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A mini-review of the development and use of expert systems in mining

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Abstract

Purpose. The mining industry is one of the sectors that have benefited from expert systems over the years. This review aims to analyze developments in using expert systems in mining.

Methods. The approach used involved searching, screening, and selecting relevant published studies following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) methodology. A total of 32 ($n = 32$) articles reporting on specific expert systems developed for the mining industry were considered for further analysis while 21 ($n = 21$) were excluded from the study. The analysis looked at the nature of the reported expert systems, their mining application areas, and the tools used to develop them.

Findings. The results reveal that there is generally an increase in the development and use of expert systems in the mining sector. The abundant availability of expert system shells and the adoption of recent digital technologies such as cloud computing and the Internet of Things (IoT) present a potential for further development of expert systems in the mining industry.

Originality. This is the first review of the trends in the development and use of expert systems in mining.

Practical implications. This work's findings give insights into the trends and opportunities for the development and application of expert systems in mining. The growing use of expert systems in making sound decisions in mining has the potential to make future mining operations safe, profitable, and sustainable.

Keywords: *expert system, mining, IoT, cloud computing, expert system shells*

1. Introduction

The different stages in the life of a mine involve activities in which a set of informed expert decisions guide their implementation. Based on this, various computer programs are used to analyze facts to help experts make informed decisions in different areas of mining operations. Computers are extensively used in orebody evaluation, mine planning, mine surveying, equipment selection and scheduling of activities, financial modeling, geotechnical information, mining operations, and mine atmosphere monitoring and ventilation [1], [2]. The industry has also benefited from using expert systems (ESs) that help and guide the decision-making process in different stages and areas of the mining sector. Some reasons behind the increased development and use of expert systems in mining and other industries are limited and expensive expert thoughts and the need to make similar decisions in similar situations [3]. Generally, in the mining sector, the use of expert systems has been witnessed in areas like geology, engineering design, and mining engineering [4]. They are computer programs that mimic experts in specific knowledge domains [5], [6] and they are mostly developed to substitute or assist human experts [3]. According to Ikram and Qamor [7], expert systems give pieces of advice and explain the logic behind the advice if necessary. This study critically analyzes the developments or trends in using expert systems in different mining activities. It focuses specifically on mining operations as well as closure and rehabilitation. Thus, it did not consider the application of expert systems in geology (including mineral exploration and orebody evaluation) and mining-related industries, such as the petroleum industry.

Expert systems are a branch of applied artificial intelligence [7], [8] concerned with acquiring and programming expert knowledge to create computer programs that work like human experts in defined knowledge fields [9]-[11]. They are intended to act like human experts, who can be consulted on some problems in their area of expertise [6]. They have numerous advantages, including the fact that they reduce the time spent learning some tasks [10], many copies of expert systems can be made thus significantly reducing the cost and time of training many people, and they can also provide constant answers and/or recommendations in similar situations [12]. On the other hand, some of the disadvantages of these systems are that they lack common sense; hence, they

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are unable to provide creative answers, any errors in the system's knowledge base can lead to wrong advice being given, and they need to be updated continuously to provide answers in a changing environment. It is important to note that, in general, the advantages of these systems outweigh their disadvantages. Consequently, expert systems have been developed and used in many fields, of which the medical field was the first [13]. Other fields that now use expert systems to support the decision-making process include geology, engineering and manufacturing, management, military, and education and training [4], [14].

The first and most popular expert system in the mineral industry is called a PROSPECTOR and was developed in the 1970s [13], [15], [16]. Since the development and use of this expert system in the industry, many other systems have been developed. According to Yatabe and Fabbri [16], the DIPMETER ADVISOR is the most complete commercial expert system developed for geology. It should be noted that as different expert systems are being developed for geology, similar efforts have been made in mining engineering. In the 1980s, Ramani and Prasad [17] proposed the development of expert systems for mine ventilation and strata control design. To date, different researchers and organizations have developed and published expert systems to support decision-making in different areas of mining.

Although expert systems are developed for different purposes and are different, they share a similar fundamental structure [18]. They all comprise an interference engine, user interface, knowledge base, and rule base. They are sometimes created using expert system shells and various artificial intelligence (AI) programming languages [19]. The general components of the expert system are listed in Table 1.

Table 1. The four important components of the expert system

Components	Description
 Interference engine	The part of the expert system responsible for reasoning to solution of the expert system. The reasoning of the expert system follows IF-THEN rules in the *backward* or *forward* chaining. This part of the expert system is responsible for determining the sequence of rules that the expert system should execute to provide a solution to the problem domain: – backward chaining: when the rules start from a goal and end with the conclusion; – forward chaining: when the rules start from a conclusion and end with the goal.
 User interface	Is a specially designed mechanism of communication between the user of the expert system and the expert system itself. It is recommended that the user interface of the expert system be easy to use with very little or no erroneous errors and that the questions and answers be clear.
 Knowledge base	The component of an expert system that contains organized factual and empirical knowledge of experts in the system's domain. It carries the rules (presented in the IF-THEN format) used by the system to solve problems or provide advice to the end-user of the expert system.
 Expert system shell	Is a special software environment for building expert systems. They are known under different names, such as expert-system builder tool or knowledge-based system toolkit. The most used expert systems shells include CLIPS, JESS, AION-DS, EMYCIN, PROLOG, ES-BUILDER, EXSYS CORVID, Art Enterprise, and MP2, to name a few.

The different types of expert systems are rule-based, web-based, frame-based, fuzzy logic-based, hybrid, model-based, real-time expert, and ready-made systems [20]-[22]. In general, the development of an expert system involves four important steps [23]:
- defining the problem and domain of the expert system;
- knowledge acquisition;
- system development through programming or the use of the expert system shell;
- testing and verification of the expert system.

2. Methods

The methodology adopted in this study followed the stepwise procedure of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) illustrated in Figure 1.

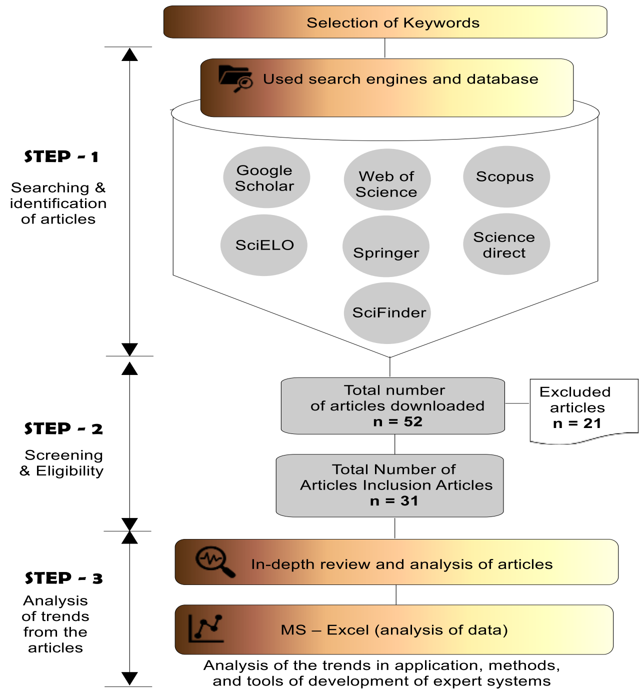

Figure 1. The PRISMA flow diagram of the systematic review process followed in the study

Academic articles reporting on the development and application of expert systems in the mining industry were gathered from different online databases. Search engines and databases, such as Google Scholar, Web of Science (WoS), Scopus, SciELO, Springer, Science Direct, and SciFinder, were used to search and/or access the relevant articles for the study. The keywords used to search for these articles were carefully selected. Among others, they included "mining expert systems," "expert systems in mining," "artificial intelligence and mining," and "expert systems and mining." In the effort to access relevant articles through search engines such as Web of Science (WoS), Boolean operators ("AND" and "OR") were employed. Examples of how these operators were used to combine search terms include:
- ("Expert system" AND "mining operations");
- ("Artificial intelligence" OR "expert systems" AND "mine planning").

It is important to note that only full-text, free, or open-access articles written in English were considered for the study. Moreover, articles whose full text were not accessible, and newsletters were excluded. In the mining context, the focus was on expert systems developed and used in the engineering aspect of mining (broadly, mine planning, operations, and rehabilitation of mined lands).

Expert system applications in mineral exploration and resource management and drilling for exploration or oil and gas exploitation were excluded. The year of publication, region, and location of the publications were not considered important criteria for the inclusion and exclusion of articles. These criteria identified 52 articles on developing and applying expert systems in the mining industry. However, approximately 21 of the gathered articles were excluded, while 31 were found eligible and were thus included in the study. Each of the eligible articles was thoroughly reviewed. The name or nature of the expert system reported, its uses in mining, and the tools or platform used to develop it were extracted and the trends were analyzed basic Microsoft Excel graphing tools were used to visually compare and highlight trends in developing, applying, and publishing articles related to expert systems in mining. As shown in Figure 2, the articles considered in this study were published between 1986 and 2023. It is important to note that the literature search process was designed to comprehensively gather and consider all relevant articles for inclusion in the study. Consequently, the search was not limited to a pre-defined period. Such expert systems have been developed and used in various mining operations, including mine planning, mining operations, equipment selection, mine ventilation, and mine closure and rehabilitation. Table 2 shows the percentage distribution of the articles reviewed in the above-mentioned mining areas.

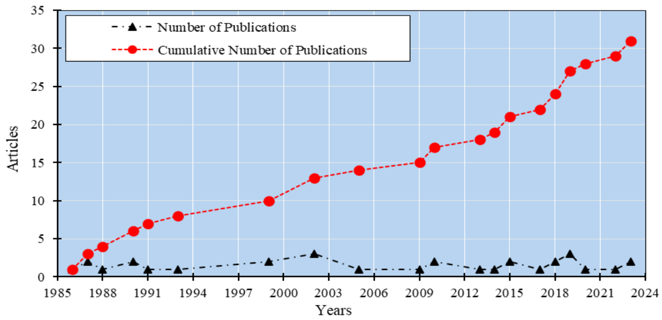

Figure 2. Articles published on expert systems developed for different aspects of mining

Figure 3a depicts the analysis of the regional distribution of the articles or studies on the development and use of expert systems in mining. In this case, countries like Canada, Poland, the United States of America (USA), and China reported a high number (4 studies per country) of studies on the general application and development of expert systems in mining. South Africa and India followed this with three studies each while Germany and the United Kingdom contributed two studies each. Chile, Australia, Turkey, Morocco, Brazil, the Republic of Serbia, and the Republic of Kazakhstan; each contributing only one study. While most developed expert systems in these countries are in mine operations and planning, South Africa, Canada, Poland, and Brazil also showed in mine closure and rehabilitation (Figure 3b-c). In general, selected studies on the use of expert systems in mining were from countries with a well-developed mining industry.

Table 2. The percentage distribution of the articles published in different problem domains

Area*	Knowledge domain	Publication No.	Publication %
MO	Mine stope stability	13	41.9
	Prevention of dilution and ore loss		
	Assess the caving output ratio		
	Safety analysis in coal mines		
	Design and evaluation of a crushing plant		
	Decision support in mining		
	Prediction of maximum explosive charge		
	Safety early warning management of coal mining		
	Managing underground coal mines		
	Automation of processes of mining and transport works		
	Estimation of mining environment (including gas and rock outburst risk)		
	Assessment of slope stability		
EQS	Monitoring of mining haul trucks	05	16.1
	Selection of equipment for surface mine		
	Selection of hydraulic excavator and truck in surface mining		
	Selection of equipment for mining thin coal seam		
MP	Mining method selection and optimization of the mining operations	03	9.7
	Support mine planning operations		
	Underground coal mine planning		
	Formulation of coal mining projects		
MV	On-line ventilation network analysis	03	9.7
	Ventilation and emergency rescue		
MCR	Prioritization of rehabilitation of mine sites (including abandoned mines and sites affected by ARD)	07	22.6
	Selection of soil for land rehabilitation		
	Provide pieces of advice on the focus of post-mining restoration		
Total		31	100

*Note: MO is mining operations; EQS is equipment selection; MP is mine planning; MV is mine ventilation; MCR is mine closure and rehabilitation

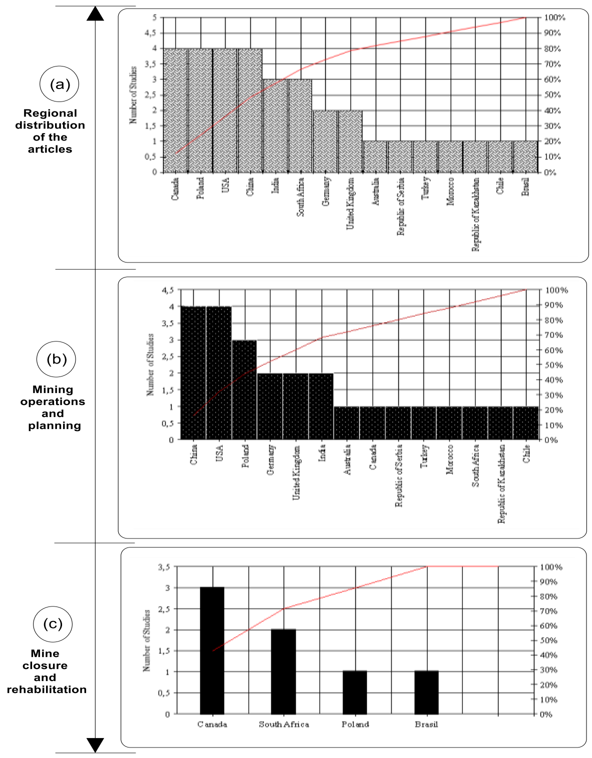

Figure 3. Regional distribution of articles of development and use of expert systems

3. Results

3.1. Areas of mining with high potential for adoption of expert systems

In general, the mining sector is characterized by numerous challenges and different forms of risks. Some of these challenges and risks are the lack of a skilled workforce [24], [25], issues related to cost and productivity, license to operate coupled with geopolitical issues, environmental problems (including climate change-related problems) [26]-[28], and the recent but fast-growing challenge related to cyber security. All these issues and others have led to the mining industry being one of the most heavily regulated industries in many jurisdictions. Moreover, the industry requires all activities be conducted with the highest level of precision to ensure compliance and sustainability. This puts pressure on a few already stressed experts in the industry. To lessen the pressure on experts and help improve the quality of their decisions, advice, and analysis, various organizations and mining entrepreneurs have developed a mixture of computer programs for the industry. Some computer programs are based on expert systems. An analysis of the development and use of expert systems in the mining industry is shown in Figure 4.

The analysis showed that the efforts and applications of these systems in the mining industry is on an increasing trajectory. This follows the general trends in the development and use of recent technologies in the mining industry, as the industry endeavors towards the 4th Industrial Revolution (4IR) [29].

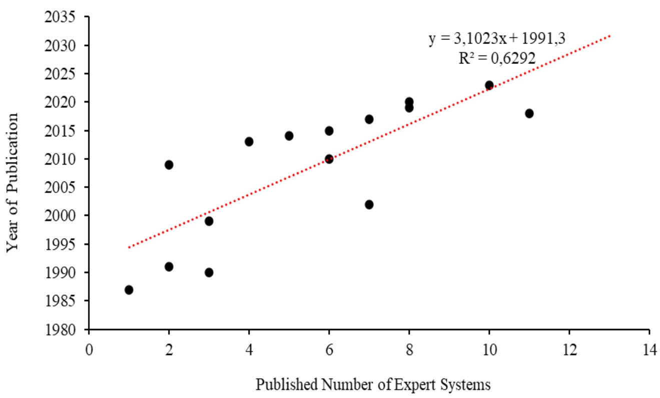

Figure 4. The trends in the development and use of expert systems in mining

In addition to the initial application of expert systems in geology, their use has grown in different areas of mining engineering [4], [17]. According to Chekushina et al. [30], many expert systems have been developed and applied to solve problems in mine planning, ventilation and operations, environmental protection, and equipment selection. An analysis of the published studies on expert systems designed for the mining industry showed that more systems have been developed for mining operations, followed by mine closure and rehabilitation, mine planning, and equipment selection. This is not surprising given that most new technologies adopted by the mining industry are applied in the production or operation stage of a mine's life [31].

In the case of mine closure and rehabilitation, the efforts to develop expert systems are exacerbated by the fact that this area is characterized by very few experts.

Moreover, in many countries with a long history of mining, there are a huge number of mines that were abandoned and need to be rehabilitated. Just to mention a few; these countries include the United States of America (USA), Australia, Canada, South Africa, Japan, Sweden, Peru, Namibia, and Ireland.

3.2. Expert system development tools

Several algorithms are available for developing expert systems. Initially, expert systems were developed using artificial intelligence (AI) languages such as LISP, PROLOG (TC-Prolog and FProlog), Java, C++, Pascal, and Fortran, to mention a few. However, other tools such as shells and rule induction software are now available. Therefore, expert systems in the mining sector have been developed using various tools or algorithms (Table 3) over the years.

However, Figure 5 shows that expert system shells are becoming more popular than traditional artificial intelligence languages in developing expert systems for the mining industry. Other highly used algorithms include fuzzy-logic systems or methods.

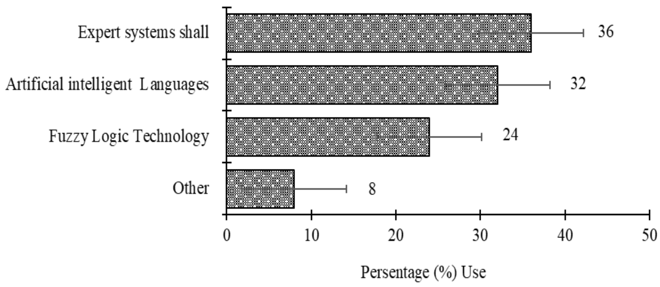

Figure 5. Percentage distribution of the use of different expert system development environments

Table 3. Development tools and algorithms

Development method	Application of an Expert System*					Reference
	MO	EQS	MP	MV	MCR	
LIPS Language	1					[32]
X-Window System	1					[19]
PROTECTOR System	1					[33]
IACC Shell	1					[34]
RapidMiner	1					[35]
ANN Network	1					[36]
Fuzzy Logic Technology	2		1		3	[4], [20], [37]-[40]
KappaPC Shell		1				[6]
Xi-Plus Shell		1				[41]
MYCIN Shell		1				[42]
Machine Learning Algorithms		1				[43]
C5.0 Algorithm			1			[44]
BABYLON-Hybrid Expert Shell			1			[45]
JAVA Language			1			[46]
Insight 2+ Language				1		[47]
IITMRULE Shell				1		[48]
KBCI				1		[49]
ES-Builder Shell					2	[5], [50]
COMDALE/X Shell					1	[23]
Total	8	4	4	3	6	

*Note: MO is mining operations; EQS is equipment selection; MP is mine planning; MV is mine ventilation; MCR is mine closure and rehabilitation

4. Discussion

Mining is expensive and risky. Consequently, justifying and implementing innovation in the mining industry is difficult [51]. On the other hand, for the mining companies to remain in business, they must embrace and implement innovation in their operations. According to many authors (including Olvera, [52]), the main drivers behind adopting innovation in the mining industry are the company's need to reduce operational costs and risks, while improving safety, increasing productivity, and ensuring sustainability. Digitization, coupled with the need for the mining industry to be efficient, has opened doors for digital technologies, such as cloud computing, artificial intelligence (AI), and the Internet of Things (IoT). Therefore, applications of artificial intelligence tools and algorithms, including expert systems across the mining value chain, have gained momentum over the years. More importantly, the findings of this study demonstrate that expert systems have been extensively applied to optimize mining operations across the entire mining value chain, while areas such as mine planning and ventilation have benefited the least from their use.

Expert system shells have been made available to make developing an expert system easy, even for people with no computer programming skills. These shells have contributed greatly to the development of expert systems (including those used in the mining sector, as supported by the findings of this study). This is partly because of the numerous advantages that expert system shells have over the use of artificial intelligence programming languages, fuzzy logic, and other platforms for expert system development. Such advantages are that the shells are readily made without the knowledge base, but with rule-chaining models. Moreover, shells are an important environment for students to learn about expert systems [53].

In recent years, the mining industry has been transforming as it aims to make mining operations safe, efficient, and sustainable using technologies involving the Internet of Things (IoT) and other digital technologies [54], [55]. This has the potential to fuel the development of IoT-based expert systems in the sector. Although these expert systems are becoming popular in agriculture, such as [56]-[58], the mining industry has not exhibited the same trend.

Similarly, the development and use of expert systems in cloud computing are well-known [59], [60]. However, according to Bouargane [61], in this knowledge domain, expected systems are mainly understood to be the main drivers behind the adoption of cloud computing. The quest to establish remote-control operations in the mining industry has forced companies to migrate to cloud computing. This will enable the sector to benefit from the expert system created and used to make cloud computing efficient and secure.

In summary, the discussion presented here suggests possible future growth in research focused on the development and application of expert systems in mining, particularly those based on IoT and cloud computing technologies, and the use of expert systems shall.

5. Conclusions

In this study, we analyzed trends in developing and applying expert systems in mining. This is the first study to critically and systematically examine the general trends in the development of expert systems across the different stages of the life of a mine. The analysis conducted in this study showed that there has generally been an increase in the development and application of expert systems in mining. This further revealed that expert system shells are becoming popular platforms or tools for the development of expert systems.

The growth in the development and availability of expert system shells and the transformation of the mining industry to incorporate the use of IoT and other digital technologies in the quest to make mining operations efficient, safe, and sustainable, have the potential to drive further development of expert systems for the mining industry.

Author contributions

Conceptualization: SEM, LK, GOA; Data curation: SEM, LK; Formal analysis: SEM, CSNC, LK; Funding acquisition: SEM; Investigation: SEM, LK, GOA; Methodology: SEM, LK, GOA; Project administration: SEM, LK, FAD; Resources: SEM; Software: SEM, FAD; Supervision: FAD; Validation: SEM; Visualization: SEM; Writing – original draft: SEM, GOA; Writing – review & editing: FAD, CSNC, LK. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Міні-огляд розвитку та застосування експертних систем у гірничій справі

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Мета. Аналіз тенденцій розробки та застосування експертних систем на різних етапах життєвого циклу гірничого підприємства шляхом системного й критичного узагальнення існуючих підходів у гірничодобувній галузі.

Методика. У дослідженні застосовано підхід, що включає пошук, відбір та аналіз релевантних наукових праць згідно з методологією PRISMA (бажані елементи звітності для систематичних оглядів і метааналізів). Для подальшого аналізу було відібрано 32 наукові статті ($n = 32$), в яких описуються конкретні експертні системи, розроблені для потреб гірничої промисловості, тоді як 21 публікацію ($n = 21$) виключено з дослідження. Аналіз охоплював характер експертних систем, сфери їхнього застосування у гірництві та інструменти, використані для їх розробки.

Результати. Встановлено, що загальна кількість розробок та впроваджень експертних систем у гірничій промисловості має тенденцію до зростання. Виявлено, що експертні оболонки набувають популярності як платформи для створення експертних систем. Визначено, що розвиток експертних оболонок та цифровізація гірничої галузі, зокрема впровадження технологій Інтернету речей, створюють потенціал для подальшого вдосконалення експертних систем у напрямку підвищення ефективності, безпеки та сталості гірничих операцій. Акцентовано увагу на необхідності інтеграції цифрових рішень у процеси прийняття рішень на різних етапах життєвого циклу гірничого підприємства.

Наукова новизна. Вперше здійснено системний огляд тенденцій розробки та застосування експертних систем у гірничій галузі з урахуванням впливу цифрових технологій на ефективність, безпеку та екологічну відповідальність виробництва.

Практична значимість. Отримані результати надають уявлення про поточні тенденції та можливості розвитку й застосування експертних систем у гірництві. Зростаюче використання експертних систем для прийняття обґрунтованих рішень може зробити майбутні гірничі операції більш безпечними, прибутковими та сталими.

Ключові слова: *експертна система, гірнича справа, Інтернет речей (IoT), хмарні обчислення, оболонки експертних систем*

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