ARTIFICIAL INTELLIGENCE (AI) APPROACHES FOR THE ASSESSMENT OF BUILDING ELEMENTS THERMAL PERFORMANCE UNDER FIRE CONDITIONS

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ABSTRACT

Study of building configurations' fire performance has traditionally relied on sample or full-scale destructive testing. Use of the powerful simulation tools currently available, in conjunction with Artificial Intelligence (AI) algorithms, is a promising approach that could reduce the need for such testing. This study examines the different types of AI, widely used in various engineering applications, and explores the potential of integrating those to the field of building materials and fire engineering. Use of physics simulation software and development of an Artificial Neural Network (ANN) provides a first insight to the prospect of such methodologies. Despite any limitations, making predictions without destructive testing is a possibility. Such an approach can stimulate new research interest in the field of fire testing of building materials and can potentially lead to the elucidation of the thermal response of building elements. The variety of Artificial Intelligence algorithms and their adaptability to suit the available data constitutes a research method worth exploring further. Applying knowledge from other civil engineering fields, can give a considerable advantage to the research of fire performance of conventional building elements.

KEYWORDS

Artificial Intelligence; Artificial Neural Networks; Building Element Assemblies; Fire Performance, Thermal Insulation

1. INTRODUCTION

This study is organised in two distinct parts; the first one providing a brief introduction to Artificial Intelligence and the second presenting a relevant case study.

Traditionally, the research of fire performance of individual building materials or building element assemblies relied on full scale or model destructive testing. Despite any disadvantages that these techniques have, they were the dominant scientific investigation method for decades. It was only when the technological advancement in the field of computing, which provided with the necessary computational power and simulation software, that enhancement and even replacement to some extent of the traditional approach was made possible. Artificial Intelligence (AI) would not come to the foreground for several years and it would only start being integrated in the workspace in the 1990's [1]. The concepts and theoretical foundation was set a long time before that, with the first mention of AI being in 1956 [2].

The core principles of Artificial Intelligence (AI) are explained in the following paragraphs. A distinction between the different types of AI is made and the main advantages they offer are compared against the methods followed traditionally. Then, focus is given to those types of AI that can be utilised in the research of fire performance of building element assemblies. The powerful algorithms of Artificial Neural Networks, that can make predictions about fire performance by identifying hidden patterns within the input data, are specifically explored.

Once the types of AI and their main features and advantages are clear, the study proceeds to examine some of their most recent research and industrial applications which expands beyond the civil and structural engineering field.

The introduction to AI and its use in engineering fields, is followed by a relevant "work in progress" case study. The steps of building an Artificial Neural Network architecture are reviewed and the initial observations and considerations of such an approach are assessed.

This aims to stimulate conversation about the applications of Artificial Intelligence, its advantages and drawbacks and explore how it can further be used to enhance the scientific community understanding about fire performance of building element assemblies.

2. ARTIFICIAL INTELLIGENCE

2.1 Why is it worth studying fire behaviour through Artificial Intelligence

Before dedicating time and effort studying and understanding details about the different types and features of Artificial Intelligence algorithms, it is worth understanding why this is an approach worth exploring in the first place. The established techniques of destructive laboratory testing in combination with the computer simulation techniques have so far provided an adequate insight to the performance of building material and assemblies under fire loading. The big contribution of Artificial Intelligence algorithms is their ability to identify underlying patterns of interconnectivity between parameters in large volume datasets. They can quantify the contribution of each one of those factors to the development of the overall process under consideration. Knowing that the fire performance of building elements is generally a multiparametric phenomenon, constitutes AI an ideal candidate; given that appropriate input datasets are available from previous laboratory testing or computer simulation.

2.2 Advantages of Artificial Intelligence

By assigning weights to each parameter, depending on their contribution, AI significantly reduces the need for further testing to explore the impact of minor variations. This subsequently mitigates the costs and complexity associated to physically constructing appropriate testing facilities, sacrificial test models and training specialised technical personnel. It also allows obtaining new results rapidly since exploring a different test arrangement only requires digitally modifying parameters on the AI algorithm rather than conducting a new experiment. Similarly, it overcomes the problem of reproducibility of complex experiments that need to be reviewed and slightly modified.

The development of cloud based services, also allows the use of remote hardware to greatly increase the speed of algorithm execution and remove the need for costly, powerful in-house computers.

2.3 Considerations when using Artificial Intelligence

Inevitably, there are matters that need to be taken into account before use of AI is considered for any application. Some coding skills are required, introducing the need for further personal development of the researcher, or involving a data scientist to the team under the guidance of a leading civil engineer/building material scientist. The input data preparation process, called data "pre-processing", can be quite time consuming and complicated. Any mistakes during that process can lead to completely meaningless results or dysfunctional algorithm. This becomes even more difficult to control due to the very complex theoretical foundation and principles of Artificial Intelligence approaches.

To add to the complexity, the underling patterns that AI is employed to identify are usually incomprehensible to naked human eye, making the whole process a "black box". There is also very limited guidance and regulation in terms of standardising the development of AI algorithms, the quality of input data and required precision of output figures, adding to the uncertainty around implementation of AI techniques.

Finally, to make this operation work effectively a large amount of input data is necessary. This is not always available, making data production through physical testing or computer simulation an integral part of the process; which counteracts some of the main benefits of using AI in the first place.

3. PRINCIPLES AND MAIN TYPES OF ARTIFICIAL INTELLIGENCE APPROACHES

3.1 Placing Artificial Neural Networks in the globe of Artificial Intelligence

The term Artificial Intelligence (AI) refers to the science of developing appropriate algorithms which enable machines to deal with ill-defined, multiparametric or inherently open end problems, by approximation, resembling the human cognitive processes and thinking [3]. Other scientific fields such as neuroscience, computer science, mathematics and statistics overlap to provide the necessary structure and foundation for AI [4]. In reality, it covers several subsections, which could be grouped under four dominant areas; the Knowledge Based Systems, Neural Networks, Fuzzy Logic and Genetic Algorithms [5]. Machine Learning (ML) is a sub-class of AI which focuses on enabling machines to identify patterns in large volumes of training data and make predictions based on those trends [1]. Finally, Artificial Neural Networks (ANNs), belong in the class of Deep Learning (DL), a branch of ML.

3.2 The principles of ANNs functionality

ANNs incorporate multiple layers of interconnected neurons. Each neuron represents a feature of the input dataset and gets assigned with a weight depending on the contribution of that feature to the overall dataset trends. The weights are initialized with random numbers but get updated to more accurate values through the iterative process of "training". Training involves passing part of the data (training data sub-set) through the algorithm several times; usually in the order of hundreds. The algorithm is then "tested" by making predictions against the known values (supervised learning) of the test data sub-set (also called the "ground truth"). Depending on the rate of accurate

predictions against known figures, the algorithm is further optimised to ensure either higher predicting accuracy or to avoid becoming extremely attached to the given dataset constituting it unusable on new input data (also called "overfitting").

In the case of making predictions for fire performance of building element assemblies, the input data could be a combination of the results of traditional laboratory testing or simulation software output. By then amending the parameters of the algorithm and based on the trends of the known data, predictions can be made regarding parameter values of unknown/untested configurations.

4. RECENT APPLICATIONS OF ARTIFICIAL INTELLIGENCE

4.1 Various non-engineering fields using AI

Acknowledging the benefits that use of Artificial Intelligence brings into research, several scientific studies and industrial sectors have utilised these tools.

These range from identification of abnormalities to scans and imagery of various body parts in medical applications (use of Convolutional Neural Networks) [6], to handling and analysing the poly-parametric problem of solid waste management (use of Artificial Neural Networks and Genetic Algorithms) [7]. In the same direction, AI helps achieve a great degree of electrical automation and operations fault control [8] in several manufacturing sectors. Other common technological applications utilising some form of AI include text analysis and translation, speech and face recognition, self-driving cars [2] etc.

4.2 Using Artificial Intelligence in Civil & Structural Engineering

As described previously, AI is a promising approach in cases where high levels of uncertainty exist, parameter optimisation is necessary, and laboratory testing is not always feasible or practical [3]. Numerous structural and civil engineering challenges bear these exact characteristics making use of AI particularly attractive. This is clearly demonstrated by the vast amount of recent AI applications in the field of engineering.

Destructive testing of historic building fabric is generally not an acceptable investigation technique. AI can be an ideal alternative for investigating properties and moisture content of historic masonry walls [9]. Optimisation of the reinforcement needed in concrete structures can have significant technical and financial benefits and is a field that Artificial Neural Networks (ANNs) can be utilised [10]. ANNs in combination with other evolutionary algorithms, trained on a vast amount of previous failure and cracking observations, can help with the estimation of remaining service life of concrete decks [11] and timber superstructure of bridges [12] or detection of structural damage on beam-like structures [13]. A challenging design field is the geometrical optimisation of highly stressed components in structures; ANNs can provide with an efficient solution in this case too, as seen in aircraft engineering [14]. Finally, with sustainability becoming a matter of increasing priority and urgency, AI can contribute in diverse ways such as achieving optimal energy use while maintaining indoors thermal comfort [15], optimising the design and control of photovoltaic systems [16], handling the inherently uncertain and dynamic nature of pollution control and mitigation processes [17] and overcome the unpredictability of the incoming quality and flow rate of waste water in sewage treatment plant facilities [18].

4.3 Applications of Artificial Intelligence in Fire Engineering

At the moment, comparatively to other civil and structural engineering fields, there are fewer, but equally important, applications of AI, in the context of fire loading impact and performance of materials and building elements.

To combat the lack of regulations' symphony regarding the common building material properties to be used when considering fire load cases, ANNs and Genetic programming can be used to derive mathematical equations that implicitly incorporate such characteristics and generate universally applicable formulas [19], [20]. Based on that and through the spectrum of Artificial Neural Networks, evaluation of the bearing capacity of concrete under extreme fire exposure has been possible [21] as well as prediction of its fire induced spalling [22]. Similarly, the serviceability performance of timber beams exposed to fire can be assessed and predicted by developing ANNs [23]. Identical techniques have been used to identify and predict the properties of modern construction materials that have not yet widely been conventionally tested and understood [24]. Finally, aiding in the assessment of remaining structural capacity following exposure to fire, AI has been used to develop formulas predicting the impact of extreme loading (ie. fire) to building material properties [25].

5. CASE STUDY METHODOLOGY

5.1 Limitations and scope of work

The following study is still "work in progress" and this summary only aims to demonstrate the applicability of AI in the prediction of temperature development on the non-exposed face of wall assemblies under fire load on one side. At this stage, all results are preliminary and indicative of the algorithm's capabilities. A second phase of algorithm optimisation, further assessment of results, addition of more load cases and interpretation of the model in the form of mathematical formulas is necessary.

The application aims to predict the temperature of the non-exposed face of an untested configuration at random time.

5.2 Finite Element simulation and data extraction

With Artificial Intelligence, and Artificial Neural Networks in specific, being an effective tool for poly parametric problem analysis, the technique was employed for the study of heat transfer through a masonry wall element, exposed to fire on one side.

Several wall configurations were modelled and analysed using the physics Finite Element (FE) software Comsol. Specifically, 16 different samples, based on alternate combinations of parameter values, were developed and executed, monitoring each time how the temperature developed on the non-exposed face of the wall. The parameters and the values used are summarised on Table 1. Consequently, a large amount of data was extracted from the simulation software and used as input for the training of the ANN.

Table 1. Parameters and characteristic values used for the development of the different simulation samples.

Parameter	***Values***
Sample Ref	Smpl0 **|** Smpl1 **|**…**|** Smpl16
Brick Density	2000kg/m³ **|** 4000kg/m³
Thermal Cond. Coef.	0.40W/(mK) **|** 0.80W/(mK)
Thermal Emissivity	0.10 **|** 0.50 **|** 0.90
Insulation Thickness	0cm **|** 5cm **|** 10cm

Insulation Type	RW | EPS | No-Ins
Insulation Position	Int | Ext | Abs-Ins
Time	30s | 60s |…| 21600s
Temperature of non-exposed face	20°C upwards as the fire case progresses

The input data consisted of a 30 seconds step time series of the temperature development on the non-exposed face of the wall elements. To ensure that interconnectivity with the rest of the parameters was possible, those were introduced as separate columns on the dataset. After merging the data extracted from the different configurations, bringing the total to 38934 observations, the pre-processing phase commenced to achieve compatibility with the requirements of the ANN.

5.3 ANN architecture development

Following completion of the data preprocessing, the architecture of the ANN itself was developed. An input layer consisting of 7 neurons, number equal to that of the input parameters, preceded two hidden layers (deep learning algorithm). Those incorporated 12 neurons each, before converging into the output layer which only had a single neuron, representing the temperature of the non-exposed face at time stamp t. This is schematically summarised in Figure 1.

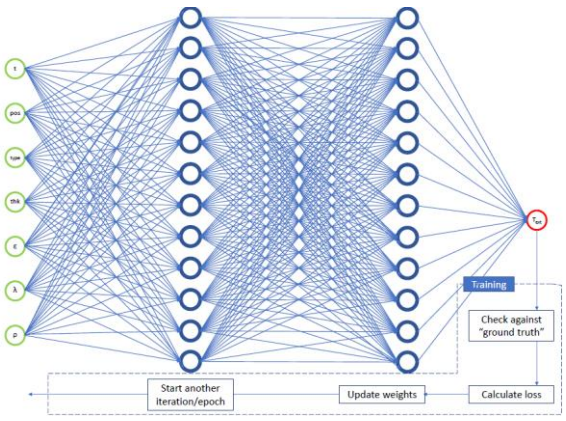

Figure 1. Schematic representation of the Artificial Neural Network architecture.

Since the predicted value was part of a continuous value range, the ANN was developed as a regression system and thus using the mean squared error loss function was considered most appropriate. The available dataset was divided on a 80% training and 20% test basis, before it was fed through the algorithm for 100 times (epochs).

6. CASE STUDY RESULTS AND DISCUSSION

Although this is a work in progress application with further optimisation of the algorithm and output assessment being necessary, the first results obtained were encouraging.

The algorithm made 7787 predictions (20% of the total dataset) and compared those to the ground truth (actual figures obtained from the simulation software). The average difference between the two was below 0.500°C, with a standard deviation of 0.711°C.

With original temperatures ranging from 20°C (ambient environment) to 267°C (non-exposed face temperature of non insulated wall), these figures are indicative of the power of the ANN. Steps need to be taken to ensure that overfitting is avoided and to establish a sequence that can be used effectively to predict the behaviour of samples completely separate from the existing dataset.

In this direction, it is considered that further trials with different hyper parameters, introduction of neuron dropout and optimisation techniques such as k-fold validation would ensure the development of a robust and versatile Artificial Neural Network.

7. CONCLUSIONS

The brief review of current applications of AI in the field of engineering shows how a set of powerful tools is developed with fast pace and is becoming available for analysis of complicated and poly-parametric challenges. The benefits AI offers in terms of analytical power, time and cost savings are great. Nonetheless, there are certain issues that need to be addressed and taken into account when such tools are considered for a specific application.

The field of fire engineering appears to be adopting such methodologies more slowly compared to other scientific disciplines. Given that the nature of fire and the situations deriving from it involve a great number of difficult to monitor and predict factors, AI can potentially offer an ideal approach to analyse and understand such cases.

A case study using Artificial Neural Networks to analyse fire and heat transfer was presented. Despite any limitations and need for further development, the initial performance of the model was satisfactory. In conjunction with FE analysis techniques, it inspires confidence that a versatile and powerful heat transfer prediction methodology can be developed.

Standardisation and regulatory guidance on the methods, quality and deliverables of AI development would be a great aid in this effort. Data availability is another issue, which could be resolved through cooperation of relevant scientific teams, review and processing of data already available from laboratory testing and simulation studies and real time input from the industry. The full capability of applied AI in fire engineering remains to be seen and a cooperative approach and constructive dialogue between different scientific disciplines, regulatory bodies and industrial entities is the initial step to be taken.

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