The utilization of machine learning techniques in the building design stage: a qualitative review

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ABSTRACT

Machine learning (ML) is a subdivision of artificial intelligence (AI) technology that has been extensively researched and applied in the building and construction industry for the past few years, particularly in the building design process. It yields significant benefits to the sector through its learning method that not only offers automation for repetitive complex design tasks and evaluation for decision-making functions but also optimization of building performances. This study investigates the existing exploration of the machine learning techniques utilized in the building design process to improve both the performance and result of the building design in the early design stage. From the 27 publications discussed in this paper, the Genetic Algorithm was the most utilized technique in the building design research area, followed by Neural Network. However, the employment of machine learning in this area mostly focused on particular building aspects, creating an opportunity for further studies to develop comprehensive building design solutions through the machine learning approach.

Keywords: *machine learning, building, design generation, algorithm*

INTRODUCTION

Like many other industries, building and construction industry is experiencing a digital transformation that has emerged from the advancement of information and data technology, enhancing computers and automation, coupled with smart systems and powered by data and machine learning. This industrial revolution has been widely adopted in the industry through the employment of digital technologies, sensor systems, intelligent machines, and smart material in its process (Berawi, 2020).

Machine learning (ML) is a subdivision of artificial intelligence (AI) that equips a system with the ability to learn and improve on its own through experiences without being programmed (Kubat, 2017). ML is a process by which a machine is trained using historical data of input-output to adapt to new data independently from the human intervention to solve problems in a wide range of areas (Hong et al., 2020; Jordan & Mitchell, 2015).

ML employments have been extensively developed in the building sector, primarily on the aspect of energy and carbon efficiency, for it is responsible for over one-third of global primary energy consumption and about 40% of the global direct and indirect CO2 emissions (W. Huang et al., 2017), as well as on the aspect of occupant well-being where people spend about 87% of their time inside the buildings (Klepeis et al., 2001). ML approach has been used as a tool to optimize building performance, thus promoting sustainable cities concerning the environment aspect by reducing energy consumption and greenhouse gas (GHG) emissions through the design of high-performance buildings.

Previous review studies in these past five years have given valuable contributions that summarized relevant research regarding machine learning applications in buildings. However, each of those studies only focused on specific building aspects, such as daylight (Ayoub, 2020), energy consumption (Bourdeau et al., 2019; Runge & Zmeureanu, 2019; Sun et al., 2020), occupancy (Dai et al., 2020; Saha et al., 2019), and safety management (Asadzadeh et al., 2020). This study attempts to identify the utilized ML approaches through a qualitative literature review to address this gap. This paper is expected to provide an up-to-date reference for both policymakers and practitioners to expand their knowledge in the utilization of ML techniques in designing sustainable high-performance buildings, which can make a contribution towards the achievement of sustainable development goals (SDGs) by increasing energy efficiency in buildings (SDG 7) and reducing the impacts of GHG emissions on the climate (SDG 13) that play a significant role in making cities sustainable (SDG 11) through technological innovation (SDG 9). By fostering digital technology, the development of smart cities can be accelerated in Pacific Rim nations to tackle the issues caused by the inevitable global climate change.

MATERIAL & METHODS

This study adopted qualitative analysis as the research method, which uncovers the current research development using specific qualitative measures for systematically collecting, analyzing, and interpreting data. The data collection process was coupled with an inclusive approach, indicating the diversity of qualitative analysis based on the relevance to the topic studied, the level of methodology confidence, and the depth of information provided.

The authors collected works published over these past ten years (2010-2020) regarding ML in the building design stage from Scopus, selected as the primary database for the articles reviewed due to its wider range of peer-reviewed scientific publication coverage and its faster indexing process escalating the retrieval for recent publications (Miraj et al., 2020). Only journal articles and conference proceedings were included; hence, bias from inadequate peer-review process can be reduced. The search teams used to collect papers from the Scopus database were ensured to cover three main fields of the customized advanced search, including title, abstract, and keywords (see Table 1).

After the titles and abstracts were screened for relevance to the research objective using inclusion/exclusion criteria, the selected 51 publications were then retrieved and read to verify their relevance. After conducting the review process, there were 19 publications deemed irrelevant, and five papers were found to be similar to some particular topics and methods used in other papers; hence the most recent ones with better data quality were preferred. The remaining 27 were qualitatively analyzed and classified based on the categorization of ML applications in the building design process adopted from Hong et al. (2020), including (1) parametric design that optimizes building performance; (2) generative design that automates design rule implementation; and (3) design evaluation that helps with the decision-making process. ML techniques used in each publication were also discussed. A meta-analysis table is presented to demonstrate the findings and to draw off the conclusion.

Category	Search terms	Selection Criteria	
		Inclusion	Exclusion
system	"machine learning"	Publications (journal articles and conference proceedings) on ML in the building design process	Books, book chapters, editorial notes, conference review, Non-English papers
algorithm	artificial neural network", "clustering", "linear regression", "genetic algorithm", "support vector machine", "bayesian", "random forest", "generative adversarial networks"		
planning stage	"project planning", "construction planning", "building plan", "building design", "conceptual design", "architectural design", "architectural space", "parametric design", "generative design", "design evaluation"		
building concept	"green building", "sustainable building", smart building", "healthy building"		

Table 1: List of utilized search terms

RESULTS & DISCUSSION

The 27 publications selected were published from 2013 to 2020. More than a third were published in 2019 alone (n=11) and followed by 2020 (n=5), indicating that interest in this research was significantly rising in the recent period. Furthermore, the examination of the origin of publications based on the affiliation of the first author shows that majority of the selected papers were contributed by United States (n=6) and China (n=6), followed by United Kingdom (n=2), Denmark (n=2), and Turkey (n=2), signifying that studies have been massively conducted in various countries for the last seven years. The outlets of these publications include Automation in Construction (n=6) and International Journal of Architectural Computing (n=4), followed by other renowned journals.

ML techniques for parametric design

The exploration in parametric design is conducted by inputting parameters to generate forms with optimal performance. Lin et al. (2013) proposed a model to calculate energy consumption and give suggestions on the energy-saving optimization using the combination of building parameterization and Genetic Algorithm (GA), while Ercan & Elias-Ozkan (2015) used the combination of parametric tools with an evolutionary algorithm as a method to generate design alternatives for shading devices that optimizes daylight and minimizes immoderate solar heat gains. Lin & Gerber (2014) utilized GA to support the design process by considering energy performance as feedback through the development of the Evolutionary Energy Performance Feedback for Design (EEPFD) design framework. Bianconi et al. (2019) also used GA to develop a model to inform the cross-laminated timber's customization process in the initial design stag

Harding & Shepherd (2017) proposed a new approach that combines graph-based parametric modeling with genetic programming, called Meta-Parametric design. From the performance test to the daylight, internal flow area, spatial connectivity, building heat, and views to city landmarks, it was indicated that this method has the potential as an alternative approach to widen the design exploration while maintains the graph representation qualities in the early design stage. Furthermore, a study by Karaoğlan & Alaçam (2019) focused on designing mass customization of disaster-relief settlemee.nts that respond to diverse users and disaster circumstances by proposing a digital model defined by a growth algorithm altered with Multi-Objective Genetic Algorithms (MOGA), while the evaluation for the various configurations through objective functions was conducted using Fuzzy Neural Tree (FNT) approach, and the combination of Neural Networks and Fuzzy Logic.

However, the utilization of GA for the parametric design was challenged by Wortmann (2019), which recommended other techniques such as Opposum's RBFOpt and Goat's Direct as alternatives.

Tamke et al. (2018) employed artificial neural networks (ANNs) to leverage a data-rich environment as a new practice for architectural design, while Lorenz et al. (2020) used it to discover the relationship between design parameters and the predicted daylight performance in order to explore the generation of geometrical design solutions. On the other hand, Liu et al. (2020) used the Clustering algorithm as the data mining method to find design patterns from the big data of existing architectural designs available on the internet, delivering an innovative building design approach.

ML techniques for generative design

Generative design method provides design solutions by meeting particular design parameters and goals. With the development of emerging technologies, computational generative design now uses AI algorithms in the design exploration process. Talbourdet et al. (2013) proposed an approach utilizing NSGA-II to design high-performance buildings by taking into account the energy characteristics and building regulations regarding accessibility, fire safety, earthquake risk, and user demand aspects.

GA was combined with an optimization tool to create a simulation to build a massing system to obtain optimal design solutions regarding building location and building floor area in the study by Huang et al. (2015). Meanwhile, Song et al. (2016) proposed an alternative design method based using the Implicit Redundant Representation Genetic Algorithm (IRRGA) claimed to be suitable for unstructured problem formulation in the design exploration with symmetry, structure, circulation, and façade selected as the design objectives. Furthermore, Tafraout et al. (2019) proposed a GA-based innovative approach in deriving potential structural configurations that can meet the preset measures and structural design requirements. On the other hand, Jalali et al. (2020) used GA to optimize the form and façade of office building designs.

As et al. (2018) presented the utilization of deep learning approaches in generating conceptual building design, where it was trained and used for evaluating existing designs merging them into new compositions, and generating new design using Generative adversarial networks (GAN) algorithm. Moreover, Newton (2019) explored the potential of GAN as a design tool capable of generating building plans, façade, and 3D massing models, while Thomsen et al. (2020) employed neutral network and GAN to generate fabrication data from interpreted design information and to predict the bent shape of knitted structural material.

Bei et al. (2019) used Graph Convolutional Neural Network (GCNN) combined with deep neural network (DNN) to develop an algorithm framework that performs building group and pattern recognition tasks, aimed to describe the spatial correlation between buildings and its nodes. In comparison, Xia et al. (2020) proposed a technique to generalize new residential building design styles using the radial basis function neural network (RBF-NN) model to explore the classification and prediction of the complex features and style categories.

Support Vector Machines (SVMs) can be used to develop a design solution addressing measurement predictions of building performance capable of learning architectural style from a style dataset to generate new designs (Strobbe et al., 2016). Chang et al. (2019) applied a reinforcement learning (RL) algorithm to propose a methodology combining generative design approach with parametric performance modeling to identify the relationships between design parameters of urban geometric forms with urban's energy performance and environmental quality. Furthermore, the Bayesian

Network technique was applied to select the most energy-efficient HVAC systems by taking into account the energy consumption factors classified from the data of energy-efficient buildings (Tian et al., 2019).

Through a combination of the Markov decision process (MDP) and a mathematical framework, Karan & Asadi (2019) proposed an "intelligent designer" system assisting the decision-making process to improve building design. Meanwhile, Rezaee et al. (2019) developed a systematic framework for the design decision-making process related to energy efficiency without needing simulation by developing an inverse procedure that calculates thermal energy performance parameters.

Authors	Year	Focus	Category			ML Approach
			generative	parametric	evaluation	
Lin et al.	2013	energy consumption		√		GA
Strug	2013	spatial relationship and design component arrangements			√	classification: kernels
Talbourdet et al.	2013	energy, cost	√			NSGA-II
Lin & Gerber	2014	energy		√		GA
Ercan & Elias-Ozkan	2015	daylight		√		GA
Huang et al.	2015	building mass	√			GA
Song et al.	2016	structure, façade	√			IRRGA
Strobbe et al.	2016	style	√			SVMs
Harding & Shepherd	2017	daylight, spatial connectivity, heat, and views to landmarks		√		Genetic Programming
As et al.	2018	architectural function	√			DNN
Tamke et al.	2018	design fabrication		√		ANN
Newton	2019	plan, style, façade	√			DL - GAN
Feng et al.	2019	environmental performance			√	fuzzy C-means
Bei et al.	2019	building pattern	√			DNN
Chang et al.	2019	energy	√			RL
Wortmann	2019	structure, energy, daylight		√		RBFOpt
Bianconi et al.	2019	timber structure		√		GA
Karan & Asadi	2019	windows	√			MDP
Karaoğlan & Alaçam	2019	shelter design		√		Fuzzy Neural Tree
Rezaee et al.	2019	energy	√			Linear Regression
Tian et al.	2019	HVAC	√			Bayesian Network
Liu et al.	2020	architectural design patterns		√		Clustering
Thomsen et al.	2020	architectural design fabrication	√			GAN
Tafraout et al.	2020	structure	√			GA
Xia et al.	2020	style	√			RBF-NN
Jalali et al.	2020	form and façade	√			GA
Lorenz et al.	2020	daylight		√		ANN

Table 2: Meta-analysis of machine learning techniques in the building design process

ML techniques for design evaluation

Strug (2013) used kernel functions of GA classification to solve designers' problem that deals with the evaluation of the floor layout design quality. In contrast, Feng et al. (2019) developed a quantitative method utilizing ML and parametric design approach to assess building environmental performance, which used the fuzzy C-means clustering method to extract case-based design knowledge based on the design scenarios and environmental performance assessment database. The summary of the discussed papers can be seen in Table 2.

ML techniques for high-performance building design

From the discussed papers above, ML algorithms were mainly employed in the design stage to optimize the design and physical form of a building to achieve optimal energy and sustainability performances. Such as some studies conducted by Lin et al. (2013), Talbourdet et al. (2013), Lin & Gerber (2014), Tian et al. (2019), and Rezaee et al. (2019) aimed to optimize building energy consumption in buildings, while Chang et al. (2019) attempted to optimize energy performance in the urban scale. Furthermore, ML was explored in studies by Ercan & Elias-Ozkan (2015), Harding & Shepherd (2017), and Lorenz et al. (2020) to optimize daylight performance. Only a small number of papers found optimizing more than one building performance, for instance, Song et al. (2016) with their study exploring structure and façade designs, and Wortmann (2019) that covered not only energy and daylight but also structural design.

As one of the critical elements of future sustainable cities, buildings need to be designed with a consideration to energy use and natural resource efficiency that are environmentally responsible while keep maintaining high-quality indoor environment for its occupants (Beetge et al., 2018). Therefore, ML techniques in the building sector must be utilized to achieve these design objectives.

CONCLUSION

The emerging technologies through the advancement of AI and ML have brought new approaches capable of automatically generating and evaluating building designs that help designers improve he design processes and solutions' performances. From the review done to the selected publications, GA can be considered the most popular technique used, which is in accordance with the situations faced in building research where the available information is usually in the form of performance measurement. It is then followed by a neural network where the learning route is done by processing inputs to form weighted results.

ML has been used to create tools to automate design and to model prediction, in which most of them were focused only on one or several aspects of sustainable building design, starting from parameters of energy and environmental performance to physical building forms comprising space, building components, structure, mass, and styles. Therefore, we argue that the employment of ML in building design aimed to optimize building performance should comprehensively take into account all sustainable building attributes as an effort to build future’s smart and sustainable cities through the delivery of high-performance buildings.

Developing building design that integrates major building performances such as energy, environment, productivity, cost-benefit, and other sustainable aspects can be a long and complicated process. Fortunately, AI technology provides digital solutions through automation that allows planners to solve design challenges and to optimize the process and the performance of the designs. Moreover, during this Covid-19 pandemic, the utilization of technology-driven innovation, such as machine learning, is essential in helping companies maintain their business, particularly in the built environment and construction industry that has a significant contribution to sustainable economic development.

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