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Metamodel-based design optimization of structural one-way slabs based on deep learning neural networks to reduce environmental impact

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ABSTRACT

This article presents a methodology for the construction and use of metamodels with Deep Learning (DL) methods that are useful for making multi-criteria decisions in the design and optimization of one-way slabs. The main motivation behind this research has been to examine the possibilities of improving slab design by including this methodology in future tools, which is capable of calculating thousands of solutions in real time based on the designer's specifications. The process of creating these metamodels begins by developing a database of millions of combinations of slab designs. These combinations are calculated with a heuristic algorithm that provides the following results: rigidity, deflection, cost per square meter, CO_2 emissions and embodied energy. Once a database including the entire universe of possible solutions has been created, a metamodel is developed that is capable of "condensing" the implicit knowledge contained in the database. This metamodel is included within a Decision Support System (DSS) that produces thousands of solutions for slabs that all comply with a range of specifications designated by the design plan. Furthermore, the methodology described herein proposes the use of Pareto-optimal solutions and graphic tools to help designers make multi-criteria decisions regarding the solutions that best fit their needs. A case study is presented to illustrate this proposal: optimizing slab design in two buildings according to technical, economic and sustainability criteria. The results indicate that the multi-criteria solutions obtained would entail a significant reduction in both emissions and embodied energy as compared to mono-criteria solutions, without significantly increasing costs.

1. Introduction

The construction industry constitutes a business sector that consumes great quantities of energy while also emitting large amounts of CO_2. Breaking down this consumption, building a reinforced concrete structure represents between 59.57% and 66.73% of the total energy consumed [1]. Likewise, a building's use phase represents a large part of total CO_2 emissions. Therefore, much research in recent years has focused on improving the energy efficiency of building operation [2]. And as the Net Zero Energy Building concept spreads rapidly, reducing CO_2 emissions and the amount of energy consumed during the manufacture of construction materials is also gaining importance. Thus, adequate design of reinforced steel elements must consider energy consumption and emissions generated during material production.

Over the past few decades, numerous studies have investigated optimizing the design of reinforced steel elements in terms of cost and emissions. For example, Park et al. [3] applies genetic algorithms (GA) to design composite columns in high-rise buildings (35 stories) and identifies specific dimensions and reinforcements that reduce cost and CO_2 emissions. Another study focuses on designing bridge piers and uses hybrid multi-objective simulated annealing (SA) algorithms, and incorporates the aforementioned objective functions (cost and emissions), as well as reinforcing steel congestion [4]. Two studies on designing reinforced concrete footings that reduce cost and CO_2 emissions should be mentioned. The first study utilizes the optimization methodology known as Big Bang-Big Crunch to optimize isolated footings in accordance with the specifications prescribed by the American Concrete Institute (ACI 318–11) [5]. The second study develops a new method called hybrid firefly algorithm (FA) to apply to spread footing [6]. Regarding the optimum design of reinforced concrete retaining walls, Khajehzadeh et al. [7] present and apply a new version of the gravitational search algorithm based on opposition-based learning (OBGSA). In this same line of research, Yepes et al. [8] present an approach to a methodology using a hybrid multistart optimization

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strategic method based on a variable neighborhood search threshold acceptance strategy (VNS-MTAR) algorithm. Another study examines a different reinforced concrete component subject to bending stress: high performance concrete for simply supported beams is designed using the same VNS algorithm [9]. And lastly, Paya-Zaforteza et al. implement a SA algorithm [10] to examine combinations of compression and stress components (columns and beams) according to Spanish building code. All these studies demonstrate the complexity involved in creating building designs that cut down on costs and emissions.

In the case of concrete slabs, how to reduce costs through better design has been studied extensively. An example of such a study can be found in the research of Merta and Kravanja [11] who include labor costs in overall manufacturing costs. Another study conducted by Tabatabai and Mosalam [12] demonstrates how two programs, designed for two separate tasks, can be integrated in an environment for performance-based reinforcement design that guarantees cost-effectiveness through optimization and structural safety through satisfying serviceability conditions. Kaveh et al. also conduct various studies focused on optimizing costs in the design of one-way reinforced concrete slabs. For example, their first study uses a harmony search algorithm and also conducts a parametric study examining the effects of beam span and loading [13]. In a later study, the authors include the materials used and the construction cost of the structure in the objective function. In this case, optimization is carried out by the improved harmony search (IHS) algorithm and the results are compared to those of the charged system search (CSS) [14]. These same authors, in another later study, compare and evaluate the capacities of several metaheuristic algorithms for optimizing the costs of a concrete slab [15]. In 2016 Kaveh and Ghafari analyzed a hybrid concrete and steel structure, and in this case optimizing the cost function is performed by enhanced colliding body optimization (ECBO) [16]. Similarly, Ahmadi-Nedushan and Varaee [17] evaluate the performance of different algorithms and demonstrate that particle swarm optimization (PSO) is a promising method for design optimization of structural elements. Other studies point out the need to incorporate additional parameters into design criteria. For example, Liébana et al. [18] analyze CO_2 emissions generated by different construction techniques, Del Coz et al. [19] incorporate thermal behavior in their proposal, and Fraile-García et al. [20] consider life cycle assessment (LCA) in the design of reinforced concrete structures.

In recent years, various decision support systems (DSS) have been developed that use machine learning models to support structural design and maintenance. For example, some research has investigated how to improve the prediction of shear resistance performance in large span beams using support vector machines (SVM) [21] or artificial neural networks (ANN) [22]. Other studies optimize the design of beams without stirrups through evolutionary polynomial regression [23] or gene expression programming (GEP) [24], with the objective of adapting those formulas included in the regulations. Other variables studied in relation to concrete are as follows: compressive strength through ANN [25][26], compressive strength of high performance concrete with adaptive network-based fuzzy inference system (ANFIS) [27], and tensile strength with GEP [28], creep with ANN [29], and abrasive wear with various models based on ANN, fuzzy logic model with genetic algorithm and general lineal models (GLM) [30]. In all of these studies, the models are tested with experimental testing data and demonstrate satisfactory results. Other authors, on the other hand, utilize models to determine risk factors and corrective measures for infrastructure. For example, Cheng and Hoang [31] estimate the risk score for bridge maintenance with the evolutionary fuzzy least squares SVM. Okasha and Frangopol also [32] develop an advanced model for life-cycle performance prediction and service-life estimation of bridges. Similarly, because reinforced concrete structures are subject to corrosion, tools have been proposed to support decision-makers in planning maintenance interventions with the fuzzy time-dependent method [33] or through ANN whose weights are optimized with an imperialist competitive algorithm (ICA) [34].

As more parameters are incorporated into structural design, the decision-making process becomes more complex. Thus, Yepes et al. [35] optimizes bridge design based on economic, structural security and environmental sustainability objectives. Castilho and Lima [36] utilize genetic algorithms (GA) to minimize the costs of continuous one-way slabs in which the concrete characteristics and joist spacing are varied. Hailong Zhao et al. [37] incorporate a greater number of design variables and construction factors and employ metamodels applied to the structural design of metal trusses to effectively reduce the computational time necessary. Gharehbaghi and Khatibinia [38] utilize metamodels trained with real data to optimize seismic design. Another study illustrates the effectiveness of using metamodels to design concrete barriers [39].

All the above-mentioned studies are based on machine learning methods, or evolutionary and bio-inspired methods of optimization. Within this field, research conducted in recent years with deep learning (DL) has advanced the design of support systems for the decision-making process. This type of technique, many of which having evolved from ANN, aim to model information with various levels of abstraction by using different non-linear interconnected layers. Among the diverse DL techniques, architectures corresponding to "deep neural networks" (DNN) are those techniques most used in supervised modeling. In this case, DNN are artificial neural networks (ANN) formed by multiple layers of neural networks with a high number of non-linear neurons per layer. Thus, DNN are often comprised of by three, four or more layers, with thousands of neurons in each one. These types of networks are very flexible which allows them to handle complex problems, but their downside is the risk of overfitting through training, and therefore losing their capacity to adequately explain the problem. To avoid this problem, current DNN training algorithms incorporate a range of mechanisms to reduce the risk of overfitting models.

Keeping in mind the current tendency to implement building information modeling (BIM) systems for structures, agile tools are necessary to make decisions during the design phase. Given this situation, combining structural analysis tools with search and optimization algorithms is considered a promising option [40].

This study proposes a methodology to develop metamodels based on deep-learning methods capable of working with multiple combinations of one-way slab design options to predict in real time: rigidity, deflection, cost per square meter, embedded energy and CO_2 emissions. These metamodels combined with other types of methods such as Pareto-optimal solutions or graphic tools can be included in decision support systems (DSS) to design and optimize one-way slabs. Such DSS can be useful for selecting the optimal design of slabs from a multi-objective point of view that takes into consideration technical, economic and sustainability criteria.

2. Methodology

2.1. Decision support system based on deep learning techniques

The decision support system (DSS) is based on a metamodel developed with deep learning (DL) techniques to optimize the structural design of one-way slabs in terms of economic, technique and sustainability criteria. The DSS incorporates a DL-metamodel (MetaDL) that is capable of quickly extracting thousands of construction solutions from stipulations indicated by the designer. Likewise, the DSS has search algorithms based on Pareto-optimals that limit the number of final solutions so that the designer is able to analyze them. To facilitate analysis of these solutions, the DSS includes graphic tools such as dendrograms and scatterplots that assist designers in choosing the most adequate solution for their proposals.