XV International Conference on Durability of Building Materials and Components
DBMC 2020, Barcelona
C. Serrat, J.R. Casas and V. Gibert (Eds)

Possible Applications of Neural Networks in Managing Urban Road Networks

Ivan Marović[1]

[1] Faculty of Civil Engineering, University of Rijeka, Radmile Matejčić 3, HR-51000 Rijeka, Croatia, ivan.marovic@uniri.hr

Abstract. *Life-cycle management of urban road networks as a part of an urban system is a very complex process from the management standpoint of social, technical and economic aspects. The complexity and multidisciplinarity of such a problem suggest the need for using soft computing tools as well as multi-criteria analysis and group decision-making. Recently, there is a significant increase in using various soft computing tools, especially neural networks, for different prediction purposes in the field of road construction planning and management. Along with known advantages of such a prediction method, yet some applications showed the shortcomings. In that sense, the focus of this research is on possible applications of neural networks related to the life-cycle phases during the management of urban road projects. This is done in both horizontal (projects' life-cycle phases) and vertical (hierarchical decision-making levels) approach. The final aim of the research is to compare and highlight the possible applications of neural networks as a prediction tool and support for decision-making in urban road management.*

Keywords: *Decision Support, Neural Networks, Project Management, Strategic Planning.*

1 Introduction

Urban development and management especially the management of urban road networks, as a part of the urban infrastructure system, is a highly complex process from the management standpoint of social, technical and economic aspects. The development of urban road infrastructure is an integral part of any urban expansion processes and often considered as a dominant transport asset. The World Road Association (2014) reported that the average length of public roads in OECD countries is more than 500,000 km with a strong tendency of increasing, and is often the largest publicly owned national asset. Therefore, in urban areas where road infrastructure covers over 20% of the whole city area (Deluka-Tibljaš *et al.*, 2013) it's quality and strategic development directly influence the citizens' quality of life (Hanak *et al.*, 2014). Developing management practices that effectively integrate the processes of urban infrastructure management is a challenging goal that many cities are struggling with nowadays, but is an important necessity to achieve desired long-term sustainability.

Public management of urban road networks is a highly complex and socially sensitive as the city governments encounter different problems during the decision-making phase when it is necessary to find a solution that would meet the requirements of all stakeholders. All solutions must be strategically aligned and be a part of the desired development concept. Initially, the different views are provided by stakeholders and experts regarding the scope, scale, and potential solutions. Such happens during the whole life-cycle of the urban road network as each municipality has a certain annual budget for its construction, maintenance, and remedial activities. Therefore, planning activities altogether with project prioritization emerges as one of the most important and most difficult issues to be resolved.

The evaluation of such investments requires explicit consideration of multiple, conflicting and incommensurate criteria that have an important social, economic, and environmental influence on various stakeholders in different ways (Jajac et *al.*, 2015). The complexity and multidisciplinarity of such a problem suggest the need for using soft computing tools, such as artificial neural networks (ANN), as well as multi-criteria analysis and various decision-making methods. The use of ANNs in solving pavement engineering problems and road management has a long history as well. Since the 1990s, ANNs have been frequently used for solving various complex problems, mostly for operational purposes, such as automatic pavement evaluation (Kaseko and Ritchie, 1993), pavement performance prediction (Banan and Hjelmstad, 1996), rutting (Simpson *et al.*, 1995), and maintenance (Fwa and Chan, 1993). A very few stressed out the importance and possibilities of their application in decision-making processes as a part of a decision support system *i.e.* DSS (Turban, 1993; Turban and Aronson, 1995).

In the 2000s, researchers followed the scientific contribution from previous decade and enhance the efficacy of ANNs in assisting asphalt mixture design and evaluation (Sundin and Braban-Ledoux, 2002; Yang *et al.*, 2003; Tarefder *et al.*, 2005; Ceylan *et al.*, 2007; Terzi, 2007; Commuri and Zaman, 2008; Ozsahin and Oruc, 2008; Tapkin *et al.*, 2009; Tušar and Novič, 2009). All these aspects were evolved to efficiently solve technical problems that occur on the operational management levels. A very few gave another insight of ANNs to be used on higher management levels such as tactical and strategic. Researches such as Loia *et al.* (2000), Quintero *et al.* (2005), Šelih *et al.* (2008), and Jajac *et al.* (2009) can be highlighted as the one where ANNs were used for solving problems on both tactical and strategic management levels based upon Turban's DSS concept. Such approach bloomed in 2010s when more and more researchers very efficiently applied ANNs for solving structured problems that occur on operational level (Gesoglu *et al.*, 2010; Xiao *et al.*, 2010; Ozgan, 2011; Ciresan *et al.*, 2012; Singh *et al.*, 2013; Ozturk and Kutay, 2014; Zavratnik *et al.*, 2016; Androjić and Marović, 2017; Zhang *et al.*, 2018; Gong *et al.*, 2019) as well as for solving semi-structured and unstructured problems that occur on tactical and strategic levels as a part of various DSS'es (Durduran, 2010; Coutinho-Rodrigues *et al.*, 2011; Dahal *et al.*, 2013; Du *et al.*, 2014; Jajac *et al.*, 2014; Jajac *et al.*, 2015; Han *et al.*, 2016; Marović *et al.*, 2018).

The main objective of this paper is to summarize the findings of up-to-date research articles concerning the application of artificial intelligence, specifically neural networks, related to the life-cycle phases during the management of urban road networks as a part of an urban system. Some of the other objectives were also assessed, such as to: (i) identify specific problems that are solved by the aid of neural networks during life-cycle management of urban road networks, (ii) evaluate and highlight the possible applications of neural networks as a prediction tool and support for decision-making on different management levels.

2 Systematic Review

Studies about neural networks and urban infrastructure management, especially road networks, were surveyed. The review reflects on papers published in peer-reviewed journals preferably articles and review papers. Researches related to neural networks in managing urban road networks published from 2000 to 2019 was reviewed. The survey was conducted using selected keywords (artificial neural network, decision support, infrastructure, multi-criteria analysis, and road management) that resulted in 1703 publications (1014 in Web of Science and 689 in Scopus) which were selected by the following criteria: year of publication (from year 2000); document type (only journal articles were taken into consideration); repetitions (duplicate between Web of Science and Scopus); and relevance and relation to the topic. This resulted in 73 selected articles. The number of publications considered in this paper and their corresponding year of publication is summarized in Figure 1. Only the papers that solely highlight the use of ANNs for solving various structured problems (operational level) and/or various semi-structured and unstructured problems (tactical and strategic level) are referred to.

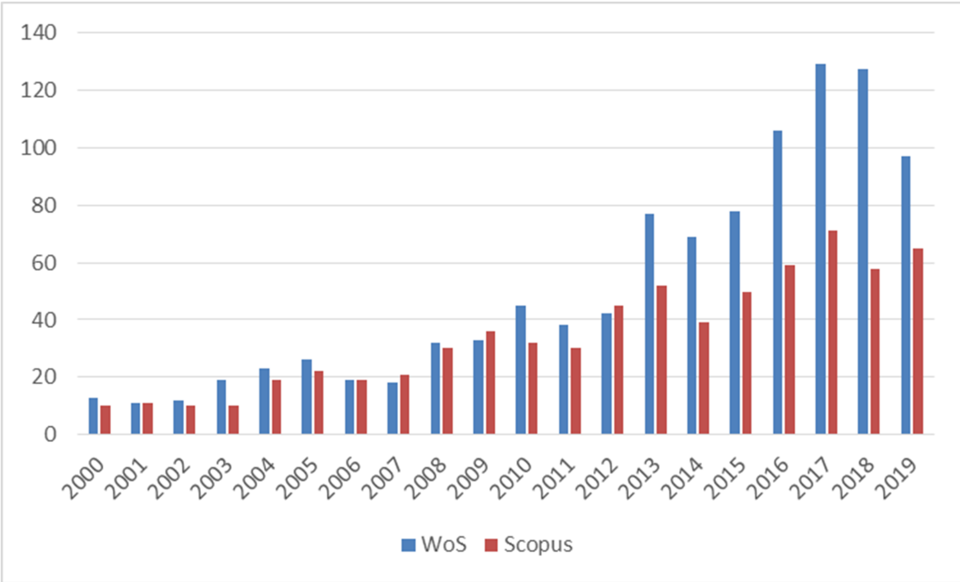

Figure 1. Number of publications and corresponding year of publication.

Collected data (Figure 1) shows the increasing interest and published papers on this topic by the research community from 2013 until now. Such is more evident regarding Web of Science than the Scopus database. For 2019, it should be noted that other papers may appear in the databases during October 2019 and later.

3 Urban Infrastructure Management

Life-cycle management of urban road networks, in general, can be seen through the interaction of horizontal and vertical aspects of urban road management (Figure 2) to achieve previously defined sustainable goals. The horizontal aspect takes into account the project management approach through four cyclically connected phases (*e.g.* initiation, planning, execution, and closure phase) thus represent the life-cycle phases. These phases do not change whether the project is managed traditionally or agile. Sure, it is obvious that projects do not appear and are not managed solely horizontally. Therefore, a vertical management component should not be forgotten and must be considered with all the difficulties that it brings. Such is observed throughout the vertical aspect of urban road management that takes into account the hierarchical management levels (operational, tactical and strategic).

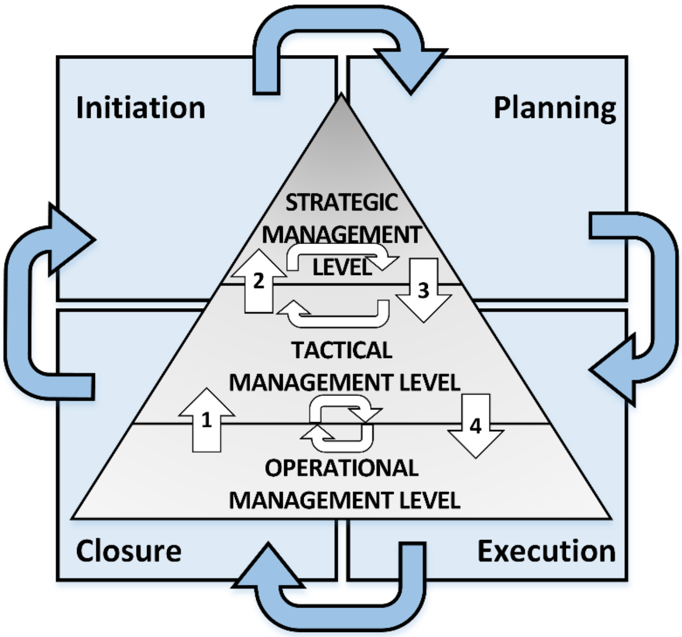

Figure 2. The horizontal and vertical aspects of urban road management.

The first management level supports decision-makers at the lowest operational management level. Besides its general function of supporting decision-making processes at the operational level, it is a meeting point of data and information where the problems are well defined and structured. This management level exclusively deals with structured problems that can be characterized as specified, detailed and narrow, clearly scheduled and internal. Additionally, it provides information flows towards higher decision levels (arrow 1 in Figure 2). A circular arrow between two management levels symbolizes interactions between the levels for purposes of solving specific problems. The decision-makers at the second management level (*i.e.,* tactical management level) deal with less-defined i.e. semi-structured problems and unstructured problems. At this level, tactical decisions are delivered, and it is a place where information basis and solutions are created. Problems that occur on this level can be characterized as broader than on lower level but still very focused and specified, clearly scheduled and internal. Based on applied models and methods, it gives alternatives and a basis for future decisions on the strategic management level (arrow 2 in Figure 2), which deals with even less-defined and unstructured problems. At the third management level, based on the expert deliverables from the tactical level, future development of the system is carried out. Strategies are formed, and they serve as frameworks for lower decision and management levels (arrows 3 and 4 in Figure 2). Problems that occur on this level are general and with a broad scope, both internal and external, and often ad hoc.

Depending on the management level and type of the occurred problem, various tools and methods could be used such as soft computing tools (for example, ANNs) as well as multi-criteria analysis and group decision-making. Many authors have studied possibilities for generating decision support tools for urban infrastructure management that convergence toward some type of decision framework is more or less similar to a basic DSS structure. According to Turban (1993; 1995), DSS's basic structure consists of three modules: database, model base, and dialog. In 2005, Quintero et al. introduced an improved DSS named IDSS (Intelligent

Decision Support System) as a solution for the future needs of urban infrastructure management. Later, Jajac *et al.* (2009) introduced the new architecture of DSS for urban infrastructure management that places the management levels in the core of the DSS structure. Such provided that the interactions between DSS modules are realized through decision-making processes at all management levels, which serve as meeting points of adequate models (from the model base) and data (from the database). The new architecture provided that complex and sensitive decision-making processes can be correctly supported if appropriate methods and data are properly organized and used. Gudac *et al.* (2014) highlighted the utter importance when decisions must be quickly made based upon real-time information, while Tijanić *et al.* (2019) proposed ANN based models to accurately estimate road construction costs.

3.1 Application of Neural Networks at the Operational Management Level

During the years various researches made a significant contribution with ANNs to efficiently solve technical problems that occur on the operational management levels in managing urban road networks. They were mostly focused on various asphalt mixtures and predictions of their properties during material production as well as during the exploitation period when the mixtures became part of the road network. In that sense, Xiao and Amirkhanian (2009) explored the application of ANN in predicting the stiffness behavior of asphalt mixtures and reported that the ANNs are more effective in predicting the fatigue life of the mixture than the traditional models. Ceylan *et al.* (2007) also reported the higher prediction accuracy of ANN compared to the existing regression models. Tušar and Novič (2009) analyzed the impact of various factors by using several models, multiple linear regression (MLR), partial least squares regression (PLS) and artificial neural networks (ANN), in the prediction process of the monitored hot mix asphalt properties. They reported that the use of MLR and PLS models show a better predictive ability that the ANN models. In 2016, Zavratnik *et al.* (2016) showed the application of ANN and MLR in the process of forecasting air void content with different used parameters on 5 types of asphalt mixtures. The authors concluded that the use of MLR models is better than ANN in the prediction of certain mixtures, but such is not the case for all asphalt mixtures together. In 2019, Androjić and Marović developed ANN and MLR models to predict the hot mix asphalt properties (air void and binder content) produced in a laboratory. The performed research on 6 types of asphalt mixtures indicates that it is possible and desirable to apply neural networks in the prediction process of the required properties of hot mix asphalt, wherein it is necessary to use a substantial set of input data. Gong *et al.* (2019) approach the fatigue cracking prediction problem in pavements by using the highly flexible ANNs through the deep learning framework. They reported that the difference between prediction performances of fatigue cracking transfer function concerning the proposed framework is 30% in favor of ANNs.

3.2 Application of Neural Networks at the Tactical Management Level

To improve conditions of road elements, as a part of sustainable development of the road infrastructure in the city of Split, Jajac *et al.* (2015) introduced the ANN that was trained and tested on road infrastructure data that come out of 236 city's road projects during the two years. Only road elements with insufficient conditions were assessed, while four network input variables were used: level of service (LOS), safety, savings on vehicle maintenance, and maintenance quality. In 2018, based on the decision support concept (Jajac *et al.*, 2009), Marović et al. showed that complex and sensitive decision-making processes, such as the ones for road maintenance planning, can correctly be supported if appropriate methods and data are properly organized and used. They designed and developed an ANN model to achieve a successful prediction of road deterioration as a tool for maintenance planning activities. Recently with drastic improvements in computing capacity, fast optimization algorithms, and new network topology enabled researchers to explore considerably more complex models such as crack detection on asphalt surfaces (Zhang *et al.*, 2018) during maintenance phases, and to actively estimate and manage cost overruns (Tijanić *et al.*, 2019). Also, there is a strong tendency for optimizing ANNs for the evaluation of asphalt pavement structural performance (Bosurgi *et al.*, 2019) to improve the efficiency of pavement management systems.

3.3 Application of Neural Networks at the Strategic Management Level

The use of ANNs for solving problems at the strategic management level is closely connected with the ones previously stated at the tactical management level. It is important to note that at this management level ANN is used as one of the models out of the model base of the DSS for urban infrastructure management as a core management framework. This is the management level where all project phases are strategically managed. A specific decision support concept focused on the planning phase was proposed by Jajac *et al.* (2014), as a part of the decision support framework for the management of urban transport projects (Jajac *et al.*, 2015). Marović *et al.* (2018) highlighted the importance of the maintenance planning aspect of DSS that is based on real-time collected and processed data by the means of ANN. As road management is a spatial problem, Coutinho-Rodrigues *et al.* (2011) proposed a spatial DSS where they highlight the importance of implementing Geographic Information Systems (GIS) for planning and decision-making purposes. Such is helpful not only for a static view of road networks, such as planning and maintenance activities but also could provide additional dynamic benefits such as traffic accidents (Durduran, 2010), all as a part of sustainable urban infrastructure management framework (Torres-Machi *et al.*, 2018).

4 Conclusions

This paper has presented a literature review concerning the applications of neural networks in managing urban road networks. In recent years, an understanding and application of neural networks have been significantly increased as they have been applied in a variety of matters. The conducted literature review gave insight in ways that the neural networks have been used in different life-cycle phases during the management of urban road networks for solving structured, technical problems that occur on the operational management levels, but also as one of the methods for solving semi-structured and unstructured problems that occur on tactical and strategic levels as a part of various decision support systems.

At the operational level, neural networks are mostly used for predictions of various asphalt mixtures properties during material production as well as during the exploitation period when the mixtures became part of the road network. At tactical and strategic levels, neural networks are often used as one of the methods for improving conditions or road elements, maintenance planning activities, projects prioritization, all as a part of a decision support framework.

Acknowledgements

This research has been fully supported by the University of Rijeka under the project number uniri-pr-tehnic-19-18 and uniri-tehnic-18-125.

ORCID

Ivan Marović: https://orcid.org/0000-0003-1524-0333.

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