DIGITALIZATION IN COST ESTIMATION OF ROAD INFRASTRUCTURE PROJECTS

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Abstract: Roads have a significant contribution to social progress and economic growth. Decision-making on the investments in road infrastructure projects is based on cost estimation. Although the introduction of digitalization revolutionized the cost estimation process and brought increased accuracy, reliability, and efficiency, recent studies show that cost estimates are still a challenging problem. In this paper, a literature review was conducted in order to review the existing digitalized approaches for cost estimation of road infrastructure projects and to analyze their basic elements, properties, and techniques. It was concluded that ML methods are widely used in developing cost estimation models, where the most common method is ANN. The implementation of digital tools, such as BIM and GIS, in the cost estimation of road infrastructure projects enables automation and real-time collaboration between stakeholders which encourages better communication and coordination leading to reduced errors. Their implementation also provides decision-makers with cost comparisons between alternative routes. It was concluded that the significant challenges faced in digitalization in cost estimation of road infrastructure projects are the quality and availability of data and the lack of skilled and trained personnel.

Keywords: *Digitalization, Cost Estimation, Machine Learning, BIM, GIS, Road Infrastructure*

1. INTRODUCTION

Transport of goods and passengers, in addition to being an indispensable component of the economy, also has a major role in social development. In 2020, road infrastructure accounted for 77.4% of total freight traffic in the EU, according to modal split data across road, rail, and inland waterways (Eurostat, 2022). Furthermore, road infrastructure emerged as the predominant mode for passenger traffic, constituting over 90% in 2018 (Eurostat, 2020). Road transport is also quite important in the European economy and society, contributing 11.5% to GDP (CEDR, 2013).

Road construction technologies have advanced over time, but investment in road infrastructure projects is as significant today as it was in the past. According to data from the World Economic

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Forum, from 2002 to 2015, the World Bank invested more funds in road construction and reconstruction than in education, health, and social services combined (World economic forum, 2015). Also, when compared to the preceding period, there has been a significant rise in investments in the construction and maintenance of road infrastructure projects over the past decade (OECD, 2022).

Decision-making on the construction or maintenance of road infrastructure projects is primarily based on cost estimations of those works and their expected benefits. Moreover, considering the importance of road infrastructure and the size of the investments in them, reliable, accurate, and user-friendly cost estimates are precious for decision-makers (Barakchi et al., 2017).

Traditionally, cost estimation in construction has relied on manual methods and historical data analysis that is time-consuming, and error-prone, leading to cost and time overruns. However, the introduction of digitalization revolutionized cost estimation process which brought increased accuracy, reliability, and efficiency. Different digital technologies (e.g. machine learning methods) and digital tools (e.g. BIM, GIS, project management software, etc.) have been employed for developing cost estimation models of road infrastructure projects so far. Although digitalization has brought enhancements in the cost estimation process, recent studies show that making accurate cost estimates during the initial stages of project development remains a challenging issue (Antoniou et al., 2023; Uysal & Sonmez, 2023).

In order to review the existing digitalized approaches for cost estimation of road infrastructure projects and to analyze their basic elements, properties, and techniques, a review of the available literature was carried out. The exhausting literature review led to the formulation of the subsequent research questions: What are the digital technologies and tools applied for developing cost estimation models of road infrastructure projects? Which methods are the most common? What are the achieved accuracies of the proposed models? How far it has come with the introduction of digital tools in the cost estimation process? What are the challenges associated with implementing digitalization in cost estimation?

2. MACHINE LEARNING AS DIGITAL TECHNOLOGY FOR DEVELOPING COST ESTIMATION MODELS

The authors use various machine learning (ML) methods to develop cost estimation models. Hashemi et al. (2020) concluded that the Artificial Neural Networks (ANN) were used in 55% of the cases to develop a highway construction cost estimation model. As well, He et al. (2021) concluded that the most commonly applied method for developing cost estimation models in construction is Multiple Regression Analysis (MRA), followed by ANN and Case-Based Reasoning (CBR). Also, Elmousalami (2020) reviewed the applied methods for the development of cost estimation models in construction and concluded that the most common methods are the ANN and hybrid models.

It can be concluded that the representation of methods depends on the set of analyzed literature. In the literature analyzed in this paper, there is a somewhat different usage of methods for developing cost estimation models of road infrastructure projects. Figure 1 shows the frequency of used methods. Certainly, the most common method is ANN, which is employed to develop cost estimation models in 70% of the analyzed studies. It is followed by MRA, which was used in 35% of the analyzed research, while the remaining methods (SVM, Random Forest - RF, and CBR), as well as hybrid models, were less frequently applied.

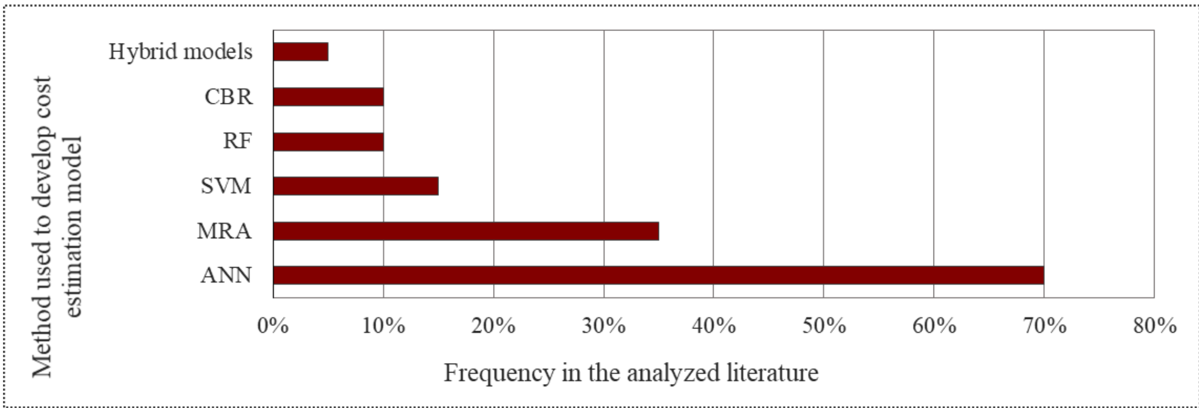

Figure 1. Methods for developing cost estimation models

One of the first studies involving the use of ML in developing cost estimation models of highway construction projects is that by Hegazy & Ayed (1998). The model was developed using ANN, and three methods were applied to determine the optimal weights: backpropagation, simplex optimization, and optimization using genetic algorithms, of which the first two methods proved to be the most suitable for the case study in question.

Wilmot & Mei (2005) examined the potential for improved performance of the ANN model in comparison to the MRA model with greater flexibility in the connections between input and output variables. It was concluded that, in general, the best results were achieved with five neurons in the hidden layer. Moreover, the results obtained using ANN demonstrated higher accuracy than the previous results obtained using MRA.

Pewdum et al. (2009) proposed a model for the estimation of the final costs and duration of road projects in Thailand during the construction phase. The results indicated a high agreement with the actual project outcomes, yielding a mean absolute percentage error (MAPE) of 2.56%. A comparative analysis between the outcomes of the proposed model and those of the existing project implementation monitoring procedure, based on the earned value method, was performed. The results revealed that the ANN model showed greater accuracy.

Elbeltagi et al. (2014) developed an ANN model for estimating highway construction costs based on projects implemented from 2001 to 2005 in Libya. The two-layer model, which contained 5 and 30 neurons respectively, after validation, showed a MAPE of 2.86%, which means that the relations within the training data are well observed.

In contrast to previous, deterministic estimates, Gardner et al. (2017) proposed a model for stochastic cost estimation. The authors believe that the stochastic approach to cost estimation reduces the impact of bias and optimism on cost estimation and increases transparency. A point ANN cost estimation model was developed and, with its further development, a model for stochastic estimation was proposed.

Tijanić et al. (2020) concluded that, in the case study of Croatian roads, the optimal model is a general regression neural network. This model is based on four input variables (road length, road width, contracted duration, and contracted costs) whose target variable is the unit cost of road construction per meter. This model gave a MAPE of 13.06%.

Peško et al. (2017) introduced models for the cost estimation of reconstruction of urban roads. The models were developed using ANN and SVM. A total of four ANN models and two SVM models were proposed. The MAPE of the ANN models for cost estimation ranges from 25% to 40%, while that of the SVM models is 7 to 15%.

Meharie & Shaik (2020) compared the performance of three groups of models developed using ANN, RF, and SVM. The models were developed based on road infrastructure projects in Ethiopia of different scopes and types of works. The models were compared using the root mean square error (RMSE). The results showed that the RF model offers cost estimates that are 18.8% and 23.4% more accurate compared to models developed using SVM and ANN, respectively.

Kim (2013) focused on developing a hybrid system for estimating highway construction costs in South Korea. The author applied the AHP method to determine the weights of individual cost drivers by pairwise and their categories comparison. Cost estimation modelling was performed using the CBR method, and performance evaluation, measured using the mean absolute error (MAE) yielded a result of 9.17%.

Mohamed & Moselhi (2022) proposed an approach for conceptual cost and duration estimation using data from US road, bridge, and drainage projects and an ensemble of ML models. An ensemble of ML models is created by combining ANN, SVM, and RF. Voting and stacking model ensembles showed the best results with an error of 4.3% and 4.5%. When comparing ANN, SVM, and RF models, the ANN model provided the highest accuracy, with an error of 14.2%.

In (Simić et al., 2023), the authors combined historical data from previous projects, expert opinions, and machine learning to develop a hybrid system. For the first time, eXtreme Gradient Boosting (XGBoost) was tested in the creation of a cost estimation model for road infrastructure projects and it yielded satisfactory accuracy with the low effort needed.

Table 1 summarizes the performance of existing cost estimation models from analyzed studies. It can be observed that, in most cases, models developed using ML methods provided higher prediction accuracy than MRA models. Also, it was observed that the application of the state-of-the-art ML methods has not yet been sufficiently tested in the application for developing cost estimation models of road infrastructure projects.

Table 1. Performance of ML cost estimation models

Source	**Project type and region**	**Method used**	**Best achieved model accuracy (error)**
(Karaca et al., 2020)	Road infrastructure projects in Montana	ANN MRA	ANN: 20% MRA: 21%
(Mahalakshmi & Rajasekaran, 2018)	Road maintenance projects in India	ANN	8.46%
(Sodikov, 2009)	Developing countries (World Bank database, the so-called Road Cost Knowledge System (ROCKS))	ANN MRA	ANN: 13% MRA: 32%
(Tijanić et al., 2020)	Roads of different classes and different scope of works realized in Croatia	ANN	13.06%
(Sodikov, 2005)	Road construction projects in Poland and Thailand	MRA ANN	MRA: 30% ANN: 19%
(Gardner et al., 2017)	Road infrastructure projects in Montana	ANN	23%
(Adel et al., 2016)	Road maintenance and new construction projects in Egypt	ANN	16%
(Peško et al., 2017)	Urban roads construction projects in Serbia (territory of the city of Novi Sad)	ANN SVM	ANN: 20.22% SVM: 7.06%

(Al-zwainy & Aidan, 2017)	Highway construction projects in Iraq	ANN	6.81%
(Kim, 2013)	Highway construction projects in South Korea	CBR	9.17%
(Tadesse & Dinku, 2017)	Road construction projects in Ethiopia	ANN	32.58%
(Mohamed & Moselhi, 2022)	Road, bridge, and drainage projects in the USA	RF SVM ANN	RF: 14.8% SVM: 16.7% ANN: 14.2%
(Elbeltagi et al., 2014)	Highway construction projects in Libya	ANN	2.86%

3. DIGITAL TOOLS FOR DEVELOPING COST ESTIMATION MODELS

Building Information Modeling (BIM) operates as a modern (digital) tool aimed at addressing both technical and economic challenges associated with construction projects (Vitásek & Zak, 2018). In most cases, the application of BIM in cost estimation in construction refers to automated quantity take-off as part of cost estimation rather than unit pricing (Morovvati et al., 2021).

Vitásek & Zak (2018) suggested a method for developing a construction works budget derived from the BIM model. The procedure includes five steps: BIM execution plan, information modeling, quantity statement (area and volume), quantity take-off, and construction budget. The implementation of the procedure was shown on case studies of two highway reconstruction projects.

Gołaszewska & Salamak, (2017) explored the potential applications of BIM technology in quantity take-off and cost estimation, using a road bridge model as an example. The authors concluded that the efficient utilization of BIM relies on effective communication within the workgroup, necessitating continual interaction among its members.

Fürstenberg et al. (2024) explored the automation of quantity take-off in practical road project (highway construction project in Norway). Based on experience from this automation, the authors gave recommendations to enhance the reusability of automated quantity take-off in road projects. These include standardizing the exported data structure and avoiding hardcoded cost breakdown structure in authoring tools.

Taking into account the impact of the project location and terrain topography on costs, a certain number of researchers have also applied Geographic Information Systems (GIS) to estimate the total costs of road construction or its individual items. Le et al. (2019) proposed a framework for the estimation and visualization of unit costs of individual cost items based on GIS and historical unit cost data. The authors point to the great influence of the project location on the unit costs.

In (Shrestha & Shrestha, 2014), authors developed a tool for cost estimation aimed at aiding Department of Transportation (DOT) offices in the decision-making process for the maintenance and improvement work of roads. They linked it with GIS interfaces for visualizing road conditions on maps and Google Earth application as well.

The system based on BIM/GIS that was proposed by Park et al. (2014) for the selection of the optimal route of the national road offers decision-makers enhanced project delivery capabilities. This system calculates overall project costs for each route, encompassing construction, operation, and maintenance costs. The suggested system facilitates decision-makers' cost comparisons between alternative routes and empowers them to choose the optimal route. The GIS platform identifies the route entities (roads, bridges, and tunnels) and their position within the route. The system also enables the estimation of costs related to earthwork and land acquisition. On the other hand, the BIM platform provides the connection among 3D visuals and route entities' specifications.

4. DISCUSSION

The benefits of digitalization in the cost estimation, as well challenges associated with its implementation are shown in Table 2.

Table 2. Benefits and challenges associated with cost estimation

Benefits	Challenges
Improved accuracy	*Data quality and availability*
Improved reliability	*Skills and training requirements*
Reduced bias	
Increased efficiency	
Real-time collaboration	

As stated in Section 2, models developed using ML methods provide higher prediction accuracy than models developed using traditional statistic methods. As well, the implementation of digital technologies and tools led to improved reliability and reduced bias in the cost estimation process, as the involvement of humans is reduced as much as possible. When compared to traditional manual methods, with ML methods, cost estimates can be obtained more quickly and with fewer resources. As shown in previous section, the use of BIM enables automated quantity take-offs which makes cost estimates more reliable and efficient. In addition, BIM enables real-time collaboration between stakeholders which encourages better communication and coordination leading to reduced errors. Using GIS, road conditions and location can be associated with the cost estimation process. This enhances prediction accuracy as project costs are greatly influenced by project location. GIS also enables better visual interpretation and provides decision-makers with cost comparisons between alternative routes.

One of the significant challenges faced in cost estimation of road projects is the quality and availability of data. This issue is not only related to the implementation of digitalization in cost estimation. Often, data is unavailable or incomplete or it lacks standard formats. The serious issue associated with implementing digitalization in cost estimation is the lack of skilled and trained personnel. The adoption of digital technologies and tools is still a challenging task in most countries and it will take time for their proper implementation.

5. CONCLUSION

Decision-making on road infrastructure projects is primarily based on cost estimations. Having in mind their importance, it is of valuable interest to have efficient, reliable, and accurate cost estimates. The digitalization in the cost estimation process represents transformative shifts offering the opportunity to enhance these goals.

Throughout this paper, the authors have explored the digital technologies and tools used for developing cost estimation models of road infrastructure projects. It is concluded that ML methods are widely used in developing cost estimation models, where the most common method is ANN, which is used in 70% of the analyzed studies. The other ML methods, ensemble models, and hybrid systems have also brought significant improvements in the cost estimation of road infrastructure projects. In addition, the implementation of BIM and GIS provides increased efficiency and accuracy of cost estimation, and real-time collaboration as well. The implementation of these digital tools is mostly limited to automated quantity take-off and should be expanded. The main challenges associated with implementing digitalization in cost estimation are data quality and availability and skills and training requirements.

Due to the required scope, this paper is limited to a certain level of analysis. Further research will include a larger scope of literature and their in-depth analysis, as well as exploring innovative solutions and strategies to overcome stated challenges associated with implementing digitalization in cost estimation. The future of cost estimation in road infrastructure projects is undeniably digital.

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