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ARTIFICIAL INTELLIGENCE IN ROAD CONSTRUCTION: PROSPECTS AND CHALLENGES

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Purpose: Artificial Intelligence (AI), along with other technologies associated with Industry 4.0, has had an expanding impact on all sectors of the economy. Implementing AI technologies in road construction promises a number of benefits, including increased safety and productivity, improved quality of work performed, and reduced costs. The paper reviews various applications of AI in road construction. Additionally, it analyses the potential challenges and risks that hinder the rapid adoption of AI in this industry.
Design/methodology/approach: In total, 54 references were analysed to determine what AI is, its main technologies, how and where these technologies are used in the road construction industry, and the challenges faced in implementing AI.
Findings: The most significant applications of AI in road construction were recognised, covering the entire life cycle of a road, from planning to maintenance. The main challenges to be overcome for further AI implementation in road construction were also identified.
Research limitations/implications: The paper is limited to technological processes related to road construction and operation and does not examine other related areas, such as intelligent transport systems.
Originality/value: The paper informs society and professionals in road construction about current trends in the use of AI technologies; it will facilitate their further adoption and address existing challenges.
Keywords: artificial intelligence, road construction, review.
Category of the paper: Literature review, viewpoint.

1. Introduction

The road construction industry is one of the vital parts of any country's economy, contributing to a better distribution of productive forces and more efficient use of resources (Rahman et al., 2020). It also strengthens interstate relationships and creates a common market.

That is why the USA, as well as the most developed countries in Europe and Asia, declared the development of road infrastructure as one of the priorities of public policy. For example, governments in the EU spent more than EUR 112 billion a year over the last decade (Meijer et al., 2018), and investments are projected to grow at a compound annual growth rate of over 6% to 2032 (Highway, Street, and Bridge Construction Market, 2032 Report). According to experts, the road network of EU countries alone spans more than 5.5 million kilometres and has shown a continuous growth trend. In Ukraine, before the war, the network of paved roads was approximately 170 thousand kilometres. This rapid growth of roads and highways demands new solutions and approaches not only in the organisation and execution of construction works but also in monitoring and maintaining the quality of existing roads. However, in many countries, including Ukraine, the road construction industry still relies on traditional labour-intensive production methods that are characterised by high energy consumption, environmental pollution, safety risks, and low productivity (Axelsson, Froberg, Eriksson, 2018; Wu et al., 2019). The situation could change with the adoption of Industry 4.0 technologies. The promising concepts of Industry 4.0 are benefiting various industries, and now they are gradually penetrating road construction. Industry 4.0 can be described as the integration of the physical and digital worlds through the adoption of new technologies such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), 3D printing, and Artificial Intelligence (AI) in industrial fields (Bongomin et al., 2020; Bai et al., 2020; Turner et al., 2021).

As mentioned above, AI is one of the key technologies of Industry 4.0. This paper aims to describe the most promising applications of AI in the road construction industry, as well as highlight the challenges and concerns that the adoption of AI in this sector may face.

Before exploring the application of AI technologies in road construction, let us define what AI is and what technologies fall under the definition of AI that we will consider further.

2. AI definition and technologies

Although the term "Artificial Intelligence" appeared in 1955 (McCarthy et al., 2006), there is still no unified definition. Many researchers (Fetzer, 1990; Lucci, Kopec, Musa, 2022) focus on the concept of intelligence, leaving it to the readers to formulate the definition on their own. Others present their definitions. Some of these definitions are summarised in Table 1. This table shows that as technology evolves over time, the definition of AI also changes. The first definition was introduced by John McCarthy with co-authors in a proposal for the Dartmouth Conference (McCarthy et al., 2006) held in 1956. They defined it as "The science and engineering of making intelligent machines". This reflects early ideas about creating machines capable of mimicking a human being. Further, John McCarthy expanded this definition: "It is the science and engineering of making intelligent machines, especially intelligent computer programs. It is related to the similar task of using computers to understand human intelligence, but AI does not have to confine itself to methods that are biologically observable".

Table 1.
The evolution of AI definition over time

Definition	Year	Researcher(s)	Reference
The science and engineering of making intelligent machines.	1955	J. McCarthy, M.L. Minsky, N. Rochester, C.E. Shannon	(McCarthy et al., 2006)
The science of making machines do things that would require intelligence if done by men.	1969	M.L. Minsky	(Minsky, 1969)
AI is the study of techniques for solving exponentially hard problems in polynomial time by exploiting knowledge about the problem domain.	1983	E. Rich	(Rich, 1983)
AI is the part of computer science concerned with designing intelligent computer systems, that is, systems that exhibit the characteristics we associate with intelligence in human behavior – understanding language, learning, reasoning, solving problems, and so on.	1981	A. Barr, E.A. Feigenbaum	(Barr, Feigenbaum, 1981)
AI is the study of the computations that make it possible to perceive, reason, and act.	1992	P.H. Winston	(Winston, 1992)
The branch of computer science that is concerned with the automation of intelligent behavior.	1993	G.F. Luger, W.A. Stubblefield	(Luger, Stubblefield, 1993)
The study of agents that receive percepts from the environment and perform actions.	1995	S. Russell, P. Norvig	(Russell, Norvig, 1995)
Computational Intelligence is the study of the design of intelligent agents.	1998	D. Poole, A. Mackworth, R. Goebel	(Poole, D., Mackworth, A., Goebel, R., 1998)
AI…is concerned with intelligent behavior in artifacts. Intelligent bahavior, in turn, involves perception, reasoning, learning, communicating, and acting in complex environments.	1998	N.J. Nilsson	(Nilsson, 1998)
AI will be such a program which in an arbitrary world will cope not worse than a human.	2004	D. Dobrev	(Dobrev, 2004)
AI is the automation of thought, where intelligent behavior is produced by any means, whether programmed or learned from data.	2015	P. Domingos	(Domingos, 2015)
AI is generally defined as the ability of a system to accurately interpret external data, learn from it, and adapt flexibly to achieve specific objectives.	2019	A. Kaplan, M. Haenlein	(Kaplan, Haenlein, 2019)
AI as a collection of all kinds of technologies and methods, which are used to execute human brain-related tasks, especially cognitive tasks such as learning and problem-solving.	2021	W. Lyu, J. Liu	(Lyu, Liu, 2021)
AI enables machines to execute cognitive tasks with minimal or no human interaction	2022	M. Ashok, R.J.A. Madan, R.U. Sivarajah	(Ashok et al., 2022)
AI is defined as an unnatural object or entity that possesses the ability and capacity to meet or exceed the requirements of the task it is assigned when considering cultural and demographic circumstances	2023	S. Kelly, S-A. Kaye, O. Oviedo-Trespalacios	(Kelly et al, 2022)

Hopfield's neural network, proposed in 1982, triggered new interest in AI, and AI began to be used for solving complex computational problems, as well as for speech recognition and translation, reasoning, etc. (Rich, 1983; Barr, Feigenbaum, 1981; Zhang, Lu, 2021).

The mid-1990s are characterised by a new concept of “intelligent agent” (Russell, Norvig, 1995; Nilsson, 1998), which interacts with the environment to achieve a goal.

In the last two decades, AI has been seen more broadly as the ability of machines to use the data they receive to make judgments and decisions on their own.

Summarising current trends, we can define AI as software that makes its own decisions based on analysing data it receives from outside whilst constantly learning to make better decisions.

AI involves a wide range of technologies, which are closely interrelated and often overlap because their algorithms and operating principles use similar methods and approaches. The main AI technologies are as follows:

- Machine Learning (ML),
- Deep Learning (DL),
- Natural Language Processing (NLP),
- Computer Vision (CV), and
- Robotic Process Automation (RPA).

All these technologies rely on big data analysis to train models, and ML is the fundamental technology on which the other technologies are built (Figure 1).

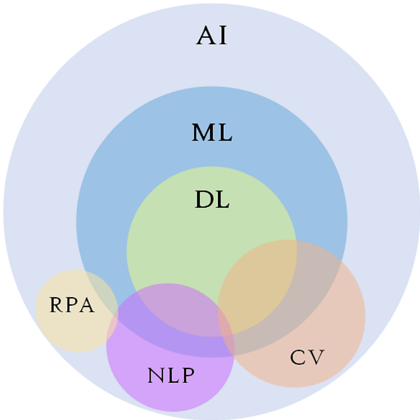

Figure 1. Basic AI technologies.

Source: Based on (Abdullah, Ahmad, 2021).

Consider the application of these technologies in road construction.

3. AI applications in road construction

Even a brief literature review has established that AI is used at all stages of a road lifecycle, from design to maintenance and pavement quality (Figure 2).

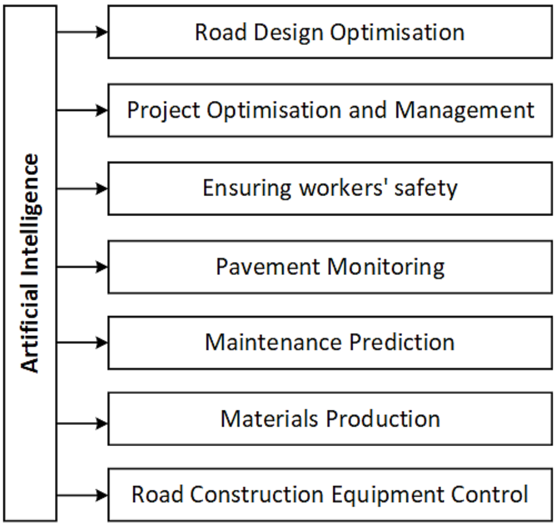

Figure 2. The main AI applications in the road construction industry.

Source: Source: Own work.

3.1. Design and project management

One of the promising uses of AI in the road construction industry is to improve the quality of project design and management. AI algorithms process big data and assess possible risks to optimise road construction planning, determine the optimal amount of materials, and develop logistics, reducing errors in the construction process, while RPA allows for a significant increase in the speed of construction (Khan et al., 2024). For example, such a solution for using AI for road construction planning is described in (Shinde et al., 2020). ML identifies patterns in multiple recorded datasets to determine how long it will take to complete road construction at a particular site, how much raw material is needed, how many workers, and more. Blockchain will ensure the integrity of contracts between stakeholders. ML can also estimate road quality and plan maintenance by analysing users' feedback.

Road construction projects are constantly faced with the problem of time and cost overruns, which negatively affect the budget and economy. In (Naik, Radhika, 2015), the authors developed various models based on Artificial Neural Networks (ANN) to estimate the cost and duration of construction works by analysing the database of previous projects. In (Tijanić et al., 2020), ANN was also used to estimate expected road construction costs. This approach is promising and helpful in the early stages of road project development when only limited or incomplete data are typically available for cost analysis. Florence and co-authors proposed an approach that uses ChatGPT to automate the generation of question-answer pairs to predict delays in road construction projects (Florence, Kikuchi, Ozono, 2024).

3.2. Asphalt production

Asphalt concrete is one of the most commonly used materials in road construction. The quality of asphalt concrete plays a crucial role in ensuring road pavements' durability, safety, and reliability. Therefore, optimising the production of asphalt concrete and controlling its quality are critical challenges in the construction industry. The application of artificial intelligence to analyse the quality of asphalt concrete can significantly improve the efficiency of road construction and maintenance. In (Arifuzzaman et al., 2021), the authors implemented ML to predict the influence of environmental factors, binder types, and Carbon Nano Tube doses on the adhesion force of the asphalt surface. This knowledge can help provide a more durable and resilient asphalt pavement. Botella et al. investigated the application of ML to estimate the degree of binder activity on a reclaimed asphalt pavement (Botella et al., 2022).

Androjić and Marović developed models based on ANN and multiple linear regression to predict the properties of hot asphalt concrete mixtures (Androjić, Marović, 2017). In papers (Sebaaly, Varma, Maina, 2018; Rahman et al., 2021; Liu et al., 2022), ML has been used to optimise the design of asphalt concrete mixtures with specified properties. The research mentioned illustrates different approaches to ML application to analyse the quality of asphalt concrete and optimise its production.

3.3. Construction

Even proper asphalt is not enough to construct a high-quality highway. To provide the road with the necessary properties, it is essential to prepare its base, deliver the asphalt to the construction site without losing its qualities, lay it following specific technologies, and compact it properly.

To prepare a road base, it is necessary to know the physical parameters of the soil. Determining soil properties under laboratory conditions is expensive and labour-intensive. Therefore, various ML techniques and ANN are used to determine the soil type, conditions and properties (Ayawah et al., 2022; Kanungo, Sharma, Pain, 2014). To improve the prediction performance, other technologies, such as Fuzzy Logic and metaheuristics, can be used along with ML (Pham et al., 2018; Tien Bui, Hoang, Nhu, 2019).

In (Kuenzel et al., 2016), an intelligent agent-based system is presented that automatically generates driving instructions for a compactor operator, guiding them on where to steer based on the vehicle's current position. The decision-making process considers the work plan, the trajectories of other compactors, the actual progress of the paver, and changes in environmental and material-related parameters.

ML is also used to control other construction machinery (Kurinov et al., 2020; Egli, Hutter, 2022), as well as to predict their failure (Lige, Hua, Feng, 2019).

3.4. Safety

In (Zhu et al., 2022), DL algorithms have been used to process images received from UAVs to survey large construction areas to automatically detect signs and guardrails to ensure that they are not missing or damaged. In addition, the authors have suggested tracking the trajectories of road construction vehicles and constructors to warn them of their dangerous behaviours early.

Road worker safety is also the focus of a paper (Sabeti et al., 2021) where DL is used to detect and classify vehicles in advance and warn workers of potential dangers by wirelessly transmitting notifications to devices using Augmented Reality (AR) technologies.

3.5. Monitoring of pavement condition

Road surface defects are a serious problem for safe and smooth traffic flow. Due to the effects of climate, poor quality of construction materials and violation of construction standards, high traffic, the road pavement deteriorates rapidly. Detecting and repairing these defects is essential to ensure traffic safety and maintain road capacity. AI technologies, particularly CV and ML, are used to detect pavement deformation, such as potholes, bumps and cracks (Emoto et al., 2023; Paramasivam et al., 2024). Such systems can operate either independently, receiving information from cameras installed along the roadside, on UAVs (Silva et al., 2023), or be integrated into autonomous vehicles (Bibi et al., 2021).

4. Benefits and challenges of AI applications in road construction

AI in road construction offers significant advantages in solving complex engineering and management problems that are difficult to solve using traditional methods (Darko et al., 2020; Pan, Zhang, 2021). In particular, AI can reduce road design time and create more optimised designs considering demographic, economic, and environmental factors. In project management, AI helps identify and address hidden and unobservable factors that affect a project's cost, timing, and success. AI technologies make it easier to monitor road construction progress, offering timely solutions to maintain the pace and timelines of construction. AI is also helping to improve workers' safety.

AI can estimate pavement quality and predict the need for maintenance work by analysing data on pavement state, weather conditions, and traffic. It facilitates preventing accidents and reduces the cost of urgent repairs. AI also helps engineers and scientists develop new construction materials.

Therefore, the use of AI in road construction can reduce costs and shorten the time period for both road construction and subsequent maintenance. In addition, AI improves labour safety and contributes to reducing environmental pollution by mitigating human error and speeding up the process of making more accurate decisions.

However, despite the evident advantages, the implementation of AI technologies in road construction presents several less apparent challenges. One such challenge is the substantial investment required for new software, hardware, and staff training.

Another concern is that AI makes decisions based on exploring large data sets. Therefore, the data's availability, completeness, and relevancy become important limitations for the effective application of AI technologies. Moreover, despite advances in ML algorithms, errors in data interpretation and decision-making are still possible, which can undermine the credibility of AI. These errors need to be identified and corrected on time.

There are also remain issues related to data intellectual property rights and privacy. The legal consequences of AI decisions are still not entirely clear, especially when errors lead to financial losses or more severe consequences.

5. Conclusions

This paper has only briefly touched on the prospects for AI applications in the road construction industry. For example, the use of AI in creating intelligent transportation systems has not been covered. Such issues as construction monitoring, road wear prediction, maintenance planning, and the control of fully autonomous road vehicles were only briefly mentioned. However, this review indicates that AI will likely play a significant role in road construction, contributing to intelligent transport infrastructure development. Current challenges and limitations are expected to be addressed through new research and the implementation of legal regulations.

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