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An Artificial Neural Network for the Pre-Estimation of Construction Costs for Electrical and Mechanical Installations on Road Tunnels

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Abstract
Electrical and mechanical (E&M) installations on road tunnels consist of several sub-systems such as ventilation, lighting, electrical power substations and distribution systems, surveillance and control, communications, closed circuit television, traffic management systems and fire safety. This paper presents the development of an Artificial Neural Network (ANN) that predicts the cost of such installations on road tunnels. A data set is formed by collecting actual construction data from road tunnels of the 670 km Egnatia Motorway in Greece. The ANN has a feedforward architecture and is trained from the collected data using backpropagation. Fundamental design parameters such as tunnel length, slope and selected lighting parameters are used as input parameters of the ANN. It is concluded that the ANN can serve as a very useful tool in the pre-estimation of construction costs of E&M installations on road tunnels.

Keywords
Electrical and mechanical installations, Road tunnels, Neural networks, Construction cost pre-estimation

1. Introduction

Pre-estimation models of construction costs can assist engineers in assessing the financial impact of design alternatives and in determining the most apporiate funding and financing strategy. In particular, the pre-estimation of electrical and mechanical (E&M) installation costs in tunnels is a difficult problem and very little research has been conducted. The primary objective of this paper is to present a pre-estimation model based on an Articial Neural Network (ANN). To demonstrate the effectiveness of this approach, a data set is formed of actual construction data from road tunnels of the 670 km Egnatia Motorway in Greece and is used to train the ANN.

1.1 Neural Networks and Cost Estimation

The application of neural networks in cost estimation has been demonstrated by several researchers. Neural network models have been used for parametric cost estimation of highway projects (Hegazy and

Ayed, 1998) and in the estimation of the cost of reinforced - concrete pavements (Adeli and Wu, 1998). Neural networks and regression models were utilized to predict the completed cost of competitively bid highway projects (Williams, 2002). Neural network cost models were developed from data collected from nearly 300 building projects (Emsley *et al*., 2002). More recently, hybrid models of neural networks and genetic algorithms were used to predict preliminary cost estimates of residential buildings (Kim *et al*., 2005). Finally, accurate estimation techniques for highway projects at the conceptual phase using artificial neural networks have also been developed (Sodikov, 2005).

Electrical and mechanical (E&M) installations on road tunnels consist of several sub-systems such as ventilation, lighting, surveillance and control, power substations and distribution systems, signalling, communciation, closed circuit television (CCTV) and fire safety. Therefore the final cost of E&M works is the sum of the cost for the different sub-systems. Since the cost of every sub-system is influenced by several parameters in a non-linear manner, the use of regression techniques can not yield satisfactory results. Hence, the use of an Artificial Neural Network (ANN) which can deal with the complexity of the problem at hand is warranted.

1.2 Electromechanical Installations on Road Tunnels

The 670 km Egnatia Motorway with a budget of 5,4 bil. € is currently one of the most important infrastructure projects in Europe. Along the length of the main axis 74 twin tunnels have been constructed amounting to a total length of 50 km (or 100 km of single tube). Although these tunnels account for only 7% of the length of the motorway, they absorb 30% of the total construction cost and therefore the study of the factors that affect their cost is considered to be very important. In the total expenditure the civil engineering works cover 85 - 90% whereas the electrical and mechanical works cover the remaining 10 - 15%. Therefore, the total cost of the tunnel electrical and mechanical installations on the Egnatia Motorway is estimated at approximately 150 mil. €. Consequently, the development of a pre-estimation tool of E&M installations can be very useful in new projects since it can provide a good first estimate of the final cost. Other researchers have used data from the Egnatia Motorway in developing road tunnel early cost estimates of civil engineering works using multiple regression analysis (Petroutsatou *et al*., 2006). It should be noted that even though the percentage of E&M installation costs during the construction phase is much smaller than the civil engineering works, this is not the case during project operation because electrical and mechanical equipment need to follow a maintenance schedule in addition to any repairs and/or replacements. Hence, the understanding of the factors that affect the construction, maintenance and operation of electromechancial installations can prove to be very significant in the life-cycle costing of road tunnels.

2. Neural Networks

The development of artificial neural networks (ANN) is based on the recognition that the human brain is an extremely complex, non-linear parallel processor. In this manner neural networks are composed of many neurons and model the way in which the human brain operates and completes several functions. Knowledge is attained through the environment by a learning procedure and is stored in the synaptic weights that connect the neurons. The most important advantages of ANN are a) they can deal with non-linear data, b) they correlate input data and output data c) they can adapt to new data d) they have a high tolerance for wrong data e) they can learn through examples and f) they recognize templates and prototypes (Haykin, 1999).

2.1 Neural Network Architecture and Learning

Artificial Neural Networks (ANN) are data processing systems that consist of many neurons in several layers which can be fully or partially connected. In many instances it is necessary to have one or more hidden layers. Figure 1 shows a fully connected network with one input layer, one hidden layer and one output layer. Signals are transferred to the synapses of neurons and are multiplied by their synaptic weight (w_{ij}). The input (x) and output (y) data helps in determining the number of neurons at the input and output layer. The number of neurons in the hidden layer depends on the number of neurons in the input and output layer, the amount of training data, the existence or not of noise in the data, the complexity of the categorization and the training algorithm.

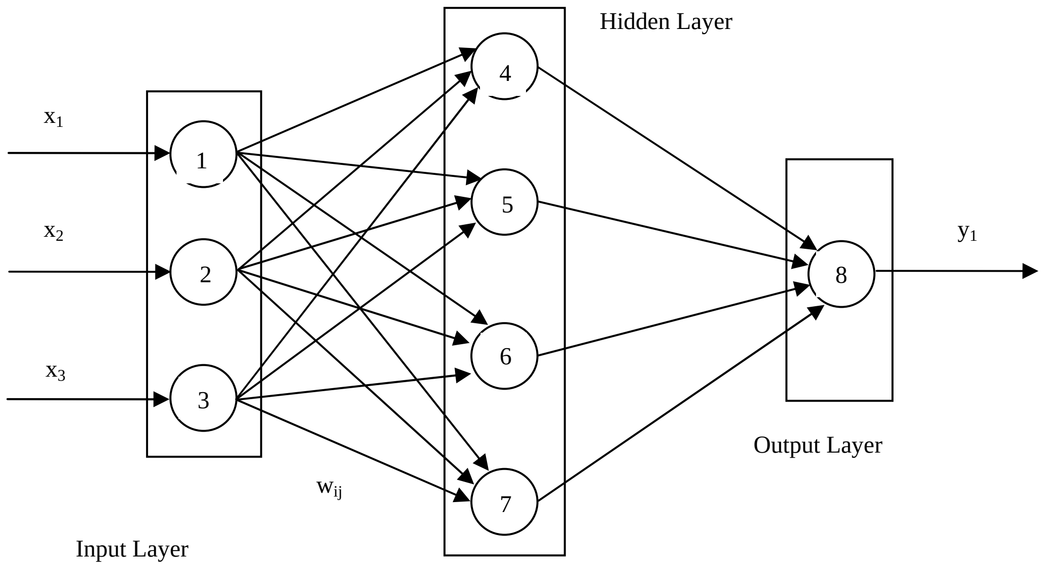

Figure 1: Fully Connected ANN

Learning of an ANN is the process in which the weights of the network are adjusted iteratively in such a way so that a certain input vector yields the desired target output vector. There are three basic types of learning: supervised learning, unsupervised learning and graded learning. The fundamental algorithms for supervised learning are Delta rule learning, backpropagation, competitive learning and random learning. The use of the training data is performed in training cycles that are called epochs. Training stops when a certain quality criterion reaches a desired level. Such criteria are the mean square error as well as the rate of change of the mean error of the training set. The mean square error (mse) is defined as the average squared error between the network output and the target outputs (Haykin, 1999). Finally, recall is the process of the calculation of an output vector for a given input vector and network weight values.

2.2 Backpropagation and the Levenberg-Marquardt Algorithm

Backpropagation network training algorithms use the gradient of the performance function to determine how to adjust the network weights. They aim in determining the percentage of the total error that corresponds to every neuron (even the ones in the hidden layer). To this extent, the mean square error between the network output and the desired output is minimized through the gradient descent optimization procedure. The recalculation of the weights is done from the output layer to the input layer by a backward pass or back propagation and computations are derived using the chain rule of calculus (Hagan *et al*., 1996). Special care must be paid in avoiding local minima or network paralysis in which case values are not modified significantly in every correction.

The Levenberg-Marquardt algorithm was designed to complete the training of networks very quickly and in fact it appears to be the fastest method for training moderate-sized feedforward neural networks. This is because whereas other algorithms use the Hessian matrix of the error in their calculations this algorithm uses the Jacobian matrix of the network error in relation to the weights and bias, which is much easier to compute (Hagan and Menhaj, 1994). For this reason, this algorithm has become particularly popular in training ANN for function approximation.

3. Fundamentals of Electrical and Mechanical Installations on Road Tunnels

Electrical and mechanical installations on road tunnels consist of several sub-systems such as ventilation, lighting, control and surveillance, power substations and distribution, traffic management, communications, CCTV and fire safety. For Egnatia motorway tunnels, design guidelines for E&M installations are detailed in Chapter 7 of the Egnatia Guidelines for Conducting Road Works Design (OSMEO). In addition, Egnatia tunnel designs comply with Greek National Standards (OMOE) as well as other appropriate international standards or guidelines for each sub-discipline. Below are briefly summarized some of the fundamental principles of operation for these systems as well as parameters that affect their design and hence their cost.

Tunnel Ventilation

Tunnel ventilation systems are designed to satisfy the following two basic purposes: a) to monitor and maintain air quality and visibility under all possible traffic conditions, by introducing fresh air to dilute pollutants (carbon monoxide, nitrogen oxides and suspended particulate matter) and b) to operate the system in case of emergency (fire) in order to control the spread of smoke and heat and allow people inside the tunnel to escape. There are several types of ventilation such as natural, longitudinal, transverse or semi-transverse. The selection of the appropriate ventilation system depends on the configuration and geometry of the tunnel, but in general the ventilation design parameters are: tunnel length, longitudinal profile, number or tubes, expected traffic, location (urban or rural) and design fire. In addition to OSMEO and OMOE, tunnel ventilation design is based on the recommendations of the World Road Association (PIARC), as well as German, Austrian and Swiss design guidelines.

Tunnel Lighting

The basic aim of tunnel lighting is to provide levels of safety and comfort as close as possible to respective conditions on the open road. To this end, visibility inside the tunnel must be such that users have sufficient information regarding the course of the road ahead, possible obstacles and the presence and actions of other users. Depending on the time of day and outside conditions, this is achieved by daytime, night time, safety and access road lighting. In addition, cross-passages and electrical rooms are also provided with lighting.

More specifically, night time lighting provides constant luminance levels inside the tunnel. Access road lighting is associated with night time lighting and provides luminance levels on the road leading to the tunnel similar to those inside the tunnel. Daytime lighting allows the adjustment of the user’s eye from the high luminance outside to the lower luminance when entering the tunnel. This adaptation is achieved by gradually reducing lighting levels from the tunnel entrance through a transition zone and into the interior zone where lighting levels are kept constant. Egnatia Motorway tunnel lighting systems are designed on the basis of CEN Report 14380: Lighting Applications – Tunnel lighting (European Standard CR 14380 adopted as Hellenic standard ELOT CR 14380) and the Guide for the Lighting of Road Tunnels and Underpasses (CIE 88-2004).

For every tunnel the L20 access luminance is estimated. This is defined as the average luminance contained in a conical field of view subtending an angle of 20° with the apex at the position of the eye of an approaching driver, and aimed at the centre of the tunnel mouth. L20 is assessed from a point at a distance equal to the stopping distance from the tunnel portal at the middle of the relevant carriageway or traffic lane. Therefore, L20 and the stopping distance (dependant on the access road slope) are the fundamental parameters considered to design a tunnel lighting system.

Fire Safety

As required by EC Directive 2004/54/EC, every tunnel longer than 500 m is fitted with an active water supply system for fire safety. On Egnatia tunnels, fire hydrants are provided at 50 m intervals for direct use by the fire department. Pump station designs are such that with four adjacent hydrants simultaneously operated, water pressure is at least 6 bar and the flow rate is 10 lt/sec at the hydrant. Typically, fire hydrants are installed inside Tunnel Emergency Cabinets (TEC) recessed into the tunnel walls. TECs also include fire extinguishers, a small power supply board, and occasionally other sensors and electronic systems. In addition, a fire detection system is installed along the entire tunnel length, including cross-passages.

Surveillance and Control Systems

Depending on what systems are installed, a tunnel may be equipped with a SCADA system (Supervisory Control And Data Acquisition) to monitor and control electrical and mechanical installations. In addition, several qualitative parameters such as pollutant levels or the L20 access luminance may be collected and transmitted to the tunnel control centre through the SCADA system. Finally, the SCADA software evaluates qualitative and quantitative parameters, as well as any warnings or alarms, and takes appropriate steps to either make automatic adjustments or provide information to control staff to allow manual action. SCADA equipment is located in the control room (display equipment, computers, communication networks), in electronic rooms (Programmable Logic Controllers) and in the field (equipment controllers and interfaces).

Communications

Almost all tunnels are equipped with emergency telephones to provide two-way communications with a staffed tunnel control centre. Tunnels longer than 350 m have telephones at all portals and at 150 m intervals inside the tunnels. Tunnels shorter than 350 m have telephones only at the portals.

Closed Circuit Television (CCTV)

A CCTV system is provided to ensure that full visual surveillance is available over the whole length of the tunnel, as well as tunnel approach roads and portal areas. Cameras mounted on brackets inside the tunnel and poles outside transmit colour images to video display and recording equipment at the tunnel control centre.

Traffic Management System

Tunnels are equipped with a traffic management system (TMS) that includes traffic lights, lane control signs, variable speed limit signs and variable message signs. Traffic parameters (volume and flow) are collected by inductive loop systems embedded in the roadway and transmitted to the TMS software (that may or may not be part of the SCADA system) controlling the aforementioned equipment. The extent of TMS equipment installed depends on tunnel length and location as well as the proximity to other tunnels.

Power Substations and Distribution System

Typically electrical power is delivered to tunnel portals at 20 kV. Substations transform this voltage to 400 V. Emergency and uninterrupted power are also provided for selected emergency and critical systems by generating sets and UPS systems respectively, also located in the substation buildings. The power is delivered to tunnel equipment via a power distribution system consisting of electrical panels and supply/distribution cables for all three types of power (normal, emergency, uninterrupted). For substations and distribution systems of any complexity other than basic, the whole system is monitored and controlled by the SCADA system.

4. Implementation of the ANN

Implementation of the ANN involved the formation of a training data set, the selection of the appropriate network architecture and training algorithm, and the final simulation to test the efficiency of the trained network.

4.1 Training Data Set

The training data set for the ANN was compiled by collecting surveyed quantities of electrical and mechanical installations of constructed tunnels of the Egnatia Motorway as well as their fundamental design parameters. In particular the training set consists of 26 tunnels of the Egnatia Motorway. The cost of every tunnel is the sum of a bill of quantities with approximately 50 line items. Therefore, the total data set required 26 × 50 = 1300 line items. Table 1 indicates the cost statistics of various electrical and mechanical installation sub-systems. The target output vector of the ANN is comprised of the final tunnel costs.

Table 1: Cost Statistics of E&M Sub-systems Training Data

Sub-system	Percentage (%)
Ventilation	19
Lighting	22
Fire safety	10
Surveillance (SCADA)	23
Communications	3
CCTV	3
Traffic Management	5
Power substations	15

Figure 2 shows the cost/m of E&M installations in relation to the length of road tunnels. For the given data set the average cost of E&M installations is about 1000 €/m. Tunnels with a length of 245-500 have a significantly lower cost than those with a greater length. This is because they typically are not fitted with expensive ventilation and radio communication systems. Tunnels with a length between 500-1500 m have the largest cost/m. Tunnels with a length over 1500 m have a slightly lower cost/m due to economies of scale. Overall the relationship between cost and length is very complex and a regression model can not yield satisfactory results.

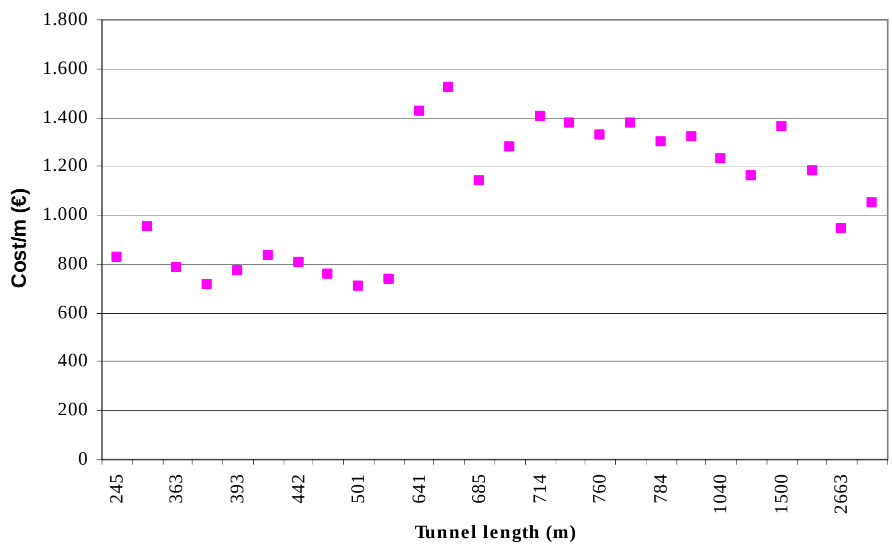

Figure 2: Cost of E&M Installations vs. Tunnel Length

The selection of the network input vector was quite challenging because there are many design parameters of E&M installations the affect the final cost. The tunnel length is the most important factor since it determines the total equipment of the tunnel as well as the presence or not of ventilation, communication and active fire safety systems. The tunnel slope affects the cost of the ventilation systems. In highly mountainous areas tunnels can have a significant slope i.e. +/- 5%. Thus, when the motion of vehicles is uphill the need for jet fans is lower than when the direction of motion is downhill. This is due to thermal buoyancy of smoke which gives it the natural tendency to rise uphill and thus requires less mechanical propulsion. The lighting inside a tunnel is not distributed in a uniform manner. Usually there is a significantly large concentration of lights at the beginning of the tunnel where the entrance zone is highly illuminated in order to provide a smooth transition for the driver from the exterior to the interior of the tunnel. Past the entrance zone the level of lighting is significantly lower until it rises again slightly toward the tunnel exit. Overall, a very important factor in determining the number of luminaires at the entrance of the tunnel is the L20 access zone luminance which was presented previously. It should be noted that although the surveillance and control (SCADA) and power substation distributions systems contribute significantly to the overall E&M construction costs the most decisive design parameter affecting cost is the tunnel length. In conclusion, after several trials the tunnel length, tunnel slope and the L20 access zone luminance were selected as the input parameters of the ANN.

Many parameters that were presented in the previous paragraph are constant for all tunnels of the Egnatia Motorway. The tunnel cross–section, environmental protection standards, safety specifications are identical for all tunnels in the dataset and therefore were not used as input parameters.

4.2 Network Architecture and Training

The network was implemented using the Neural Network Toolbox 5 of MATLAB software (Demuth *et al.*, 2007). The ANN is a multilayer feedforward network with three inputs, one hidden layer with ten neurons and a single output. It is noted that several trial runs were performed in order to obtain the number of neurons of the hidden layer. The tan-sigmoid activation function was used for the hidden layer and the linear transfer function for the output layer. The training data was stored in the network input vector p and the target output vector t. With the use of an appropriate function the training data was preprocessed and converted to a scale from -1 to 1 and stored in the vectors pn and tn.

After the appropriate training parameters and the learning rate were selected the network was trained using the Levenberg-Marquardt training algorithm. The training data set was split into 3 groups for training, validation and testing. In this way 60% of the data is used to train the network and 20% is used to validate the generalization of the ANN. The training stops when the error of the validation data stops decreasing. Finally, the remaining 20% is data that the network has not seen at all. The performance measure is the mean squared error (mse). After 17 epochs the training according to the Levenberg-Marquardt algorithm converges as the mse reaches a value of less than 1% of the average tunnel E&M installation cost. At this point the software has calculated all the values of the weights and biases of the network.

4.3 ANN Simulation

The simulation of the trained network was performed to calculate the outputs based on the initial input data. Thereafter a regression was performed between the outputs of the simulation of the trained network (Y) in relation to the initial output targets (T) of the training data set. In the ideal case Y should be equal to T. The correlation coefficient R for this regression analysis on the training, validation and testing data was 0.975 0.993 and 0.957 respectively. From the simulation it can be concluded that the network performs well since the correlation coefficient R of the regression is close to 1.

With the confidence derived from the successful simulation the trained ANN can be used as a pre-estimation tool for the cost of E&M installations in new tunnels. By providing values for the tunnel length, slope and the L20 access zone luminance value the ANN can provide a prediction of the final cost. Therefore, the application has achieved its goal in providing project managers a useful tool in the estimation of the cost of E&M installations in road tunnels.

5. Conclusions

This paper has succeeded in demonstrating how an ANN can be used as a reliable pre-estimation tool for the costs of E&M installations on road tunnels. Significant effort was spent in creating a training data set for an ANN. The analysis of the collected data has provided useful insight into the parameters that affect the cost of electromechanical installations. Three input parameters and one output parameter were identified. The Levenberg-Marquardt algorithm yielded very good results in a feedforward neural network architecture.

Future work can be directed in increasing the size of the training set by using data from a greater number of tunnels and in increasing the input parameters. In addition, an ANN could be developed to combine the costs of civil engineering works with those of electrical and mechanical installations. Finally, this research can potentially be a stepping stone towards the complete life cycle costing of road tunnels.

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