction projects are summarized in Table 1.

4 Opportunities and Challenges for the Use of AI in Design and Construction

The rise of AI and machine learning in the construction industry has facilitated the construction process. It created and resulted in a more efficient and productive manner in managing the projects. This can be attributed to its application in any stage from design to pre-construction to construction to operation and maintenance. Recent advancement in technological solutions that integrates AI-powered algorithms has helped key players to tackle some of the challenges including cost and schedule overruns and safety concerns. However, in spite of the high return on investment and significant management interest in AI solutions, few construction companies and owners have the capability to employ them. One of the main challenges in implementing AI faced by these companies is the lack of critical mass data. AI is based on learning from past activities, decisions, and performances which requires a significant amount of data to train it. The other issue is the tremendous restrictions on data sharing and data ownership.

Therefore, the largest construction companies are potentially able to benefit more from AI applications in the near future. On the other side, some of the AI solutions that encourage the construction industry to adopt it are as follows: 1) project schedule optimizers which include millions of alternatives to improve project planning, 2) image recognition and classification to evaluate video data collected at the job site to determine the unsafe areas or behaviors, 3) analytical platforms to collect and assess the real-time data from various sensors installed at the job site to help project managers implement real-time solutions. Even though the construction industry is behind with technology adoption compared to other industries, now is the time to act and secure a place at the cutting-edge of implementing AI solutions and techniques into the sector.

5 Conclusions

The adoption of AI is slowly progressing in some areas of AEC, but there is still a long way to go. This study focused on identifying and leveraging synergies

between AI techniques and AEC with the aim of providing a better understanding of potential applications of AI and making AI part of AEC's digital journey. In order to provide a vision of some of the AI applications in AEC, an overview of some of the AI techniques is first explained and then application of AI specifically in AEC is summarized. This enables us to

understand the potential applications of AI methods in the AEC domain. There are new ways to incorporate AI into the construction process to help the workforce become more efficient. The trend has already started and it will accelerate when using AI becomes more feasible.

Table 1. Summary of AI Applications in AEC

Construction Project Phases	Construction Activities	AI Applications	Notes
<i>Feasibility Study</i>			
	Collect historical information, process, and procedure	Pattern recognition	Apriori algorithm [26]
	Identify initial stakeholders	ANN	
	Identify feasible options	Neural Networks	Neural Networks, Fuzzy Cognitive Maps, Genetic Algorithms, Bayesian Models can be used as critical success factors identification [27]
	Understand business case	Fuzzy Cognitive Maps	
	Develop project objectives	Genetic Algorithms Bayesian Models	
<i>Planning</i>			
	Collect project requirements, constraints, and assumptions	Neural Networks Fuzzy Cognitive Maps Genetic Algorithms Bayesian Models	Neural Networks, Fuzzy Cognitive Maps, Genetic Algorithms, and Bayesian Models can be used as critical success factors identification [27]
	Determine standards and codes	Stochastic models	Cognitive computing and strategies can be used to develop stochastic models [16, 25]
	Identify risks	Cognitive analytics	Natural language processing (NLP) offers advanced algorithms to process unstructured data.
	Develop project management plan	ANN	Management by algorithm
	Define scope	ANN	
	Develop schedule	ANN	ANN can be used to optimize project duration. The mathematical model is developed based on the project network diagram, resource leveling, and time-cost trade-offs [30].
	Estimate cost and determine budget	ANN CBR	ANN and CBR can be used as a project cost optimizers to optimize the project's cost. The mathematical model is developed based on the project network diagram, resource leveling, and time-cost trade-offs [29, 30].
	Plan resource management	Generic Algorithms	GA can be used to search for an optimum solution for resource allocation and leveling integrated with time-cost trade-off model, resource model, and resource leveling model [29, 30].
	Estimate activity resources	CBR ANN	
	Perform qualitative and quantitative risk analysis and plan risk responses	CBR	Risk Mitigation

<i>Design</i>			
Schematic design/rough sketches	Generative Design	Kiviat diagram, better known as a spider diagram [24].	
Refining the design			
<i>Construction</i>			
Construct the project according to the design	CBR	CBR can be used during the construction phase [28].	
Manage stakeholder engagement	CBR	CBR will be helpful for resource engagement and management [28].	
Safety	Image recognition and classification	Classify safety issues to the fatal four. Pictures and video data collected at the job site can help to identify unsafe worker behavior.	
<i>Maintenance & operation</i>			
Maintenance and operation of the project	ANN GA CBR	ANN, GA, and CBR can be used to assist the diagnosis and monitoring during the maintenance and operation phase [28, 30, 31].	

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