CCC 2020
Proceedings of the Creative Construction e-Conference (2020) 010
Edited by: Miroslaw J. Skibniewski & Miklos Hajdu
https://doi.org/10.3311/CCC2020-010

Will Artificial Intelligence (AI) Take over the Construction World? - A Multidisciplinary Exploration

Souhail Elhouar[1], Elodie Hochscheid[2], M. Ammar Alzarrad[1] and Chance Emanuels[1]

[1] *Bradley University, Peoria, USA*
[2] *MAP-CRAI (UMR 3495), School of Architecture, Nancy, France*

Abstract

The late Stephen Hawking was reported to have said, "Computers will overtake humans with AI within the next 100 years. When that happens, we need to make sure the computers have goals aligned with ours." This statement is frightening to most, as very few people may like the idea of seeing computers take over the world. However, what can be more frightening is for those few people who like the idea to also make use of Hawking's suggestion and find a way to make sure the computers have goals that are strictly aligned with only theirs. There is a distinguishable apprehension among people of the role AI is set to play in the future of humanity, and this apprehension is transcending disciplinary boundaries. In the particular fields related to construction, there seems to be a genuine interest in integrating AI in each phase of a project to improve quality, enhance safety, and reduce costs, but this interest is countered by a legitimate concern that many types of jobs would be lost to AI-enhanced machines. In this paper, the authors tried to shed some light on how AI might change the face of the construction industry. The authors, spanning generations and disciplines in the industry, tried to answer the question "will AI take over the construction industry?" each from their own perspective including architectural, structural, and construction management. A synopsis of the status of the application of AI in construction and related fields is first provided, and then the authors offer their individual views with respect to how they expect AI to affect their side of the industry. This paper is an effort to gain insights into the perceptions of current and future construction related professionals of the role of AI and the impact it may have on the industry.

Keywords: artificial intelligence, construction automation, deep learning, future of construction, machine learning

1. Introduction

Charles Babbage, an English mathematician, inventor, and computer pioneer of the late eighteenth and early nineteenth centuries, was reported to have said that "At each increase of knowledge, as well as on the contrivance of every new tool, human labour becomes abridged" [1]. This assertion, which is still relevant about two hundred years after it was made, strikes at the heart of the subject of this paper. In a MarketWatch article that was published in early 2019 by Associated Press, the author quoted a Brookings Institution report that predicted that soon more than 30 million U.S. workers will lose their jobs to Artificial Intelligence (AI) [2]. And a briefing that was published about the same time quoted AI experts stating that automation could replace 40% of the world's jobs in as little as 15 years [3].

According to Makridakis [4], AI is set to bring about considerable change that will affect all aspects of society and life, just as the industrial and digital information revolutions did. How people will react to this change will mostly depend on their perspective and role. To researchers in the field, AI may just be a tool, or a set of concepts and tools, through which human thinking and decision-making processes are transferred to machines, which then can use their inherent capabilities to solve complicated problems faster and more accurately than any human would be able to do. But for many other people, the growing inclusion of AI in most areas poses a threat to their job security and, perhaps more importantly, the dreaded risk of losing control to the machine. However, would this latter group acknowledge those applications of AI that can assist people in achieving a better performance at their jobs instead of replacing them? Or are they more concerned that the services of architects, engineers, and construction managers may be at risk of being taken over by intelligent machines. Can AI enhanced machines be as creative as humans in solving problems? Do architects, engineers, and construction managers have the same expectations and apprehensions of the role of AI in their respective sectors? And who would assume the liability for any problems that may arise from, say, "machine error"? These are important questions that will need to be addressed by the industry as an increased integration of AI in the design and construction processes is inevitable.

This article is not meant to provide the answers to these questions but rather be a thought-provoking exposé to stimulate a comprehensive discussion about AI and its role in the construction industry. The authors hope that such a discussion will help in consolidating the directions of AI research in construction and its related fields or defining new ones.

2. Historic relevance of Artificial Intelligence

The idea of using other than human intelligence is not new and some researchers even trace the concept back to Greek mythology [5], although the name, Artificial Intelligence, of this now major area of computer science was not formally adopted until the middle of the twentieth century. A careful observation of the progression of humans' use of knowledge over time would ultimately reveal that the advent of AI was bound to take place and that its continued integration in all aspects of human life is unavoidable. Just as a carriage evolved into a car, a train, an airplane, and then a rocket that can transport people to outer space, and just as most of the people who were around when the first carriage in the world was made could not have imagined a rocket lifting off into space, the manipulation and undoubtedly further enhancement of human knowledge by machines will continue to evolve and will eventually reach levels that most people living today cannot even fathom or think about.

In the past fifty to sixty years, the world has witnessed an explosion of research and in-depth analysis of the human thought and decision-making processes in an attempt to create machines that can mimic those processes. If only one thing was to be inferred from all of the work that has been performed in the field so far, it would be the fact that intelligence cannot be restricted to one aspect or another of human cognitive abilities. This is an extremely important observation to consider moving forward because, whether knowingly or unknowingly, people typically use a combination of their cognitive and reasoning abilities to solve problems, and many of these abilities are yet to be adequately suited for automation. This, however, does not mean that those abilities will never be automated. The first person who attempted to fly did not succeed but persistence allowed mankind to eventually land a rover on Mars. So, if history is a measure, AI is coming to stay, and people will adapt to it just like they have adapted to the use of engines, electricity, phones, and computers.

3. AI for architectural design

Architectural design (AD) is a creative and iterative problem-solving approach whose purpose is to organize living spaces for any kind of human use [6]. Rather than an aesthetic position, architecture is based on an ethical position (i.e. environmental approach), spatial practice (ways of living and mores of a society), and a working progress (methods and tools used to pursue the design) [7]. Past cases help the designer to refine solutions [8]: this is called case-based design. Research in the design cognition field has demonstrated that designer's background and the immediate design environment also influence the emergence of solutions [9]. These can evolve from general environment to details (top-down approach) or from basic elements to general ones (bottom-up). It appears that the thinking of human designers simultaneously works both ways [9].

Generative Architectural Design (GAD) refers to the use of algorithms (i.e. cellular automata, genetic algorithms, shape grammars, etc.) to support architectural design [9]. These algorithms have been around for decades and are part of the history of AI. The first uses of AI techniques for AD date back to the 1960s [10], even though the idea that an algorithm could "creatively solve problems" [6] was not new at the time. The Architecture Machine Group at MIT has been a pioneer in this field; its leader, Nicholas Negroponte, considered that the AD process can be "assisted", "augmented", and eventually "replicated" by the computer [11]. More generally, two visions of AI coexisted: the first postulates that the role of AI is to be able to mimic human intelligence; the second assumes that its goal is to make the computer more useful to humans by performing tasks that require intelligence [10]. The second vision largely prevails.

Some very recent work using AI for AD will now be examined. Several AI applications are intended to stimulate designer's creativity in very early stages of design, by generating images (street ambiances in the GAN Loci project [12]) or 3D models [13]. Classification possibilities of CNN are often exploited to retrieve examples that match a design, for assisting a designer in a situation of case-based design to find relevant cases of previous designs (like for example the DANIEL project [14]). This type of operation is now often associated with evaluation and optimization algorithms [15].

Architectural solutions have also been generated with AI algorithms. Here are a few examples of very different approaches. Spacemaker [15] is an ML-based software for urban design that covers generation, evaluation and optimization of urban designs. AI-generated solutions maximize indicators as sun exposure, noise reduction, etc. Habx [16] is a property development company that developed an ML-based algorithm that draws apartment plans (partitions and room assignment). Based on reinforcement learning, the algorithm does not use a database (training set), but design constraints had to be made explicit in order to train the algorithm to make consistent floorplans. Stanislas Chaillou [17] has developed for his PhD a GAN-based algorithm that generates apartment floorplans with furniture in an exclusively top-down approach. The algorithm generates building footprints, partitions apartments, and positions furniture. The designer can intervene at each stage to provide input and choose the most suitable design for the next step. While the Spacemaker algorithm is mainly based on performance, Chaillou's algorithm rather offers options to the designers.

As generation algorithms can quickly generate large amounts of possibilities, classification algorithms are generally used complementarily, in order to give the opportunity to the designer to browse through the large range of solutions. AI has also made it possible to drastically optimize simulation durations to real-time simulations approximations, by projecting the results of previous simulation cases on new similar ones. This introduces a kind of "intuition for decision making" [18] for designers.

Digital design has four main components that AI algorithms can already realize: generation, representation, evaluation (analytical and judgmental processes) and performance (programmatic, performative and contextual considerations) [19]. While some solutions let algorithms manage a large part of the design process, others, on the contrary, aim at giving the designer the possibility to master the algorithm itself, in order to combine the sophistication of a human design process with the power of algorithm generation. Algorithms are limited by the solutions that can be found in their learning set, or by the constraints they have been given. Some initiatives give the designer control over the algorithm itself, making it easier for him to access it without having any particular machine learning skills (i.e. Lobe.ai, a visual programming tool). AI solutions will probably gradually be integrated into professional design tools to enhance designer's creativity (*via* solutions generation, retrieval and classification), "intuitions" (*via* real-time analysis) and constraints integration (*via* optimization). But as any other innovation in the construction sector, AI adoption will probably be slow. Human intervention will still be necessary and desirable although it may be reduced for certain types of projects.

4. AI in structural engineering

The field of structural engineering is a fertile ground for applications in AI. In general, civil engineering problems are multifaceted and usually require a variety of solution techniques that go well beyond deterministic computations. In structural and other civil engineering disciplines, these may include past experience, judgment, and creativity: traits that require respectively increasing levels of difficulty to automate. Moreover, the role of a structural engineer is very central to the successful completion of a project and carries a sizeable share of liability. A successful structural design not only must meet the strength and serviceability requirements as stipulated in the applicable building and design codes and standards, but it also must accommodate the needs of other disciplines, such as mechanical, electrical, plumbing, and specialty trades, in addition to meeting architectural requirements. Additionally, there may be numerous options to consider during any one particular design in terms of materials and construction methods to achieve most benefit.

Research related to the use of AI for structural design goes back to the mid 1960's [20], but to the best of the authors' knowledge, there has never been an attempt to produce a comprehensive AI-based tool for the design of a structural system. What is meant by comprehensive here is the ability to produce a detailed design of structural system starting from an architectural model and without human intervention at any stage of the design process. When one considers all the intricacies and implications of the structural design process, it becomes evident that if an AI-based tool is to be developed to comprehensively address structural engineering problems, it must have a number of necessary abilities that will allow it to tackle the various aspects of the problem in a reliable and consistent way, namely, and just to name a few:

- Access to all applicable building and design codes and an inherent ability to interpret and apply their provisions to the problem at hand
- Ability to produce conceptual models of possibly feasible structural systems based on architectural or other relevant information
- ability to produce structural modeling information from conceptual models
- Ability to execute the design process and interpret structural design information
- Ability to perform a holistic assessment of the integrity of the designed system

Each one of these items can be the subject of the implementation of an AI-based application of its own, and many of them may be amenable to the production of a number of AI-based applications for the same item. For example, the ability to execute the design process and interpret structural design information can be integrated in different tools that deal with different types of structural systems and materials. As a matter of fact, the literature is rich with examples of uses of the various AI tools, such as expert systems, neural networks, deep learning, fuzzy logic, and others to assist structural engineers in specific aspects of the design process. However, the availability of commercial software that makes serious use of AI for design is still lacking. This could be due to a number of reasons including the lack of software developers who are well versed in structural design as well as AI, the lack of comprehensive platforms for the development and maintenance of AI-based engineering applications, and the prohibitive cost of developing and maintaining AI applications in the absence of such platforms.

Will AI take over the structural engineering world? The answer to this question will depend on what is actually meant by "take over." If taking over means that the world will see the demand for structural engineers plummet because designs will be completely automated using AI-driven software, then the most likely answer is no, or at least not in the foreseeable future. Other than the absence of the required AI technology to allow for that to happen, there are also serious liability implications for letting a machine be responsible for independently producing a design. Consequently, any advances in AI that will lead to the development of such a system will have to be accompanied by changes to the legal system. The most likely scenario though is that the effect of AI on the practice of structural engineering will be similar to the effect that the introduction of computer technology had on the industry some forty years ago or so. Computers did not replace structural engineers. Instead, engineers became able to design larger and more complex structural systems using more computationally intense analysis and design methods that found their way into applicable building and design codes. The authors anticipate that AI enhanced design tools will start finding their way into the structural engineering practice as add-ons that would be designed to work with established commercial software, and the expansion of web and cloud-based computing will play a big role in allowing such tools to thrive.

5. AI in construction management

Construction is a high-risk industry with countless opportunities for accidents, miscommunication, and running over budget or behind schedule. From front end planning to construction documentation, preconstruction to handover, many stakeholders and changes can overwhelm even the most organized project managers. Artificial intelligence (AI) can significantly improve construction project management effectiveness. The potential applications of AI in construction are vast. AI applications in the construction industry are forecasted to reach $4.51 Billion by 2026 [21]. The easy risk mitigation of quality and safety, coupled with saving the time and cost of the construction projects, will drive the growth of the market.

Most construction projects run over budget [22]. AI could help to predict cost variance based on aspects such as project size, contract type, and the experience level of project managers. Historical data such as project start and end dates are used by predictive models to predict accurate timelines for future projects. AI helps staff get training material remotely, which helps them enhance their skills and knowledge rapidly. This reduces the time taken to train new resources, and consequently, project delivery will be expedited.

Today, 3D modeling and Building Information Modeling (BIM) transformed the buildings' design process significantly. To accurately plan and design the construction of a building, the BIM models need to consider all project systems such as architecture, structural, mechanical, electrical, and plumbing (MEP) systems and the sequence of activities to build these systems. The main challenge is to ensure that the different systems do not clash with each other. Machine learning, which is a branch of AI, could help to create 3D models of MEP systems while concurrently making sure that the routes for MEP systems do not clash with the building architecture/structural components.

Construction projects are exposed to countless forms and degrees of uncertainty and risk [23]. The larger the project, the more significant the risk, as multiple teams are working on different trades in parallel on the job site. AI could be used to monitor possible risks on job sites so that the contractors can come up with more effective contingency plans. Project managers can also prioritize on mitigating high risks when AI determines one.

Many construction firms are investing in AI and data science to boost the industry's low productivity and solve the labor shortage problem. Construction companies could boost productivity by as much as 50% through real-time analysis of data according to a 2017 McKinsey report [24]. Construction companies are starting to utilize AI and machine learning to improve resources allocation and resources leveling. An AI-based application could continually evaluate job progress and the location of resources to enable project managers to tell which job sites have enough resources to complete the project on time, and which might be falling behind where additional resources could be deployed. AI could help robots to perform repetitive tasks more efficiently than their human counterparts, such as pouring concrete, bricklaying, welding, and demolition, etc. [25]. This releases up human workers for other construction activities and reduces the overall time required to complete the project.

Laborers are killed on construction sites five times more often than other industries [26]. The leading causes of deaths in the construction industry were falls, followed by struck by an object, electrocution, and caught-in or between machinery [27]. AI-based applications that utilize visual processing algorithms are a vital risk monitoring and prevention tool for safety managers. Safety monitoring solutions that use AI scan large amounts of photos and quickly identify workers and instances that are not following safety protocol. For example, AI could help identify safety hazards, such as workers not wearing appropriate PPE gear.

6. AI in construction from a student's perspective

We can do it, but should we do it, when deciding whether to allocate cognitive and physical labor from humans to that of artificial intelligence. The consequences of our decision on outsourcing our cognitive labor to AI will only be fully understood in hindsight [28]. And at the moment, there is a terrifying amount of work automation in warehouses and labs around the world. From a student's perspective, it is reasonable to believe that AI poses the ability to improve quality, enhance safety, and reduce cost within the construction workflow. How will AI impact the quality, safety, and cost, and how will the impact be measured to ensure that AI's goals are aligned with the good for humans? The following sections describe how AI will impact construction.

The construction industry has been through economic revolutions before, but the robot revolution is different. Universal robots are requiring minimal maintenance with a minimum lifetime of 35,000 hours and a return on investment that outperforms the meat-based competition [29]. Construction companies constructing complex buildings, large scale projects, and demanding deadlines may feel the need to adopt robots to stay competitive against other companies. Currently, Boston Dynamics has made a construction robot named SPOT that can inspect progress on construction sites, create digital twins, and compare as-built conditions to building information models [30]. Spot can perform quality management of workmanship, and, a key area focused on during an undergraduate degree in construction management; the robot performs the task autonomously. Will AI take over all of the construction managers' roles and duties? Only time will tell. Currently, construction managers can keep their employability by continuing education and finding ways to adapt and work next to artificial intelligence instead of being replaced by machines [31]. In the meantime, while humans are still the majority of the construction workforce, Artificial Intelligence and digital transformation will swiftly creep into the workforce by providing convenience to the people it serves. Enabling/Empowering people to accomplish more work with the help of computers has established a lasting presence for computers within the construction industry.

Safety in construction is a collective priority and has improved significantly since the early 1900s. Many lives have been saved and injuries prevented from job safety analysis and safety programs established to keep workers aware of the risks present while completing work. As Job Safety Analysis becomes digitized, it will become behoove of the companies to utilize the data for safety inference. Such inference will help ensure EMR rates remain low and help keep workers aware of the risks present while performing individual job tasks. AI will be coupled with big data to help determine unsafe acts, and statistics will be used to increase awareness of potential injuries. The most likely injury can sometimes be prevented by doing toolbox talks to cover the hazards seen most frequently. AI could take the form of a bot on a safety app that notifies workers of unique hazards while the user is filling out the form. The Job Safety Analysis is intended for workers to think about the dangers present. Safety is somewhat of a stochastic environment that concerns the occurrence of freak accidents and a safety manager will still need to be present to ensure that people are complying with the program and give human intuition on safety concerns.

AI can also play a significant role in reducing construction costs. Intelligent systems were initially discovered in the 1960s when Allen Newell, Herb Simon, and John McCarthy were questioning what human-level intelligence is [32]. The researchers broke down human-level intelligence into three pieces: perception, deciding what to do, and then acting, today known as the decision loop [32]. Machine learning has contributed to the decision portion of the loop; before machine learning became fashionable, humans wrote the predictions of what happens next which was limited to decision making such as chess and instead had computers observing historical data to predict what happens next through making artificial neural networks [32]. The key here is that during the decision-making process, advanced intelligent systems can accomplish planning by weighing possible sequences of actions and finding the probability of the outcome. Then the system chooses the most likely one and acts based on the choice, followed by the perception of a new situation. AI poses the ability to reduce cost by giving inference on what potential outcomes are possible and helping humans make decisions with less time by providing information faster than traditional construction information gathering.

7. Conclusions

Every creature in the world is born with a Knowledge-Base, to use an AI term, that allows it to perform the required functions it needs to be able to survive. What sets humans apart is their ability to simultaneously use the different types of the knowledge they already have and in unpredictable different ways to create new knowledge that may be of a completely different nature that what they started out with. It may be this ability that defines a large portion of what is referred to as intelligence, of which creativity, intuition, and, to a certain extent, inspiration.

AI offers powerful tools that can outperform humans in many areas of design and management, but so did computers when they were first introduced to help in computationally heavy professions, such as accounting, for example. The fact is that the advent of computers did not kill the need for accountants. To the contrary, and although computers did take over the world of accounting, there may be more accountants per capita in the US today than there were 50 years ago. Moreover, computers created new opportunities for computer savvy accountants to find rewarding careers in software development and consulting while allowing practicing accountants to focus on the specifics of the information at hand, rather than on performing arithmetical operations.

AI will inevitably take over the construction industry by becoming more integrated into the software and equipment that is being used by the industry and its related disciplines. AI will also most likely trigger a big change in the way the industry conducts its business by introducing more automation and robotics and affecting design methods and the means and methods of construction. AI may not end up reducing the need for architects, engineers, and construction managers. Instead, these professionals of the industry and others may see their roles and the way the perform their duties permanently changed to become aligned with the new reality of an AI driven world. How this will play out will be an interesting thing to witness but the industry will have to make a choice between riding the wave on the front or being dragged by the tide.

8. Acknowledgements

The publication of this article was made possible by the support of MAP-CRAI (UMR 3495), School of Architecture, Nancy, France.

9. References

[1] W. E. Hearn, Plutology, or, The theory of the efforts to satisfy human wants, London: Macmillan and Co., 1864.
[2] "Over 30 million U.S. workers will lose their jobs because of AI," 24 01 2019. [Online]. Available: https://www.marketwatch.com/story/ai-is-set-to-replace-36-million-us-workers-2019-01-24. [Accessed 12 2 2020].
[3] D. Reisinger, "A.I. Expert Says Automation Could Replace 40% of Jobs in 15 Years," 10 01 2019. [Online]. Available: https://fortune.com/2019/01/10/automation-replace-jobs/. [Accessed 12 02 2020].
[4] S. Makridakis, "The forthcoming Artificial Intelligence (AI) revolution: Its impact on society and firms," Futures, vol. 90, pp. 46-60, 2017. https://doi.org/10.1016/j.futures.2017.03.006.
[5] P. McCorduck, M. Minsky, O. G. Selfridge and H. A. Simon, "History of Artificial Intelligence," in Proceedings of the Fifth International Joint Conference on Artificial Intelligence (II), CAMBRIDGE, MASSACHUSETTS, USA, 1977. Available: https://www.ijcai.org/Proceedings/77-2/Papers/083.pdf.
[6] M. Steenson, Architectural Intelligence: How Designers and Architects Created the Digital Landscape, MIT Press, 2017. ISBN: 978-0-262-03706-8..
[7] A. Penn, Making Digital Architecture, R. Glynn and B. Sheil, Eds., UCL Press, 2017, pp. 12-13.
[8] M. Pearce, A. Goel, J. Kolodner, C. Zimring, L. Sentosa and R. Billington, "Case-Based Decision Support: A Case Study in Architectural Design," IEEE Expert, vol. 7, no. 5, pp. 14-20, October 1992. https://doi.org/10.1109/64.163668.
[9] V. Singh and N. Gu, "Towards an integrated generative design framework," Design Studies, vol. 33, no. 2, pp. 185-207, 2012. https://doi.org/10.1016%2Fj.destud.2011.06.001..
[10] J. S. Gero, "Special Issue Artificial intelligence in computer-aided design: Progress and prognosis," Computer Aided Design, vol. 28, no. 3, pp. 153-154, 1996. https://doi.org/10.1016/0010-4485(96)86821-7 .
[11] N. Negroponte, Soft Architecture Machines, Cambridge, MA: MIT Press, 1975. http://www.medientheorie.com/doc/Negroponte.pdf, p. 133.
[12] K. Steinfeld, "Can neural nets reveal the tacit properties that make a “space” a “place”?," 2019. [Online]. Available: https://towardsdatascience.com/gan-loci-e2bbd1b4926f.
[13] K. Steinfeld, K. Park, A. Menges and S. Walker, "Fresh Eyes A framework for the application of machine learning to generative architectural design, and a report of activities at Smartgeometry 2018," in "Hello, Culture!" Proceedings of the 18th International Conference, CAAD Futures 2019, Daejeon, Korea, 2019. ISBN 978-89-89453-05-5.
[14] D. Sharma, N. Gupta, C. Chattopadhyay and S. Mehta,, "DANIEL: A deep architecture for automatic analysis and retrieval of building floor plans," in 14th IAPR International Conference on Document Analysis and Recognition (ICDAR), 2017. https://doi.org/10.1109/icdar.2017.76.
[15] V. Eisenstadt, C. Langenhan and K.-D. Althof, "Supporting Architectural Design Process with FLEA – a Distributed AI Methodology for Retrieval, Suggestion, and Adaptation of Room Configurations..," in "Hello, Culture!" Proceedings of the 18th International Conference, CAAD Futures 2019, Daejon, South Korea, 2019. ISBN 978-89-89453-05-5.
[16] B. Dolla, "habx," in Conference for the launching of the “Intelligence Artificielle & Architecture” exhibition at the Pavillon de l'Arsenal, Paris, France, 2020. https://www.pavillon-arsenal.com/fr/arsenal-tv/conferences/ia-architecture/11484-2-bastien-dolla-habx.html.
[17] S. Chaillou, "AI + Architecture | Towards a New Approach," PhD Thesis, Harvard University, 2019. https://www.academia.edu/39599650/AI_Architecture_Towards_a_New_Approach.
[18] M. Tamke, P. Nicholas and M. Zwierzycki, "Machine learning for architectural design: Practices and infrastructure," International Journal of Architectural Computing, vol. 16, p. 123–143, 2018. https://doi.org/10.1177/1478077118778580 .
[19] R. Oxman, "Theory and design in the first digital age," Design Studies, vol. 27, no. 3, pp. 229-265, 2006. https://doi.org/10.1016/j.destud.2005.11.002 .

[20] W. R. Spillers, "Artificial Intelligence and Structural Design," Journal of the Structural Division, vol. 92, no. 6, pp. 491-497, 1966.
[21] "Reports and Data, Artificial Intelligence (AI) in Construction Market By Technology, By Component, By Phase, By Deployment Type, By Applications, By Organization Size, By End-use, And Segment Forecasts," July 2019. [Online]. Available: https://www.reportsanddata.com/report-detail/artificial-intelligence-ai-in-construction-market.
[22] M. A. Alzarrad, G. . P. Moynihan, H. T. Muhammad and S. Song, "Fuzzy Multicriteria Decision-Making Model for Time-Cost-Risk Trade-Off Optimization in Construction Projects," Advances in Civil Engineering, pp. 1-7, 27 November 2019. https://doi.org/10.1155/2019/7852301.
[23] M. A. Al-Zarrad, G. P. Moynihan and S. C. Vereen, "Guideline to Apply Hedging to Mitigate the Risk of Construction Material Price Escalation," in Proceedings of the 5th International/11th Construction Specialty Conference, Vancouver, British Columbia, June 7-10, 2015.
[24] F. Barbosa, J. Woetzel, J. Mischke, M. . J. Ribeirinho, M. Sridhar, M. Parsons, N. Bertram and S. Brown, "Reinventing Construction: A Route To Higher Productivity," 27 February 2017. [Online]. Available: https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/reinventing-construction-through-a-productivity-revolution.
[25] M. A. Alzarrad and S. Elhouar, "3D Printing Applications in Construction from the Past and into the Future," in Proceedings of the 2019 Creative Construction Conference, Budapest, Hungary, 2019. https://doi.org/10.3311/ccc2019-103 .
[26] Y. M. Goh and C. U. Ubeynarayana, "Construction Accident Narrative Classification: An Evaluation of Text Mining Techniques," Accident Analysis and Prevention, vol. 108, pp. 122-130, 2017. https://doi.org/10.1016/j.aap.2017.08.026 .
[27] "Commonly Used Statistics," 22 June 2017. [Online]. Available: https://www.osha.gov/data/commonstats. [Accessed 5 2020].
[28] D. Kahneman, Thinking, fast and slow, New York: Farrar, Straus and Giroux., 2015.
[29] Universal Robots, [Online]. Available: https://www.universal-robots.com/media/8641/ur_brochure_gb.pdf.
[30] Boston Dynamics, [Online]. Available: https://www.bostondynamics.com/spot.
[31] C. B. Frey and M. . A. Osborne, "The future of employment: How susceptible are jobs to computerisation?," vol. 114, no. C, pp. 254-280, 2017. https://doi.org/10.1016/j.techfore.2016.08.019.
[32] A. W. Moore, Interviewee, J.P. Morgan Distinguished Lecture Series on AI - AI in 2020: How we see it at CMU. [Interview]. 26 11 2018. https://www.jpmorgan.com/global/technology/artificial-intelligence/ai-distinguished-lecture-series.