Application of an Artificial Neural Network Based Tool for Prediction of Pavement Performance

Adelino Ferreira[1], Rodrigo Cavalcante[2]
[1]Pavement Mechanics Laboratory, Research Center for Territory, Transports and Environment, Department of Civil Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal, adelino@dec.uc.pt
[2]Pavement Mechanics Laboratory, Research Center for Territory, Transports and Environment, Department of Civil Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal, rodrigo.cavalcante@student.uc.pt

ABSTRACT

Artificial Neural Networks (ANN) have provided a convenient and often extremely accurate solution to problems in all fields, and can be seen as advanced general-purpose regression models that try to mimic the behaviour of the human brain. This paper presents a briefly state-of-the-art of the application of ANN-based methods in pavement performance prediction. Then the paper presents the application of an ANN-based tool for prediction of the performance of Portuguese road pavements. The ANN structure is constituted by several partially or fully connected processing units (neurons), which are disposed in several vertical layers (the input layer, hidden layers, and the output layer). Associated to each neuron is a linear or nonlinear transfer function which receives an input and transmits an output. Each connection (link between two nodes in the network) is associated to a synaptic weight, which is a typical example of a network unknown to be determined during the network design process. The final part of the paper contains a reflection on the main difficulties encountered so far and presents the developments planned for the near future.

Keywords: Artificial Neural Networks; Pavement performance; Pavement management.

1. INTRODUCTION

Artificial Neural Networks (ANN) can be seen as advanced general-purpose regression models that try to mimic the behaviour of the human brain, although at present no ANN is anywhere near to recreating the complexity of the brain. However, the progress that has been made since their inception is remarkable, and it is certain that the development and applications of these algorithms will keep growing in the future [1, 2]. The adoption and use of ANN-based methods in the Mechanistic-Empirical Pavement Design Guide [3] is a clear sign of the successful use of ANNs in pavement engineering.

2. ANN APPLICATIONS IN PAVEMENT PERFORMANCE PREDICTION

In this section, a quick overview over the state-of-the-art application of ANNs in pavement performance prediction is addressed. The main ANN features used to predict pavement quality parameters are presented in Table 1. Figure 1 represents a general structure of an ANN with several input parameters, an input layer, two or more hidden layers, and an output layer that provides the value of the parameter which we want to predict. Prediction modelling of pavement deterioration, a stochastic and nonlinear phenomenon, is crucial for an effective Pavement Management System, where the goal is planning the maintenance and rehabilitation of pavements of the road network. According to Table 1, the multi-layer perceptron (MLP) is the most commonly used network type in pavement applications. Also according to this Table, the most used learning algorithms in pavement applications so far are Back-Propagation (BP), the most used, and Levenberg-Marquardt (LM). Tabatabaee *et al*. [4] proposed an ANN to predict pavement performance in terms of Present Serviceability Index (PSI), considering a Recurrent Neural Network (RNN) with 8 input layers, 5 hidden layers and 1 output layer (8-5-1 RNN), the LM learning algorithm, and the hyperbolic tangent transfer function. Further details about any topic regarding ANNs can be found in well-known books such as [2] or [5].

TABLE 1. ANN features employed in pavement performance prediction [6]

Parameter	Architecture	Learning algorithm	Hidden/output Transfer function
Roughness	x-15-4 WNN	BP	Mexican hat wavelet/linear
	3-50-50-2 MLP	LM	Hyperbolic tangent/linear
	9-80-50-30-1 MLP 9-3-1 MLP 9-8-1 MLP	LM	Hyperbolic tangent/linear
Skid resistance	2-3-1 MLP	LM	-
Cracking	3-150-3 MLP	BP	-
	8-40-40-1 MLP 9-40-40-1 MLP 7-40-40-1 MLP 9-40-40-1 MLP	BP	Logistic
	26-7-7-7-1 MLP 26-5-5-1 MLP 29-7-7-7-1 MLP 31-6-6-1 MLP	BP	Hyperbolic tangent/-
	4-7-2 MLP	BP	-
	8-12-8-2 MLP	BP	Logistic
PCR	5-3-2-1 MLP	BP	Logistic
PSI	8-5-1 RNN	LM	Hyperbolic tangent/-

KEY: PCR - Pavement Condition Rating; PSI - Pavement Serviceability Index; WNN - Wavelet Neural Network; MLP - Multi-Layer Perceptron; RNN - Recurrent Neural Network; BP - Back-Propagation; LM - Levenberg-Marquardt.

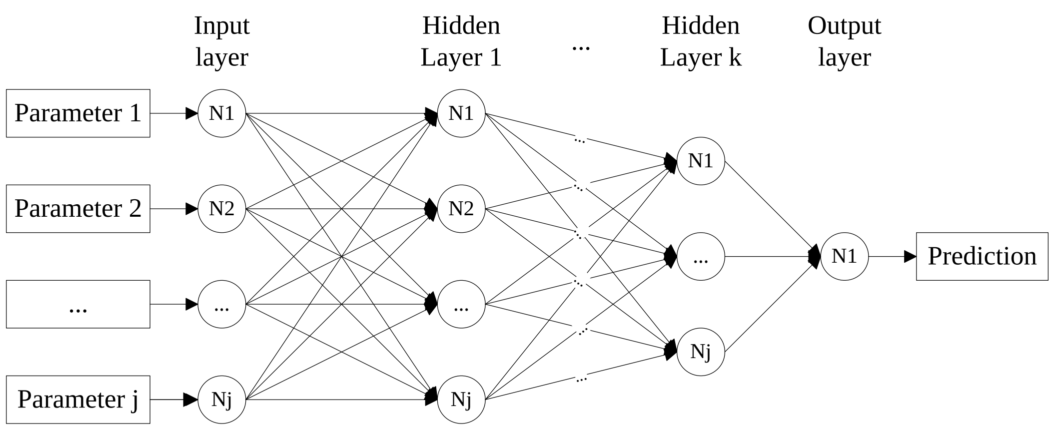

FIGURE 1. The general structure of an ANN

3. APPLICATION OF AN ANN-BASED TOOL TO PORTUGUESE PAVEMENTS

The ANN structure (Figure 2) can be seen as a fully connected processing units (neurons) network, which are disposed in several vertical layers (the input layer, hidden layers, and the output layer). Associated to each neuron is a linear or nonlinear transfer function which receives an input and transmits an output. Each link between two nodes in the network is associated to a synaptic weight, which is a typical example of a value to be determined during the network design process. The way in which the neurons of the ANN are structured and linked define what is known as the network architecture. This is a feedforward ANN, i.e. the signal flow through the network progresses in a forward direction from left to right, and on a layer-by-layer basis, and exhibits at least the input layer, one hidden layer and the output layer. By adding one or more hidden layers, the network is enabled to extract higher-order statistics from its input [2]. Nevertheless, we want to test other network types (WNN, RNN, etc.). Figure 2 represents a 4-layer feedforward network, also referred to as 5-3-3-1 (5 input nodes, 3 hidden neurons in the first hidden layer, 3 hidden neurons in the second hidden layer, and 1 output neuron). As can be seen, each node in each layer links to every node in the next layer, typically called a fully-connected network, i.e. the output signals of one layer will serve as input signals of the next layer, unless stated otherwise. In this case the network is partially connected (PC). Nodes in each layer do not connect to each other and no connections across the input and the output layers are allowed.

Each processing unit (neuron) plays a crucial role in the ANN's performance. There are three basic elements in a typical model of a neuron (Figure 3): (i) connecting links, also called synapses, between each input signal (X_j) and neuron k, which are characterized by their synaptic weights (W_{jk}); (ii) a summing junction (S_k) to add up the weighted input signals that converge to the neuron; and (iii) a transfer function (φ_k) which receives S_k and the neuron's bias (b_k) as input and provides neuron's output (Y_k). In the ANN design, the transfer functions are user-defined (e.g. logistic, linear). The synaptic weights and the neuron's bias need to be computed through the learning process. The learning algorithms to be considered in this ANN are Back-Propagation (BP) and Levenberg-Marquardt (LM).

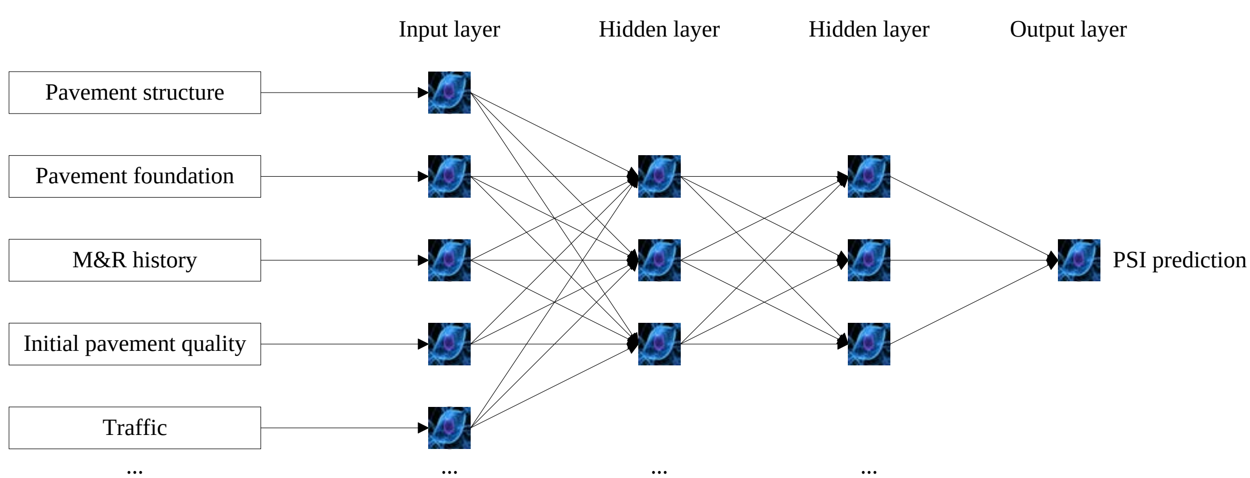

FIGURE 2. ANN structure

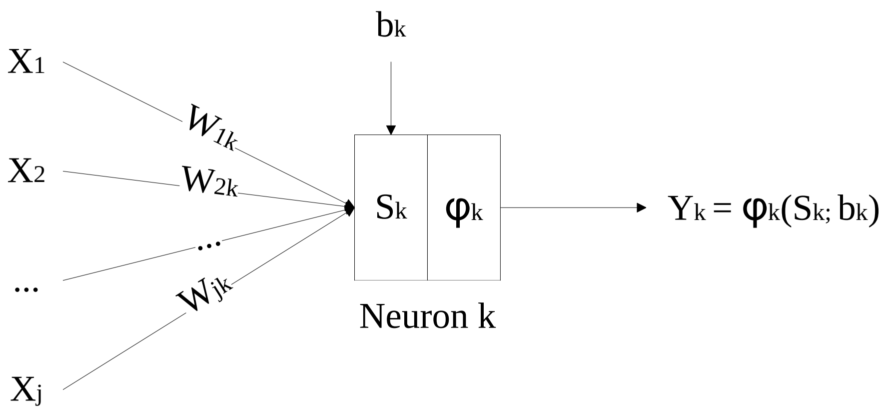

FIGURE 3. Modelling a neuron

4. CASE STUDY

The ANN-based tool will be applied to the pavements of the Portuguese road network in collaboration with the company called *Infraestruturas de Portugal*. Figure 4 presents the sixteen different pavement structures considered in the Portuguese manual [7]. This manual recommends pavement structures in relation to traffic class, from T1 to T6, and pavement foundation class, from F1 to F4 (Tables 2 and 3). The traffic class is defined by the number of 80 kN equivalent single axle load (ESAL) applications for a design life or design period calculated depending on the annual average daily heavy-traffic ($AADT_h$), the annual average growth rate of heavy-traffic (g_h) and the average heavy-traffic damage factor or, simply, truck factor (α). On the other hand, the pavement foundation class is defined by the California Bearing Ratio (CBR) value and the design stiffness modulus (E). The Portuguese manual considers 16 different flexible pavement structures for different combinations of traffic and pavement foundation. These pavement structures were defined using the Shell pavement design method [8], with verification by using the University of Nottingham and Asphalt Institute pavement design methods [9, 10].

		Flexible Pavement Design Alternatives															
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
HMA Surface Layer	Thickness (mm)	40	40	40	40	50	50	40	50	50	60	50	60	50	60	60	60
	Material	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete
HMA Base Layer	Thickness (mm)	60	80	120	140	140	160	180	170	190	180	200	200	230	220	240	260
	Material	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete	Asphalt Concrete
Sub-base Layer	Thickness (mm)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
	Material	Granular	Granular	Granular	Granular	Granular	Granular	Granular	Granular	Granular	Granular	Granular	Granular	Granular	Granular	Granular	Granular
Total HMA Layer Thickness (mm)		100	120	160	180	190	210	220	220	240	240	250	260	280	280	300	320

Illustration

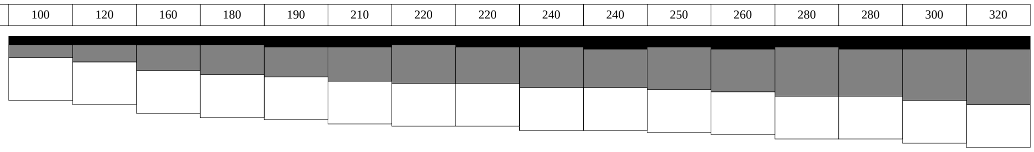

FIGURE 4. Pavement structures of the Portuguese manual

TABLE 2. Characteristics of pavement structures

Pavement ID	Surface layer				Base layer				Sub-base layer				SN
	Material	t_S (cm)	E (MPa)	ν	Material	t_B (cm)	E (MPa)	ν	Material	t_{Sb} (cm)	E (MPa)	ν	
P1	AC	4	4,000	0.35	AC	6	4,000	0.35	G	20	200	0.35	2.36
P2	AC	4	4,000	0.35	AC	8	4,000	0.35	G	20	200	0.35	2.63
P3	AC	4	4,000	0.35	AC	12	4,000	0.35	G	20	200	0.35	3.17
P4	AC	4	4,000	0.35	AC	14	4,000	0.35	G	20	200	0.35	3.43
P5	AC	5	4,000	0.35	AC	14	4,000	0.35	G	20	200	0.35	3.61
P6	AC	5	4,000	0.35	AC	16	4,000	0.35	G	20	200	0.35	3.87
P7	AC	4	4,000	0.35	AC	18	4,000	0.35	G	20	200	0.35	3.97
P8	AC	5	4,000	0.35	AC	17	4,000	0.35	G	20	200	0.35	4.01
P9	AC	5	4,000	0.35	AC	19	4,000	0.35	G	20	200	0.35	4.28
P10	AC	6	4,000	0.35	AC	18	4,000	0.35	G	20	200	0.35	4.32
P11	AC	5	4,000	0.35	AC	20	4,000	0.35	G	20	200	0.35	4.41
P12	AC	6	4,000	0.35	AC	20	4,000	0.35	G	20	200	0.35	4.58
P13	AC	5	4,000	0.35	AC	23	4,000	0.35	G	20	200	0.35	4.81
P14	AC	6	4,000	0.35	AC	22	4,000	0.35	G	20	200	0.35	4.85
P15	AC	6	4,000	0.35	AC	24	4,000	0.35	G	20	200	0.35	5.12
P16	AC	6	4,000	0.35	AC	26	4,000	0.35	G	20	200	0.35	5.39

KEY: AC - asphalt concrete; G - granular material; t_S - thickness of surface layer; t_B - thickness of base layer; t_{Sb} - thickness of sub-base layer; E - stiffness modulus; ν – Poisson's ratio; SN - structural number.

TABLE 3. Traffic, pavement foundation and pavement structure

Traffic						Pavement foundation			Pavement structure
Traffic class	AADT	$AADT_h$	g_h (%)	α	ESAL (20 years)	Foundation class	E (MPa)	ν	Manual
T6	1,500	150	3	2	$0.29\text{x}10^7$	F1	30	0.35	NAF
T5	3,000	300	3	3	$0.88\text{x}10^7$	F1	30	0.35	NAF
T4	5,000	500	4	4	$2.17\text{x}10^7$	F1	30	0.35	NAF
T3	8,000	800	4	4.5	$3.91\text{x}10^7$	F1	30	0.35	NAF
T2	12,000	1,200	5	5	$7.24\text{x}10^7$	F1	30	0.35	NAF
T1	20,000	2,000	5	5.5	$13.28\text{x}10^7$	F1	30	0.35	NAF
T6	1,500	150	3	2	$0.29\text{x}10^7$	F2	60	0.35	P3
T5	3,000	300	3	3	$0.88\text{x}10^7$	F2	60	0.35	P7
T4	5,000	500	4	4	$2.17\text{x}10^7$	F2	60	0.35	P11
T3	8,000	800	4	4.5	$3.91\text{x}10^7$	F2	60	0.35	P13
T2	12,000	1,200	5	5	$7.24\text{x}10^7$	F2	60	0.35	P15
T1	20,000	2,000	5	5.5	$13.28\text{x}10^7$	F2	60	0.35	P16
T6	1,500	150	3	2	$0.29\text{x}10^7$	F3	100	0.35	P2
T5	3,000	300	3	3	$0.88\text{x}10^7$	F3	100	0.35	P4
T4	5,000	500	4	4	$2.17\text{x}10^7$	F3	100	0.35	P6
T3	8,000	800	4	4.5	$3.91\text{x}10^7$	F3	100	0.35	P9
T2	12,000	1,200	5	5	$7.24\text{x}10^7$	F3	100	0.35	P12
T1	20,000	2,000	5	5.5	$13.28\text{x}10^7$	F3	100	0.35	P14
T6	1,500	150	3	2	$0.29\text{x}10^7$	F4	150	0.35	P1
T5	3,000	300	3	3	$0.88\text{x}10^7$	F4	150	0.35	P3
T4	5,000	500	4	4	$2.17\text{x}10^7$	F4	150	0.35	P5
T3	8,000	800	4	4.5	$3.91\text{x}10^7$	F4	150	0.35	P8
T2	12,000	1,200	5	5	$7.24\text{x}10^7$	F4	150	0.35	P10
T1	20,000	2,000	5	5.5	$13.28\text{x}10^7$	F4	150	0.35	P12

Note: NAF - Not an adequate foundation for a flexible pavement with an asphalt base layer according to the Portuguese Manual.

At this moment the ANN-based tool is in the phase of validation using problems defined in the literature with input data and output results. In the next months, the ANN-based tool will be applied to the Portuguese pavements to predict its quality in terms of Present Serviceability Index (PSI).

ACKNOWLEDGEMENTS

The present research work has been carried out in the framework of project PAVENERGY – Pavement Energy Harvest Solutions (PTDC/ECM-TRA/3423/2014), co-financed by the European Regional Development Fund (POCI-01-0145-FEDER-016676) through the Operational Program for Competitiveness Factors (COMPETE) and by national funds through the Portuguese Foundation for Science and Technology (FCT). The authors also thank the ACIV for its financial contribution for the presentation of this research work in the 2018 ISAP Conference.

REFERENCES

[1] Flood, I. Towards the next generation of artificial neural networks for civil engineering. *Advanced Engineering Informatics*, 22(1), pp. 4–14, 2008.

[2] Haykin, S. *Neural networks and learning machines*. New York, Prentice Hall/Pearson, 2009.

[3] NCHRP (2004). *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*. NCHRP 1-37A Final Report, Champaign, IL. Available at: http://onlinepubs.trb.org/onlinepubs/archive/mepdg/guide.htm (access March 8th, 2017).

[4] Tabatabaee, N, Ziyadi, M, Shafahi, Y. Two-stage support vector classifier and recurrent neural network predictor for pavement performance modelling. *Journal of Infrastructure Systems*, 19(3), pp. 266-274, 2003.

[5] Du, K., Swamy, M. *Neural networks and statistical learning*. London, Springer-Verlag, 2014.

[6] Abambres, M. and Ferreira, A. Application of artificial neural networks in pavement management, *Proceedings of the International Conference on Traffic Development, Logistics & Sustainable Transport*, CD Ed., pp. 1-11, Opatija, Croatia, 2017.

[7] JAE. *Manual of pavement structures for the Portuguese road network,* Junta Autónoma de Estradas, Lisboa, Portugal, pp. 1-54, 1995 (in Portuguese).

[8] Shell. *Shell pavement design manual - asphalt pavements and overlays for road traffic*. Shell International Petroleum Company Ltd., London, UK, 1978.

[9] Brunton, J., Brown, S., and Pell, P. Developments to the Nottingham analytical design method for asphalt pavements. *Proceedings of the 6th International Conference on Structural Design of Asphalt Pavements*, Ann Arbor, Michigan, USA, 1, pp. 366-377, 1987.

[10] AI. *Thickness design: asphalt pavements for highways and streets*. Asphalt Institute, Lexington, KY, USA, pp. 1-98, 2001.