MSA UNIVERSITY ENGINEERING JOURNAL

Architectural Design in The Light of AI Concepts and Applications

Nihal A. Amer[1,a]

1 Associate Professor, MSA University, Cairo, Egypt
E-mail: [a]namer@msa.edu.eg,

Abstract

In the early stages of projects, architects always face a huge amount of data needed for the design. Currently, computational facilities are available to assist the designer to utilize data and information easily and efficiently to achieve this goal. Artificial Intelligence, AI, is a new science that utilizes, interprets and manipulates data to achieve goals and to accomplish tasks. Currently, AI has been spread among different disciplines and encompasses a wide variety of sub-fields (Modelling, anomaly detection, association and clustering). The present work aims at clarifying the privilege of adopting AI in the architectural design, and to encourage architects to start using it friendly. This is accomplished through a two-fold methodology: highlighting the related literature and demonstrating a summary of selected published case studies of applied and intended projects. It is expected that AI will be applied and play a substantial role in architecture practice more widely in future projects

Keywords: Computational facilities, Architectural software, Artificial intelligence

ENGINEERING JOURNAL Volume # Issue #
Received Date Month Year
Accepted Date Month Year
Published Date Month Year
Online at https://engj.org/
DOI:10.4186/ej.20xx.xx.x.xx

1. Introduction

Artificial intelligence (AI) is an interesting term that describes a machine that mimics human cognitive functions, like problem-solving, pattern recognition, and learning. Machine learning is a subdivision of AI that uses statistical techniques to provide computer systems the ability to learn from data, without being obviously programmed. The more the machine is exposed to data the better it becomes at understanding and providing insights. Thinking means how a lot of numerous data can perceive, understand, predict and manipulate a world for larger and more complicated than itself Machines simply learn from data, and the application of data is artificial intelligence (AI). AI goes further as it attempts not just to understand but also to build intelligent entities. AI is a significant science appeared in the late 40s of the 20^{th} century, while it got its name in 1956 [1].

Although AI was initially associated with microbiology, it spread among other disciplines. Recently, AI incorporates a wide variety of subfields from general-purpose areas such as learning and perception to specific tasks as diagnosing diseases, marketing, engineering, economy and others. Kaplan and Haenlien, 2019 gave a clear definition of AI as "Systems' ability to interpret external data correctly to learn from such data, and to use these learnings to achieve specific goals and tasks through flexible adaptation" [2]. It is then obvious that data is the corner stone of AI activity, hence, it goes parallel to the developments in computing facilities and the amount and quality of data stored in global resources. Any discipline tries to utilize and interpret data form its own perspective. Through relevant algorithms, AI makes possible self-driving cars, distant operation, smart homes or other tasks. Therefore, we can say that AI is a tool for any discipline to redefine itself.

This article could be considered as an approach to those architects who may consider AI as an illusion. It should be clearly mentioned that AI would never substitute or carry out their creative architecture role in design and planning. Usually architects use past construction data, design and building data and users' needs to tackle new projects. But many designers and planners see this process as something still in the past. The ability to use large amounts of data in extremely limited time to enhance the architectural design process could produce wonders.

As a matter of fact, in the early stages of design architects face an enormous amount of data covering the details of the different components of the project. Currently, many software has been developed to assist the designer to handle and utilize data and information to achieve his design easily, efficiently, and properly and to save a lot of time.

The main objective of this study is to encourage architects to get closer with and to be familiar with recent and advanced computational techniques and software which are the basis of AI. To achieve this goal a two-fold methodology is adopted in this article: first a brief review of literature tackling related software and AI; second a concise summary of published case studies of applied and hypothetical projects

2. AI in Data Management and Design Options

Computational technologies employed with architectural purposes are increasing. In this respect the amount of data globally produced in the last decade is enormous and subject to increase [3]. Most of the data is about built environment and human activities which are the playground for architecture. However, computational technologies and AI are badly needed in architecture to create analytical information that have significant influence of decisions in any phase of design. Moreover, computer-aided design (CAD) programs and algorithmic parametric design tools can generate forms that could not exist without computation [4].

Architects usually face great amount of data to process in the first phases of design. These data include physical environment analysis, users' needs, functional requirements, previous case studies, legal codes, etc. All of these data need to be processed. Here comes the role of AI that provides major support to deal with all these data that may be very difficult to process without computational technologies. Consequently, this is positively reflected on the design process by reducing the time required for the starting phase of design.

Advanced commercial software on the use of AI in architecture is available. For example, CATIA, which stands for Computer Aided Three-dimensional Interactive Application, is used as an algorithmic design application. It shows the consistency and applicability of the new technologies, materials, machinery, progressive methods and information tools that enable more efficient use of materials [5]. Another software is Grasshopper, which is a graphical parametric tool working under Rhinoceros. Schneider used Grasshopper for the development of urban design proposal at a teaching exercise [6].

Beside the available software, different researchers continue studying methods to apply AI in architecture leading to design development [7, 8 & 9]. Also Chillou, 2019 applied AI to floor plan analysis with the aim of generating different options of floor plans [10]. In 2017, Nagi and his team developed the Project Discover, which is an application of generative design for space planning [11]. Sharma et al., 2017 developed the software DANIEL, which is a deep architecture for automatic analysis and retrieval building floor plans [12]. As et al., 2018 demonstrated how to use Generative Adversarial Networks (GANs) to generate unique and original design variations [13].

2.1. Application of AI in design options

One of the interesting examples that shows the potential of AI in the architectural organization of space is Stanislas Chaillou's contribution in developing a new system [14]. Chailllou was able to utilize deep learning and GANs in generating floor plans by focusing on functionality and style as main parameters as shown in "Fig. 1". Soon architects may benefit from this feasible tool opening up many iterations of the projects and producing appropriate floor plans. Accordingly, it establishes a base for a more analytical process and generation of creative ideas by the architect. This experience highlights the potential of AI in providing a tool that helps informing knowledgeable decisions within a limited time during the design phase.

Moreover, an architectural office in Copenhagen (3XN) developed an important research project that emphasizes how a distinguished architectural practice positions itself according to the development of technologies. This project identified three main aspects where AI could contribute positively in: Research (organizing information), Design (a better iterative process) and Knowledge Management (developing an internal database of experience). The research division in the office is preparing for a paradigm shift and planning for five years ahead to develop the studio for the onset of AI into architecture practice [14].

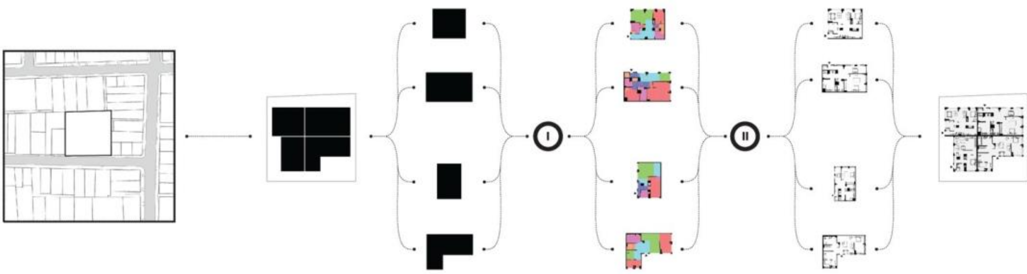

Fig. 1. Utilizing Deep Learning and GANs in Generating Floor Plans [14]

2.2. Application of AI: AI as a style guide

Additionally, AI can be used to find and duplicate elements, such as compositions and materials, profiles, storey heights, window and stair specifications, and more. For example, BricsCAD is an all-in-one CAD design solution that answers all architects needs related to 2D drafting, 3D modelling and BIM. The objective of BricsCAD is to use AI to assist architects with time-consuming and precise tasks, in order for them to innovate focus on the important design choices [15]. In BricsCAD, AI examines a sample model first before using the same style in a new project. For instance, flooring on the ground floor may have a different composition from floors above as shown in "Fig. 2", or walls on the south side of a structure may automatically receive a thicker insulating coating. AI eliminates a lot of manual labor and lowers the possibility of overlooking crucial information [16].

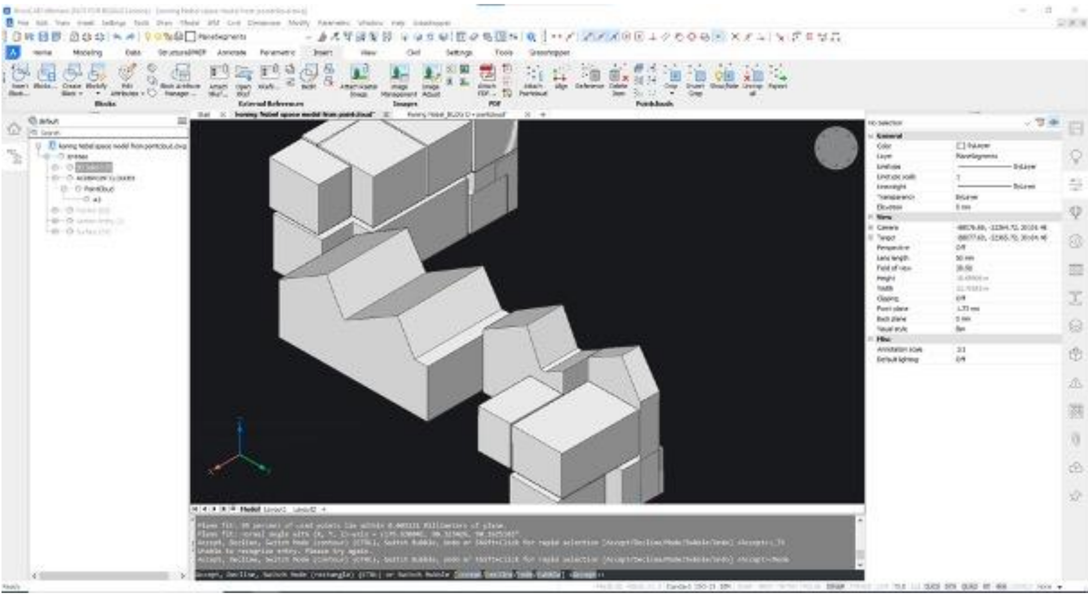

Fig. 2. Through BricsCAD, AI applies same style in a new project after analysing an example model [16]

2.3. Application of AI: AI to Add Detail

Increasing the level of detail (LOD) is the next step in the design process. A common illustration is the intricate connection between a wall and a floor slab, where the many layers come together in a certain arrangement. Artificial intelligence can be used to construct this intricate link only once, after which BricsCAD will automatically duplicate it in other places on the model as shown in “Fig. 3”. This can be accomplished by a tool called ‘Propogate’ which is included in BricsCAD BIM that saves the architects a lot of time [16].

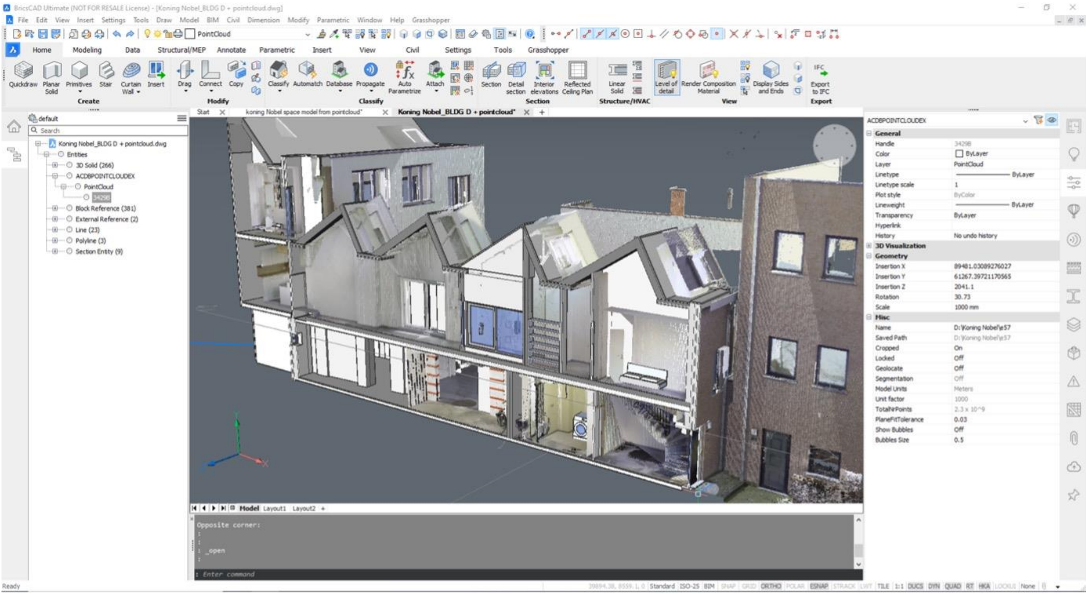

Fig. 3. Integrating the Level of Detail in the design process [16]

3. AI in Building Information Modelling

Building information modelling (BIM) is a popular term in the field of contemporary architecture. It is a multi-disciplinary approach that strengthens the relationship between different contributors of the construction industry such as architects, engineers and contractors. Eastman et al., 2008 considered it as a process change rather than simply a technology change. BIM describes the simulation of the building design in virtual environment. Azhar et al., 2008 mentioned that the resulting BIM is a data-rich, object oriented, intelligent and parametric digital representation of the facility. Consequently, views and data appropriate to various users' needs can be extracted and analysed to generate information that can be used to make decisions and to improve the process of developing the facility. In this respect AI provides a strong support regarding the extreme complexity of the multi-layered and multi-disciplinary structure of BIM software.

BIM is a 3D model-based process that provides architecture, engineering and construction experts insights to plan, design, construct and manage infrastructure and buildings in an efficient way. In order to plan and design the construction of a building, the 3D models should take into consideration the architecture, engineering, mechanical, electrical and plumbing (MEP) plans and the sequence of tasks of the relevant teams. Ensuring that the different models from the sub-teams don't clash with each other is very challenging. Through machine learning, generative design is used to identify and mitigate clashes between the different models generated and designed by the different teams during the planning and design phase thus preventing rework.

3.1. Application of AI in building information modeling

Numerous technological developments are built on machine learning algorithms, which are pushing AI to the top of the list of BIM trends as having the most potential to enhance the design process.

By automating repetitive activities, BricsCAD BIM eliminates bottlenecks in the design process by using the strength of AI and machine learning. Geometry is a major BricsCAD BIM principle. With the 3D modelling tool in BricsCAD, architects can quickly build any shape they can think of. Correct BIM classification can be introduced afterwards and is not necessary during the creative, conceptual, design phase. The clever "Bimify" tool makes use of AI and quickly assign BIM classifications to the geometry. However, architects always have the last say and can change the classification manually as shown in “Fig. 4” [16].

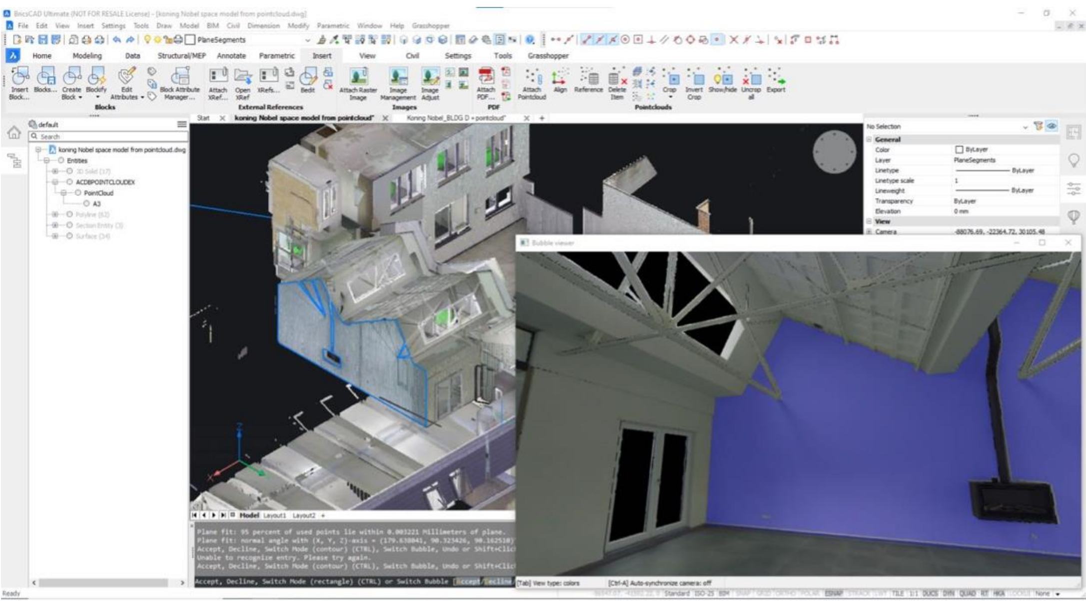

Fig. 4. Application of AI in Building Information Modelling [16]

3.2. AI in renovation: scan-2-BIM

There are no 3D models available when it comes to remodelling old buildings. One method is to make a digital replica of the building (a point cloud) using laser scanners. Converting these unstructured points into useful geometry is the key difficulty here. The Bricsys team is developing semi-automatic techniques to acquire these 3D solids**.** A point cloud's planar surfaces are first found using BricsCAD. The wall and floor surfaces are flat, so this is straightforward. An artificial intelligence program can readily fit a surface to a group of points that are roughly coplanar with a manually chosen point. It is simple to produce a volume that represents a particular room in a structure by semi-automatically fitting numerous surfaces and stitching them together.

Surfaces in the actual world are rarely completely vertical or horizontal in practice. However, no architect wants small deviations due to measurement or calculation errors to occur in their final model. AI can be used here to optimize geometry. Finally, depending on the room volume planes, BricsCAD applies a clever algorithm to build the outside walls, floor slabs, roofs, and internal walls. Artificial Intelligence in BricsCAD BIM can consequently not only be used to make existing 3D geometry smarter, but can also generate geometry directly from a point cloud [16].

4. AI in Analysis of Building Performance

The process of inspection of building's behavior under certain effects is referred to as building performance analysis. It becomes easier and more reliable to conduct this process through applying AI and BIM. Specialized software in performance analysis in combination of BIM software are used for more fruitful and significant results. Energy and structural performance are the main types of building performance [17, 18 & 19]. Attia et al., 2009 consider that software for energy performance analysis (EPA) are evaluated through the following criteria: usability and information management of interface, integration of intelligent design knowledge-base, interoperability of building modelling and the accuracy of the tool and its ability to simulate complex and detailed building components [20]. Currently, there are many accessible EPA tools that mostly operate as plugins under other software. For example, 'Ladybug' is a tool to work in collaboration with Grasshopper, with an effort to support the full range of environmental analysis in a single practice platform [21]. Moreover, there is another important analysis called automated building performance analysis that can eliminate the traditional time-consuming methods by utilizing machine learning ML that can in generating the best options for a set of parameters automatically. This performance analysis is considered an integrated approach that focuses on the interrelations between single performance aspects. For example, it allows users to realize how natural ventilation rates affect indoor air quality and how daylighting affects energy efficiency and HVAC system sizing. Therefore, by organizing the tediousness of data crunching to machines, automated BPA frees up time for design teams to focus on what they do best which designing. Figure 5 shows another model for integrating automated building performance analysis in the design process [22].

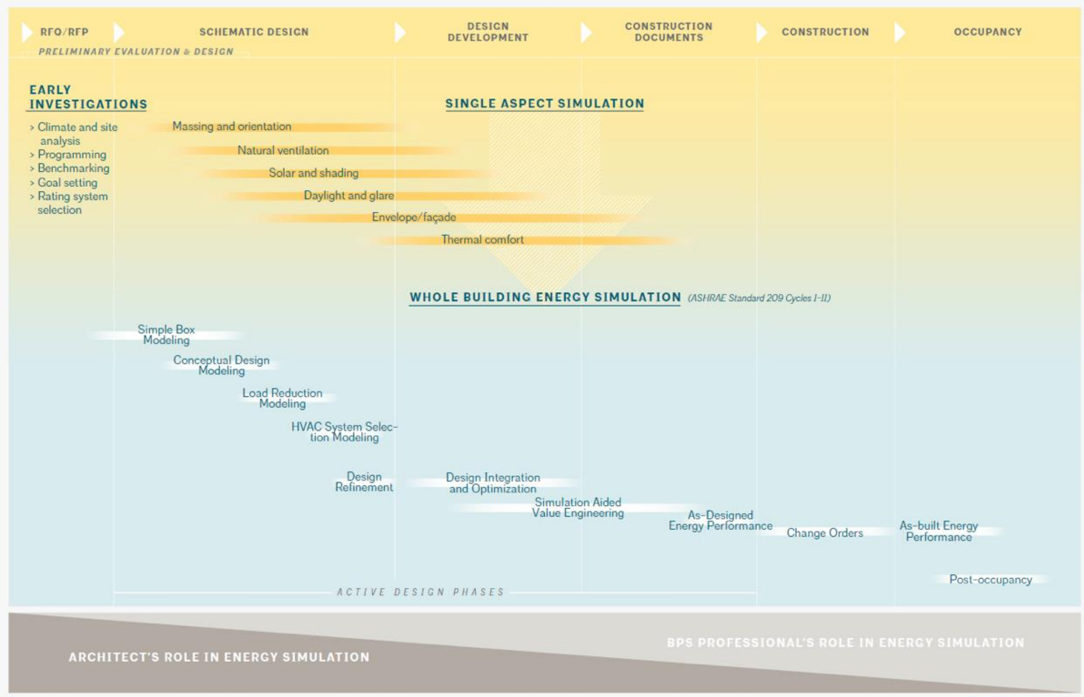

Fig. 5. An Alternate Model for Integrating Automated Building Performance Analysis in the design process [22]

Moreover, Cove.tool is an intelligent building performance and energy modelling platform that offers an array of tools necessary for sustainable data-driven design as shown in "Fig. 6". The platform's analysis tool integrates machine learning to aid architects, engineers and developers optimize high performance design options. Its scope covers façade design, water, glare, solar and climate. It can be used in Revit, Rhino 3D, sketchup and more for analysis [23].

Structural performance analysis is an important problem that must be handled properly to avoid disasters caused by improper or poor structural design. This analysis is a domain in the interaction between engineering and architecture which deserves special attention during the design process.

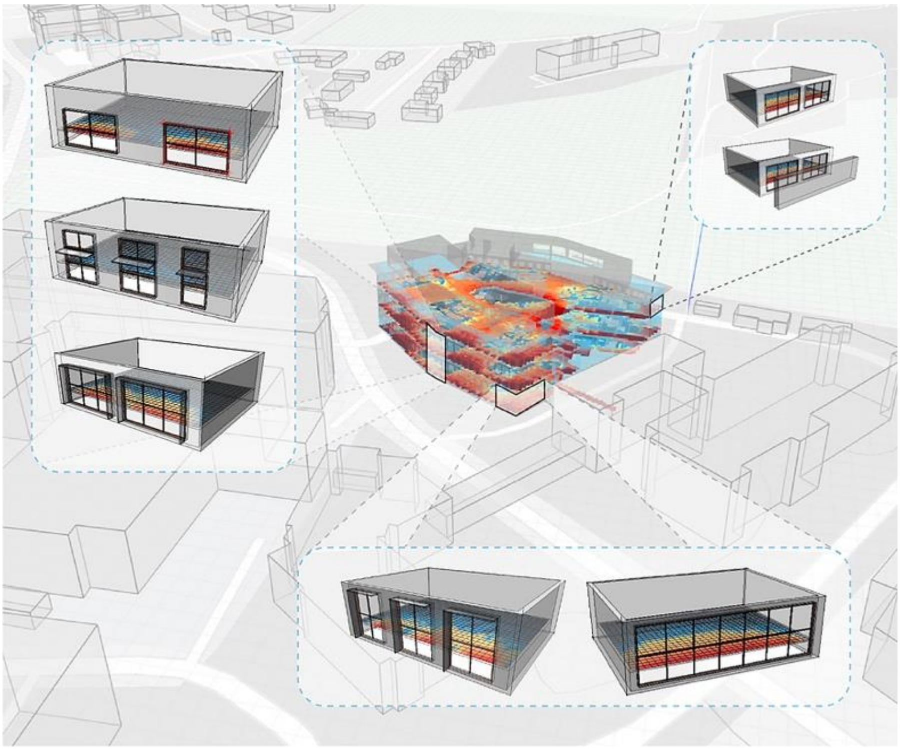

Fig. 6. Automated Design Platform for Intelligent Building Performance through Cove.tool [23]

5. AI in Architectural Representation

Architectural representation is an inevitable step to demonstrate the produced design. Currently, every design tool in CAD applications has an interface for representation. Computational technologies and AI provide wide alternative media for visualization, upgrading representation to a high advanced level. Yang, 2020 considers that the virtual technology of architectural animation provides a new digital mode for the promotion of architectural image, which is considered an important means of architectural expression [24]. Software and tools are available that provide high quality of visual products with the help of AI such as 'Vray'. Other software 'Lumian', 'Twinmotion' and 'Cinema 4D' make animations with realistic renderings easy to produce. Dounas, 2020 considers animation as a computational understanding of architectural design [25].

Other new representation methods emerged with virtual reality (VR) and augmented reality (AR) in architecture as interactive techniques. Interactive visualization of architecture provides a way to see current and future stances of buildings [26]. VR and AR options were added to visualization methods of some existing programs through plugins like 'Enscape' or

‘VR Sketch’, while some other software as ‘EyeCAD VR’ and ‘IrisVR’ completely focus on VR experience as a representation method for architectural products.

6. AI for Smart Construction

The evolution of construction industry has passed through different stages starting with traditional methods to modern construction techniques [27]. Hence, AI could provide a considerable support effectively through collaboration with robotics, BIM and AR technologies. Using additive manufacturing is a way that AI could support construction. Additive manufacturing or 3D printing is recently a new but effective way of constructing buildings. Previously it was an expensive process, but it has become now one of the most cheap, affordable and eco-friendly ways of constructing buildings [28]. Moreover, automation is becoming an important innovation in construction. Systems like automated building construction, shut rise and steel frame remote releasing are examples of automated construction [29]. Wang and Love, 2012 stated that industrialization of the construction process requires a high level of automation, which happens to the site work tasks that require high integration of information and physical intensive resources [30].

The potential applications of machine learning and AI in construction are enormous. Change orders, requests for information and vulnerable problems are standard during construction. Machine learning can be considered as a smart assistant that can scrutinize this huge amount of data. AI alerts project managers about the critical things that need their attention [31]. The following examples demonstrate the benefits of AI in construction:

6.1. Prevent cost overruns

Artificial Neural Networks (ANN) are utilized in projects to predict cost overruns based on aspects such as contract type, competence level of project managers and project size. Predictive models use historical data such as scheduled start and end dates to visualize realistic timelines for future projects. Staff can remotely access real-life training material through AI which enhances their skills and knowledge quickly, reducing time taken to onboard new resources onto projects. Thus, project delivery is accelerated.

6.2. AI and the generative design

BIM provides architects, engineers, and construction workers with information they can use to effectively plan, design, build, and manage infrastructure and structures. In order to design and plan the construction of a project, the 3D models must consider the architecture, engineering, mechanical, electrical, and plumbing (MEP) plans and the sequence of activities of the respective teams. The challenge is to ensure that the various models from the sub-teams do not conflict with one another. To discover and resolve conflicts between the many models produced by the various teams, the industry leverages machine learning in the form of AI-powered generative design. This reduces the need for rework. Now softwares explore every possible variation of a solution and generates design alternatives using machine learning algorithms. Once a user sets up requirements in the model, the generative design software creates 3D models optimized for the constraints, learning from each iteration until it comes up with the ideal model.

6.3. Risk mitigation

Each construction project carries some level of risk, which can take many different forms, including quality, safety, time, and cost risk. The more subcontractors working on various crafts simultaneously on job sites, the bigger the project, the greater the risk. General contractors can now monitor and prioritize risk on the job site using AI and machine learning solutions, allowing the project team to concentrate their limited time and resources on the biggest risk issues. AI is utilized to automatically allocate priority to issues. Subcontractors are rated based on a risk score so construction managers can work closely with high-risk teams to mitigate risk.

6.4. Project planning

One construction company launched in 2017 with the potential that its robots and artificial intelligence solved late and over budget construction projects. Robots were used to autonomously capture 3D scans of construction sites. The company then feeds that data into a deep neural network that categorizes how far along various sub-projects are. The management team deals quickly with small problems before they become major issues if things seem off track. Algorithms use an AI technique known as "reinforcement learning." This technique allows algorithms to learn from the trial and error process. It can evaluate infinite alternatives based on similar projects. It helps in project planning as it optimizes the best track and corrects itself over time.

6.5. AI for productive jobsites

Some companies are starting to offer self-driving construction machinery to perform repetitive tasks more efficiently than their human counterparts, such as pouring concrete, bricklaying, welding, and demolition. Excavation and preparation work is being performed by autonomous or semi-autonomous bulldozers, which can prepare a job site with the help of a human programmer to exact specifications. This frees up human workers for the construction work itself and reduces the overall time required to complete the project. Project managers can also track job site work in real time. They use facial recognition, onsite cameras, and similar technologies to assess worker productivity and conformance to procedures.

6.6. AI for construction safety

An algorithm is created to analyze photos from the job site, scan them for safety hazards (i.e., workers not wearing safety protective equipment) and correlate the images with its accident records. Risk ratings for projects can be potentially computed. Consequently, safety briefings can be held when an elevated threat is detected.

6.7. AI for addressing labor shortages

Construction organizations can enhance productivity by approximately 50 percent through real-time data analysis. Planning the distribution of labor and machinery across job is enhanced through AI and machine learning. Project managers can instantly detect which job sites have adequate equipment and workers to finalize the project on time and which are delayed where additional labor can be employed by using a robot which constantly evaluate the job progress.

6.8. Off-site construction

In off-site factories, robots can piece together components of a building which are then collected together by workers on-site. Autonomous machines can construct structures like walls in an assembly-line fashion, leaving human employees to do the finishing touches on the plumbing, HVAC, and electrical systems once the structure has been put together.

6.9. AI and Big Data in construction

AI systems are exposed to an infinite quantity of data to learn from and improve daily at a time when enormous amounts of data are being created every day. Every construction site becomes a potential source of data for AI. A pool of information has to be created from the data produced by photos and videos taken with mobile devices, drone footage, security sensors, building information modelling (BIM), and other sources. This offers the chance for clients and professionals in the construction sector to study and gain from the data insights produced with the use of AI and machine learning systems.

6.10. AI for post-construction

A long time after construction is finished, building managers can still use AI. Advanced analytics and AI-powered algorithms gain useful insights into the operation and performance of a building, bridge, road, and nearly anything in the built environment by gathering information about a structure using sensors, drones, and other wireless technologies. As a result, AI can be used to spot problems before they become serious, predict when preventative maintenance is necessary, or even guide people's actions to ensure maximum security and safety.

7. Discussion

The present study discusses how architecture profession can benefit from the recent rapid developments in the field of electronic computation software and AI. These facilities are strong support for architects to achieve their designs and plans efficiently and to save a lot of time. By no means, software and AI would substitute the architects or carryout their duties in design and planning. These facilities are only powerful tools to help architects in getting alternative designs using tons of data in so limited time.

The future benefits of AI in construction may appear in many aspects. Costs associated with construction can be cut by up to 20% using robotics, AI, and the internet of things. Engineers can send tiny robots into newly constructed structures while wearing virtual reality goggles. These robots follow the task as it is done using cameras. Modern structures' plumbing and electrical systems are being routed using AI. AI is being used by businesses to create workplace safety solutions. Artificial intelligence is managed to monitor the interactions between employees, equipment, and objects in real-time and notify managers of potential safety hazards, construction mistakes, and productivity problems.

8. Conclusion

Despite the expectation of considerable job losses, AI is not likely to completely replace the labor force. Instead, it will change business strategies in the construction sector, lessen costly mistakes, lessen workplace accidents, and improve building operations.

9. Recommendations

Construction industry executives should focus their investments on areas where AI has the greatest potential to meet the specific demands of their organization. Early adopters will determine the industry's course and profit in the future.

10. References

[1] S.J. Ussel, and P. Norvig, "Artificial Intelligence: A Modern Approach". 2nd Edition, Pearson Education, 2003.

[2] A.M. Kaplan, and M. Haenlein, "Siri, Siri, in My Hand: Who's the Fairest in the Land? On the Interpretations, Illustrations, and Implications of Artificial Intelligence"**,** Business Horizons, 62(1): pp. 15-25, 2019.

[3] A. Holst. (2020). "*Volume of data/information created, captured, copied, and consumed worldwide from 2010 to 2024***",** Statista. Available: https://www.statista.com/statistics/871513/worldwide-data-created. [Accessed: 6 June 2022]

[4] M.W. Steenson. (2018). "*Why Architecture and Artificial Intelligence?"***,** XRDS: Crossroads, The ACM Magazine for Students, 24(3): pp. 16-19 Available: https://doi.org/10.1145/3187013 [Accessed: 14 May 2022].

[5] R. Dubovska. J. Jambor. and J. Majerik (2014). *"Implementation of CAD/CAM system CATIA V5 in Simulation of CNC Machining Process*", Available: https://doi.org/10.1016/j.proeng.2014.03.037 [Accessed: 2 February 2022].

[6] C. Schneider, A. Koltsova, and G. Schmitt, G. “Components for parametric urban design in Grasshopper from street network to building geometry”, in *The 2011 Symposium on Simulation for Architecture and Urban Design*, 2011, pp. 68-75.

[7] M. Mohammadi, A. Al-Fuqaha, and J.S. Oh,, “Path Planning in Support of Smart Mobility Applications using Generative Adversarial Networks”, *IEEE Conference on Internet of Things, Green Computing and Communications, Cyber, Physical and Social Computing, Smart Data, Block chain, Computer and Information Technology, Congress on Cybermatics*, 2018, pp. 878-885 Available: https://doi.org/10.1109/Cybermatics_2018. 2018.00168 [Accessed: 25 July 2022].

[8] S. Ahmed, M. Liwicki, M. Weber, and A. Dengel, A., “Automatic Room Detection and Room Labeling from Architectural Floor Plans”, *IAPR International Workshop on Document Analysis Systems,* 2012, pp. 339-343 Available: https://doi.org/10.1109/DAS.2012.22 [Accessed 2 July 2022].

[9] F. Marson, S. R. Musse, S.R., “Automatic Real-Time Generation of Floor Plans Based on Squarified Treemaps Algorithm”, *International Journal of Computer Games Technology*, 2010, Available: https://doi.org/10.1155/2010/624817 [Accessed: 9 August 2022].

[10] S. Chaillou, “AI+Architecture: Towards a New Approach”, PhD Thesis, Harvard Graduate School of Design, USA, 2019.

[11] D. Nagy, L. Damon, L. John Locke, S. Jim, V. Lorenzo, W. Ray, Z. Dale and B. David, “Project Discover: An Application of Generative Design for Architectural Space Planning”, in *The Symposium on Simulation for Architecture and Urban Design*, 2017, pp. 59-66.

[12] D. Sharma, N. Gupta, C. Chattopadhyay, S. Mehta, S., “DANIEL: A Deep Architecture for Automatic Analysis and Retrieval of Building Floor Plans”, in *The 14th IAPR International Conference on Document Analysis and Recognition*, 2017, pp. 420-425.

[13] I. As, S. Pal, and P. Basu, “Artificial intelligence in architecture: Generating conceptual design via deep learning”, *International Journal of Architectural Computing,* Vol. 16, no. 4, pp. 306–327, 2018. Available: https://doi.org/10.1177/1478077118800982. [Accessed: 25 August 2022].

[14] A. Cuturei. (2020). *Six Practices Bringing AI into Architecture.* Available: https://www.archdaily.com/936999/pioneers-6-practices-bringing-ai-into-architecture [Accessed: 6 June 2022].

[15] B. Olaf. (2022). *BricsCAD Review & Product Details.* Available: https://www.g2.com/products/bricscad/reviews/bricscad-review-6656033 [Accessed: 28 July 2022].

[16] W. Nys. (2021). *Artificial Intelligence in BIM and renovation.* Available: https://www.bricsys.com/en-eg/blog/artificial-intelligence-in-bim-and-renovation [Accessed: 25 August 2022].

[17] M. Anderson, (2021). *AI in Architecture: Is It a Good Match?* Available: https://www.iflexion.com/blog/ai-architecture [Accessed: 25 August 2022].

[18] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, “BIM handbook: A guide to building information modelling for owners, managers, designers, engineers and contractors”, Wiley, New York, 2008.

[19] S. Azhar, M. Hein, and B. Sketo, “Building information modelling: Benefits, risks and challenges,” in *The 44th Associated Schools of Construction National Conference*, Auburn, AL, 2008.

[20] S. Attia, L. Beltran, A. D. Herde, and J. Hensen, “Architect Friendly: A Comparison of Ten Different Building Performance Simulation Tools”, in *The Eleventh International IBPSA Conference*, Glasgow, Scotland, 2009, pp. 204-211.

[21] M. S. Roudsari, and M. Pak, M., "Ladybug: A Parametric Environmental Plugin for Grasshopper to Help Designers Create an Environmentally-Conscious Design", in *The 13th Conference of International Building Performance Simulation Association*, BS2013. Chambery, France, 2013, pp. 3128-3135.

[22] AIA, (2021). *“Architect’s Guide to Building Performance: Integrating simulation into the design process – AIA”,* Available: www.aia.org [Accessed: 10 May 2022].

[23] T. Henin, (2022). *“Building Energy Analysis: A Comprehensive Guide”,* Available: www.oneistox.com › blog › building-energy-analysis-guide [Accessed: 21 July 2022]

[24] H. Yang, (2020). *“Architectural Roaming Animation Based on VR Technology”.* Available: https://doi.org/10.1007/978-3-030-62746-1_55 [Accessed: 5 August 2022].

[25] T. Dounas, (2020). *“Animation as a computational framework for architectural design composition”,* Available: https://doi.org/10.1080/00038628.2019.1709037 [Accessed: 7 June 2022].

[26] D.G. Aliaga, P. A. Rosen, and D. R. Bekins, "Style Grammars for Interactive Visualization of Architecture”, *IEEE Transactions on Visualization and Computer Graphics*, vol. 13, no. 4, pp. 786-797, 2007.

[27] M. Rohani, M. Fan, and C. Yu, (2014), *"Advanced visualization and simulation techniques for modern construction management"*, Available: https://doi.org/10.1177/1420326X13498400 [Accessed: 15 May 2022].

[28] R. Mathur, “3d Printing in Architecture”, *International Journal of Innovative Science, Engineering & Technology*, vol. 3, no. 7, pp. 583-591, 2015.

[29] J. Maeda, (2005). *"Current Research and Development and Approach to Future Automated Construction in Japan"*, Available: https://doi.org/10.1061/40754(183)39 [Accessed: 16 May 2022].

[30] X. Wang, and P. E. Love, “BIM + AR: Onsite Information Sharing and Communication via Advanced Visualization", in *The 2012 IEEE 16th International Conference on Computer Supported Cooperative Work in Design*, 2012, 850-855.

[31] S. Rao, (2022). 10 Examples of Artificial Intelligence in Construction, The Benefits of AI in Construction. Available: constructible.trimble.com › the-benefits-of-ai-in-construction [Accessed: 12 August 2022].