Possibilities of using expert methods for sewer system maintenance optimisation

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Subject review

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This paper provides an overview of the state-of-the-art research on the possibilities of using expert methods (artificial neural networks, genetic algorithms, expert systems, decision trees, Markov chains, and ant colony algorithm) for optimising maintenance of sewerage systems. Timely maintenance of sewerage systems is significant as it ensures their proper functioning, repair cost reductions, basic operation of the system, drainage of waste water from households to wastewater treatment plants, and discharge to the receiving water body. Possible uses of expert methods for optimising maintenance of sewerage systems, aimed at reducing maintenance costs, are presented.

Key words:
expert systems, sewerage system, maintenance, optimisation, artificial intelligence

Pregledni rad

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Mogućnosti primjene ekspertnih metoda za optimizaciju održavanja sustava odvodnje

U radu je dan pregled dosadašnjih istraživanja o mogućnostima primjene ekspertnih metoda (umjetne neuronske mreže, genetski algoritmi, ekspertni sustavi, stabla odlučivanja, Markovljevi lanci i algoritam kolonije mrava) za optimizaciju održavanja sustava odvodnje. Pravodobno održavanje sustava odvodnje važno je zbog njegova pravilnog funkcioniranja, manjih troškova popravaka i osiguranja osnovne funkcije sustava odvodnje, te odvođenja otpadne vode iz kućanstava do uređaja za pročišćavanje otpadnih voda i ispuštanja u prijamnik. Navedene su moguće primjene ekspertnih metoda u optimizaciji održavanja sustava odvodnje čiji je cilj smanjiti troškove održavanja.

Ključne riječi:
ekspertni sustavi, sustav odvodnje, održavanje, optimizacija, umjetna inteligencija

Übersichtsarbeit

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Möglichkeiten der Anwendung fachkundiger Methoden zur Optimierung der Wartung von Abwassersystemen

In dieser Arbeit werden bisherige Forschungsergebnisse zu den Möglichkeiten des Einsatzes von fachkundigen Methoden (künstliche neuronale Netze, genetische Algorithmen, Expertensysteme, Entscheidungsbäume, Markov-Ketten und Ameisenkolonie-Algorithmus) zur Optimierung der Wartung von Abwassersystemen vorgestellt. Die rechtzeitige Wartung des Abwassersystems ist wichtig, da es ordnungsgemäß funktioniert, die Reparaturkosten senkt und die Grundfunktionen des Abwassersystems sicherstellt sowie das Abwasser aus Haushalten in die Kläranlage leitet und in den Auffangbehälter ablässt. Es werden mögliche Anwendungen von fachkundigen Methoden zur Optimierung der Wartung von Abwassersystemen mit dem Ziel, die Wartungskosten zu senken, aufgeführt.

Schlüsselwörter:
Expertensysteme, Abwassersystem, Wartung, Optimierung, künstliche Intelligenz

1. Introduction

A sewerage system can be defined as a group of structures and facilities that are used for the collection, evacuation, treatment, and final discharge of wastewater [1, 2]. The basic objective of every sewerage system is to rapidly evacuate wastewater from the vicinity of people, by applying the most favourable sanitary, technical, technological, and economic solutions in the process. An additional role of sewerage systems is to clean the collected wastewater to an adequate level and to discharge it into an appropriate water body, all in accordance with environmental requirements, good engineering and operating practices, and statutory regulations [3, 4]. Good maintenance is paramount to ensure proper fulfilment of all these objectives.

In fact, adequate and regular maintenance of sewerage systems is the basic precondition for rational management of this costly urban infrastructure, and for achieving appropriate sanitation in urban areas and good environmental protection. In addition, it is a major prerequisite for sustainable development and for maintaining proper health standards in urban areas, which is why a considerable attention must be paid to this highly sensitive issue [5-8]. The term *adequate and regular maintenance* implies use of an appropriate and cost-effective maintenance strategy that takes into account possible deficiencies and malfunctions (thus placing emphasis on preventive maintenance).

Maintenance includes a wide range of different activities and procedures that are carried out so as to ensure proper functioning of the facility and any of its parts, to guarantee to all its beneficiaries safe use of the facility, and to ensure good state of repair and long service life of the facility [9-12]. When properly maintained, a sewerage system evacuates wastewater from households and buildings and carries it to wastewater treatment plant, thus protecting human health [7, 8].

Although many maintenance strategies are currently available, two most important ones are preventive maintenance and corrective maintenance [11, 13]. They will be considered in grater detail in Section 2 below. An appropriate design of sewerage systems is one of the most significant prerequisites for simple and cost-effective maintenance, and for achieving a full design life expectancy of the facility. When designing sewerage systems, designers are faced with many questions, problems and decisions, as many important criteria must be fulfilled. Some of the criteria to be met to ensure proper functioning of the sewerage system are: pipe diameter must be sufficient to evacuate appropriate quantity of sewage, speed of sewage flow through pipes must be limited, proper filling of pipe cross section must be ensured, adequate longitudinal slope must be provided for proper drainage, etc. However, in all cases, the sewerage system must be designed to be cost-effective. In general terms, multicriteria decision-making is a complex and it can be quite helpful in reaching the final decision when a greater number of alternatives are considered. Multicriteria decision-making will be considered in Section 3 where an overview of expert methods that may help in optimising maintenance of sewerage systems will also be given.

2. Maintenance of sewerage systems

As already indicated, maintenance activities are *inter alia* carried out to ensure proper fulfilment of the basic function of the facility which involves, in the case of sewerage systems, transport of sewage to the wastewater treatment plant, and satisfaction of all necessary requirements.

Proactive and preventive maintenance of sewerage systems is more cost-effective than the traditional approach to maintenance, which involves application of the so called reactive maintenance [14]. The issue of maintenance must be properly addressed already in the scope of design of sewerage systems, because maintenance activities actually dictate (of course not fully) requirements relating to minimum pipe diameters. At the start of sections, the quantities of sewage are often very small, especially for evacuation of sanitary wastewater in separate drainage systems. It would theoretically be possible to use very small pipe cross sections based on small initial flow rates and longitudinal slope. However, practical experience has shown that the use of small cross sections is unfavourable, and that it often results in pipe blockage. The use of small pipe sections in sewerage systems increases the cost of maintenance of gravity-flow sewerage systems considerably, as the pipes need to be cleaned quite frequently. For the above reasons, the smallest pipe diameters in public gravity-flow sewerage systems usually vary from 250 to 300 mm [15].

Various biological, physical and chemical processes that take place in sewerage systems have proven to be harmful for proper functioning of sewerage systems. Biological processes result in vegetation growth and decomposition. Chemical processes involve formation of acids that erode parts of sewerage systems, while material deposition can be mentioned as a typical physical process [16]. If a sewerage system is well designed and realised (according to good engineering and operating practices and in accordance with relevant regulations), then maintenance activities are reduced to periodic cleaning of deposits such as mud and sand and, of course, to regular inspections [17]. The system can be cleaned mechanically or by rinsing, depending on the quantity of deposits, presence of tree roots in pipes [18, 19], clogging by waste substances discarded by users, etc.

Some preconditions for good maintenance of sewerage systems include good knowledge of the system and its characteristics, sufficient number of well organised employees, sufficient funding [3, 15], and control and supervision of all maintenance activities [20]. All these activities are interlinked. Without sufficient funding, the number of employees will not be sufficient for proper maintenance of the system. Without good organisation and maintenance plan, employees will not be able to maintain the system efficiently, even if their number is sufficient. Even if the above conditions have been met, an adequate level of sewerage system maintenance can not be obtained without good knowledge of the system. As every sewerage system is a unique facility, it is indispensable to adopt a unique approach for the management and maintenance

of each particular system. An appropriate management and maintenance plan should be adopted for each part of the sewerage system [3, 5].

Two types of maintenance can be differentiated: corrective maintenance and preventive maintenance [11, 12]. Corrective maintenance is a reactive type of maintenance that is most often needed in the cases when the equipment or the system fails or is worn down. Systems that rely only on this type of maintenance will not operate at their optimum, especially as the system ages. Corrective maintenance is also known as the "emergency maintenance" where two situations can be differentiated: "normal" situation and "extraordinary" situation. Normal situation is the situation that can occur on a daily basis, i.e. pipe blocking or cracking. Frequency of such situations reduces if an efficient maintenance program is implemented. Extraordinary situations are events such as storms, floods, earthquakes or other unforeseeable events that could cause malfunction of the system or any of its parts. Full reliance on corrective maintenance prevents proper planning and allocation of work tasks, and hinders allocation of sufficient and adequate funds to the budget, while also leading to frequent breakdowns of the equipment and system. Preventive maintenance is a proactive type of maintenance, i.e. it is a programmed and planned maintenance aimed at preventing disturbances and malfunctions. The frequency of maintenance activities can be determined based on historic data or by setting specific time periods. Preventive maintenance leads to an improved performance of the system, except in cases when system problems are due to errors in the design or during construction of the system. As maintenance activities can be planned and scheduled, the resources needed for maintenance can be procured on time and planned in the budget [5].

Sewerage systems are very long and extensive structures that are composed of many parts, which is why it is difficult to predict all possible problems (especially during initial operation of the system). Therefore, regular inspections must be conducted and a proper emphasis should be placed on those parts of the sewerage system that are likely to pose problems. However, haphazard inspection of a sewerage system aimed at predicting its condition is expensive, which is why it is important to concentrate on those parts of the system that are more prone to damage [21]. It can be concluded from the above considerations that maintenance of sewerage systems is a highly complex task [22, 23] and that an efficient arrangement of preventive maintenance activities is highly significant as it reduces the total costs of maintenance of sewerage systems [24]. The use of expert methods can be of considerable help in the process of solving the complex task of sewerage system maintenance.

3. Expert methods for sewer system maintenance optimisation

Multicriteria decision-making, which is also used in maintenance of sewerage systems, is applied in situations when decisions are based on a number of mostly conflicting criteria [25, 26]. Optimisation is highly significant in the resolution of such problems. The task of optimisation is to select the best possible alternative (best solution) out of a number of possible alternatives, or out of a number of favourable alternatives, based on appropriate selection criteria. In mathematical context, optimisation is always reduced to finding the criterion function extreme (one function or a vector of several functions). Optimisation is conducted using various methods, which is dependent on the type of relation used in mathematical model, on criteria functions, and on limitations [27]. Mathematical models consist of variables, coefficients, and mathematical operators. Mathematical modelling will not necessarily solve

Table 1. Chronological list of expert methods with basic characteristics and areas of application in sewerage system maintenance optimisation

Expert method	Authors of the method	Year	Source	Area of application
Markov chains	Markov	1913	[34]	Deterioration assessment of sewerage system pipes [35-44]
Artificial neural networks	McCulloch and Pitts	1943	[45]	Predicting sewerage system condition [46] Predicting sewerage system service life [47] Pipe defects detection [48-52]
Decision trees	Belson	1959	[53]	Planning inspection of sewerage pipes [54] Predicting sewerage system blockages [55]
Expert systems	Buchanan, Feigenbaum and Lederberg	1968	[56]	Defining priorities in case of renewal of sewerage system [57] Defining system inspection priorities [58, 59] Predicting critical parts of the system [60] Support in making decisions about the use and maintenance of sewerage systems [61-63]
Genetic algorithms	Holland	1975	[64]	Selection of an optimal system renewal method [65-68] Assistance as related to the inspection of sewerage pipes, definition of pipe malfunction risk, inspection cost and repair [69]
Ant colony optimisation	Colorni, Dorigo and Maniezzo	1991	[70]	Optimal planning of maintenance schedules for infrastructure buildings [71]

the problem, but will probably shed some light on the problem and clarify the situation that is being analysed [28]. As a rule, modelling and model solving is operated by means of a computer and an appropriate software [27].

A wide spectrum of engineering problems can be solved using optimisation methods [29] and one of such problems is the optimisation of sewerage system maintenance activities. In general terms, optimisation is aimed at reducing costs and energy consumption, maximising profits, minimising risk [30], etc., and all these parameters can be implemented in the maintenance of sewerage systems. In modern-day engineering practice, most technical systems can be designed and realised in a variety of ways, depending on the designer's decision. In this respect, the problem arises as to how to achieve the characteristics that that would make the system optimal under given circumstances. The notion of optimality is relative and strictly dependent on the optimality criterion. Optimisation is a procedure that is aimed at achieving the best possible results under given circumstances. In order to properly set the optimisation task, it is indispensable to clearly identify the subject of optimisation and the objective or criterion of optimisation [31]. Artificial intelligence has historically been defined as the science of fabrication of machines that are capable of performing activities requiring human intelligence [32, 33].

Expert systems are also one of the areas in which artificial intelligence is applied. Expert systems are *inter alia* used to facilitate decision-making by the designer, i.e. to facilitate and speed up the earlier mentioned optimisation of maintenance activities that are performed by employees of the municipal company operating the sewerage system. The following information is given in Table 1 for every expert method (presented in chronological order): the authors of the method, the year in which the method was first released, the source and area of application of the expert method for sewerage system maintenance optimisation, and the corresponding literature. It should be noted that, for some methods, the year of release is relatively unclear and can not accurately be defined as contradictory times of release are given in the literature available to the authors (deviations vary up to three years). That is why the times indicated in the table reflect the data given in the literature considered relevant by the authors, i.e. the year of release more often mentioned in relevant literature was adopted.

3.1. Markov chains

Markov chains (after Andrej Andrejevič Markov) [72] constitute one of the simplest random evolution models. Simple structure of Markov chains enables us to obtain a great quantity of information on their behaviour and, at the same time, the Markov chain class is wide enough for use in various applications. Markov chains are currently used in statistics, biology, and even in literature. This makes Markov chains the most significant example of random processes [72].

A Markov chain is described via state diagrams that consist of states (circles) and allowed transitions between the states (lines with arrows) (Figure 1) [73].
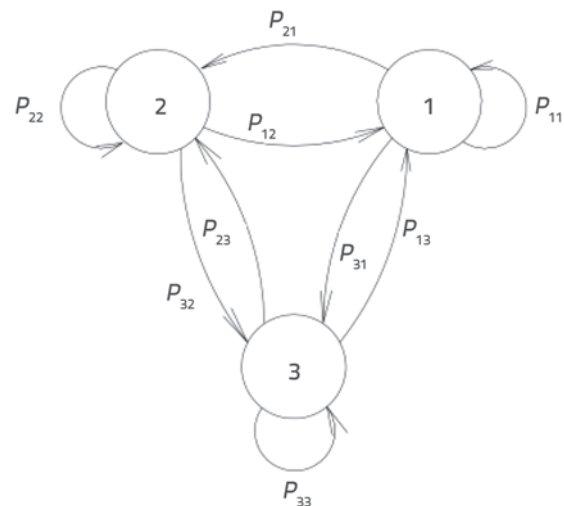

Figure 1. Diagram of Markov chain transition values [74]

In case of continuous time Markov chains, transitions can occur at any moment and are described by the exponential distribution parameter [72]. Markov chains constitute a set of states of a system. At every given moment, the system may assume a new state, or may remain in the same state. Changes of state are called transitions. If a sequence of states has a Markov property, that means that every subsequent state is independent of every previous state.

Ana and Buwens [35] have modelled the deterioration process of an urban stormwater drainage by means of a Markov chain. Markov model is a powerful mechanism for modelling the ageing process of sewerage pipes because, not only is its concept simple, but also its structure allows complex and hereditary events such as pipe ageing and deterioration.

In their paper, Wirahadikusumah, Abraham and Castello [36] use the Markov decision-making process in the rehabilitation of a sewerage system. Proper understanding of the sewerage system deteriorating mechanism enables the experts responsible for the maintenance and control of such systems to develop a model for predicting whether or not a malfunction in the sewerage system can reasonably be expected. The use of deterioration models, together with appropriate life cycle cost analysis (LCCA), enables us to cut down construction, management, and maintenance costs. Marzouk and Omar [37] have created an algorithm for the multicriteria optimisation of a sewerage network renewal activities. The Markov chain for predicting the sewerage network ageing process is used in the model. Markov models offer a reliable mechanism for the development of prediction models. Transition matrix is square in form. The module used for estimating condition of sewerage systems can predict the system state for the next fifty years. Micevski et al. [38] have developed a Markov model for predicting the deterioration process of stormwater drainage pipes. The model

was calibrated using the Bayes' method and structural information from the database kept by the city of Newcastle (Australia). Markov transition probabilities were estimated using the Metropolis-Hastings algorithm. The authors have demonstrated that the Markov model is suitable for the pipe deterioration modelling. It was established that the ageing and deterioration process is affected by various pipe properties such as: pipe diameter, material, type of soil, a level of exposure in terms of pipe distance from the coastline. Baik, Abraham and Gipson [39] have used Markov chain in the ageing model that was developed using data collected from the sewerage system of San Diego.

A paper written by a group of authors [40] describes the life cycle cost analysis for the management of an underground infrastructure, based on optimum maintenance and renewal activities. Markov chain (and the corresponding deterioration model) is used to help explain the pipe ageing process over years. Markov chain models have been successfully used in the forecasting of ageing process for various infrastructure facilities. The sewerage system deterioration curve is exponential rather than linear, which shows that the ageing rate of sewerage systems varies over time.

Baik, Jeong and Abraham [41] have developed Markov chain-based ageing models for the management of sewerage systems. It was established that the data needed for the successful and accurate prediction of the sewerage system ageing process include: pipe installation depth, type (condition) of soil, ground water level, sewerage system overflow frequency, etc.

In their paper [42], Lubini and Fuamba have developed a probabilistic model for analysing the state of sewerage pipes as related to operating conditions and maintenance method applied. They claim that the Markov chain model has been most frequently applied for the prediction of deterioration of infrastructure systems, bridges and sewerage systems in particular, as will be shown in the conclusion of this paper. In conclusion, they state that additional parameters, such as alkalinity, concentration of organic matters and metal concentration, etc., are needed to increase the accuracy and reliability of the model. A larger database is also needed in this respect.

Wirahadikusumah, Abraham and Iseley [43] claim that there are two reasons behind the dominant use of the reactive maintenance method: first, sewerage systems are underground facilities and their condition can usually be determined and seen only after a malfunction or breakdown occurs and, second, sewerage systems are operated by local communities, and so no universal methodology and regulations are applied with regard to maintenance activities. In their paper, they use Markov chains in combination with nonlinear optimisation as a basis for developing an appropriate sewerage system deterioration model. The system ageing model must *inter alia* be based on an extensive historical data base. The deterioration of sewerage systems is also greatly influenced by the following data: type of pipe material, ground water level, type of fill placed above pipes, and depth of cover.

In their paper, Jin and Mukherjee [44] have developed a stochastic model that can be used in the characterisation and prediction of random failure of infrastructure systems; they place emphasis on sewerage system clogging that results from the combination of various factors, including deterioration. Data on the sewerage system available to a small size local community were used. In conclusion, these authors state that the model can be applied not only to sewerage systems, but also to other infrastructural system for the prediction of random failures.

3.2. Artificial neural networks

A simple and accurate definition of artificial neural networks (ANN) was formulated in 1990 by Alexander and Morton; according to this definition a neural network is a "massively parallel distributed processor made up of simple processing units having a natural propensity for storing experiential knowledge and making it available for use, and is similar to brain in the way it acquires and stores knowledge" [75, 76]. Neural networks acquire knowledge through the learning process, and they store it through the strength of interneuron connections [75, 76]. The study of neural networks started with the publication written by McCulloch and Pitts [77]. Each neural network is composed of a large number of structural processing units - neurons [78-81]. Neurons are interconnected by links containing permeable (weight) coefficients and, according to their function, they are similar to synapses of biological neurons [78].

Najafi and Kulandaivel [46] have developed a model based on the artificial neural network that predicts the state of sewerage pipes based on historic system-condition prediction data. They used the following neural network modelling data: pipe length, pipe diameter, type of material, age of sewerage pipes, depth of cover, the slope and type of sewerage system. The authors conclude that artificial neural networks can be used for predicting state of sewerage systems, and that the model accuracy depends on the size of the sample and on the quantity of data.

An artificial neural network for predicting service life of concrete sewerage pipes, based on the corrosion level modelling, is presented by Jiang et al. [47]. The ANN was trained and validated with experimental data (the experiment involving the use of laboratory corrosion chambers lasted 4.5 years). The verification was made using real data obtained on selected locations along the Australian sewerage network. Pipe corrosion predictions were quite accurate, and it was concluded that the ANN can be used for improving understanding of corrosion mechanisms.

In their paper, Moselhi and Shehab-Eldeen [48] deal with automatic detection of surface defects in sewer pipes. The recording of sewerage pipes, inspection of recorded material and, finally, and most importantly, detection of surface defects, usually requires a lot of time and effort, and is also quite costly. Errors are also possible due to the loss of concentration of (human) experts performing this job. The automation in this area includes computer recordings, digital video recordings, processing and analysis of such recordings, and analysis and

classification of samples by means of ANN. The artificial neural network was trained to recognise pipe defects, and the software program *NeuroShell* 2 was used for that purpose. After network training, it was established that the ANN can also be used for detecting defects on concrete and clay pipes.

Sinha and Fieguth [49], use ANN to detect buried pipe defects, such as randomly shaped cracks and holes, broken joints and laterals, etc. In this paper, the ANN is used to classify and recognise images with the above mentioned defects. Although the artificial neural network must be trained, care must be taken not to overtrain the network as, in such cases, results may be less accurate than the ones obtained before the training [49].

Similar issues are treated in papers presented by Tran, Perera and Ng [50, 51]. These papers deal with the problem of deterioration of the sewerage pipe structure, but are only concerned with pipes for stormwater drainage. Both papers deal with pipes used in Australia. Surveys were usually made using CCTV (closed-circuit television) cameras and the recordings obtained in this way were used to estimate pipe condition. The ANN model that would predict condition of concrete sewerage pipes based on specified data (input factors) is proposed in these papers. Concrete pipes were selected as such pipes are used on most sewerage systems of this type. The MATLAB software was used in these ANN predictions.

A problem that frequently occurs during maintenance of sewerage systems involves transport and deposition of sediments (sedimentation). The sedimentation often occurs due to alternation in flow in pipes. Ebtehaj and Bonakdari [52] use ANN to predict sediment transport through sewerage pipes. The sediment deposition issue is significant as accurate prediction of the sediment quantity and sediment deposition zone may greatly reduce sewerage pipe maintenance costs. These authors conclude that the ANN-based prediction of sediment deposition is very close to real measurement results.

3.3. Decision trees

The term decision tree denotes a tree-like graph that is used to show all possible solutions to a problem, to present all possible results of an event, or to classify appropriate data [82, 83]. Each branch of the decision tree can usually be presented as a single IF-THEN rule [82]. Although the structure is similar, it is important to differentiate between two completely different domains of decision tree use: decision tree in machine learning and decision tree in decision theory [82, 84]. There are two types of nodes in decision tree:

- **decision node:** defines a particular criterion in form of values of the attribute from which branches meeting specific values of this attribute emerge [85],
- **end node:** is the node by which a particular tree branch ends [84]; end nodes define the class that contains examples meeting requirements for that particular tree branch [85].

Harvey and McBean [54] use decision tree when planning sewerage pipe inspections. It is very difficult to predict pipe condition. However, the task of selection pipes to be inspected has been greatly facilitated through the use of decision trees. The decision tree concept is in itself quite general and the model obtained can be understood even by those who are not familiar with data mining methods and the knowledge required for the use of statistical methods or machine learning methods. The following attributes are used in data mining: material, age, type (main pipeline or lateral), diameter, length, slope, pipe bottom depth, depth, type of pipe overburden, water main breaks within 3 m of the pipes, structural condition. The authors conclude that decision trees are a simple and effective method that provides a deeper insight of the way in which structural condition of pipes is influenced by specific pipe parameters. A trained decision tree classifier shows that pipe age is significant for determining structural state of sanitary sewerage systems. In addition, the decision tree shows that the possibility of pipe malfunction increases in the case of shallow burial depths, in the case of longer pipe length or smaller pipe diameter, and when a water-main failures are registered in the vicinity of the pipe under study.

Proactive maintenance is needed so as to reduce frequency of sewerage system clogging, to cut down costs, and to minimise harmful impact on people and environment. An accurate model for predicting sewerage system malfunctions/problems is indispensable for an efficient prioritization of maintenance activities. In their work, Bailey et al. [55] have developed a decision tree based model that relies on historic data about problems (incidents) and maintenance of sewerage systems. The results have revealed that possibilities for defining maintenance priorities are limited.

3.4. Expert systems

Expert systems (ES) are programs and methods for the systematized use of knowledge in a specific domain [86, 87]. They are a form of artificial intelligence [32, 88, 89] and are often used in making decisions with regard to complex problems [88, 90]. Traditional expert systems rely on the procedure of logical deduction that takes place in steps (cycles), covering the initial state, target state, and a whole array of instantaneous states. The decision is made by comparing instantaneous states with general cause and effect relationships stored in knowledge bases. The reasoning procedure can be based on forward chaining or backward chaining processes. Starting from an initial state, the set of possible solutions is narrowed down in steps, through dialog with the user, until the target state is achieved. Dubious situations are solved by applying a knowledge-base rule having a higher level of certainty [91]. Expert systems are used to solve problems that can generally be classified into one of the following categories: interpretation, prediction, diagnosis, design, planning, monitoring, repair, instruction, and control [92, 93].

Tagherouit, Bennis and Bengassem [57] have developed an ES as a support to decision-making about priorities in the rehabilitation of sewerage networks. The contribution lies in the development of a ranking scheme for sewerage rehabilitation

priorities. An index of properties is calculated for every part of the sewerage network, separately for structural, hydraulic, and global properties, taking into account condition within the pipe, hydraulic properties of pipes, and environment of the pipes under study. Pipes with similar hydraulic and structural properties were classified differently if they had a different level of site vulnerability. Being more accurate, this classification offers some advantages when making decision about which pipes to rehabilitate. An advantage of this kind of evaluation does not only lie in the fact that it takes into account a number of various parameters, but also that it considers their interrelationship.

Hahn, Palmer and Merrill [58] have developed an expert system for determining priority of sewerage system inspections. The expert system is used to determine potential risk and possible consequences, to propose an appropriate inspection method, and to warn the user when additional data are needed to make more accurate decisions. The Bayesian network was used in the inference engine, which is one of integral parts of the expert system [94, 95].

An expert system with the corresponding knowledge base was developed in the paper presented by previous three authors [59] and by Lukas, as a support in decision-making about sewerage system inspections. The expert system was developed using the Bayesian network that allows uncertainties in the knowledge of experts throughout the decision-making process. The database and the expert system were evaluated in the scope of several case studies, and it was established that they are efficient in simulating knowledge of real-life experts. The expert system known as SCRAPS (abbreviated from: Sewer Cataloging, Retrieval and Prioritization System) is based on the Bayesian network. In addition, as the sewerage system ages, the inspections and controls become more expensive, and inspections must be scheduled by placing focus on the part of the system presenting the greatest risk. The database of the analysed system was created and calibrated based on more than one hundred cases of sewerage pipelines. When making evaluations, the way of reasoning exhibited by SCRAPS was similar to that of a human expert, but was however more conservative compared to the reasoning by human experts.

The same expert system (SCRAPS) is used in the paper published by Giovanelli and Maglionico [60] as a means to predict critical parts of the sewerage system. The following data were entered into the SCRAPS database: pipe diameter, overflow frequency, root intrusion, sedimentation, corrosion, pipe age, ground water level, depth of the pipe, etc. It was established that the use of SCRAPS, together with hydraulic modelling, can be quite useful in the evaluation of sewerage system knowledge, and in scheduling inspections that are needed to preserve fixed level of serviceability.

An expert system for the support in the sewerage system maintenance has been developed by Sousa et al. [61]. The expert system is used as an aid and support to facilitate prioritization in the sewerage system cleaning, and to enable proper scheduling of inspections. The following parameters are used in the model: type of material, pipe age, pipe diameter, slope,

pipe laying depth, infiltration, and inspection shaft (manhole) characteristics. The expert system was also developed because the data at the disposal of the municipal company were very scarce, and the optimisation was considered necessary as a means for saving time and money. This expert system is of general type because of the above mentioned scarcity of data although, if more data were available, the expert system could be of greater use, and the real ageing pattern of the sewerage system could be modelled more realistically.

Ortolano, Le Coeur and MacGilchrist [62] have developed an expert system that assists in the maintenance of the sewerage system in Paris, France; it also has an ES segment for detecting the need to make repairs to the sewerage system. The authors conclude that the sewerage system maintenance database should be created, and that more case studies should be made to make the ES more accurate in the prediction of maintenance activities.

Ana and Bauwens [63] provide an overview of decision-support tools for the support in making decisions on the management, operation, and maintenance of sewerage systems. One of the tools mentioned in the paper is the APOGEE (abbreviated from French name: *Analyses et Programmation Optimise pour la Gestion, l'Entretein et l'Exploitation des Reseaux d'Assainissement*, while full English name is: *Analysis and Optimal Programming for the Management, Maintenance and Use of a Sewer Network*). This tool has been developed to optimise annual planning and rehabilitation of the sewerage network. The system is composed of three basic components: database, expert system and modul for planning interventions and repairs in the sewerage network.

3.5. Genetic algorithms

In general terms, an algorithm can be defined as a method, procedure, or rule for finding solution to a problem or for achieving an objective, i.e. an algorithm is a set of unambiguous practicable steps [96]. Genetic algorithms (GA) were first conceived by John Holland in the 1960s, and were then developed together with his students at the University of Michigan in the 1960s and 1970s. Holland's initial goal was not to design algorithms for solving specific problems, but rather to explore the phenomenon of adjustment as it occurs in nature, and to develop the ways in which natural adjustment mechanisms could be implemented in computer systems [97]. Genetic algorithms have been recognised as being very suitable for the problems involving multicriteria optimisation [98].

In their paper, Yang and Su [65] consider the issue of sewerage system maintenance based on CCTV imaging and neural networks for classification of structural failures from images. Genetic algorithms are used for choosing an optimum sewerage system rehabilitation method. Genetic algorithms are also used for determining an optimum rehabilitation method and for choosing the substitution material. At the end, a geographical information system (GIS) was used to prepare the sewerage system rehabilitation plan, and everything was presented in graphical form [65].

The paper [66] prepared by the same authors describes preparation of an optimisation model that is used to develop an appropriate method for the rehabilitation of sewerage pipes, and to identify material to be used in such rehabilitation, all this within a preset budget. Thus the savings of as much as 20% were realized compared to standard professional estimates. Halfway, Dridi and Baker [67] presented properties similar to those given by Yang and Su [66] and the genetic algorithm was used to determine cost-effective solutions for rehabilitation of sewerage systems. The authors of this paper have noted that there is a significant lack of literature about sewerage system maintenance optimisation based on genetic algorithms.

Ward and Savić [68] have used GA for developing a methodology for the optimisation of sewerage system rehabilitation activities. The following three conflicting criteria were included in the multicriteria optimisation model: maximum improvement of structural condition of system, minimisation of construction costs, and minimisation of sewerage system failure risk. The above model was tested on the sewerage system operated by South West Water, UK. It was established that the model strives toward optimum solutions that would otherwise be over looked. Berardi et al. [69] discuss a multicriteria approach to the inspection of sewerage pipes. They use genetic algorithm to perform multicriteria optimisation of pipe failure risks, inspection costs, and repair costs.

3.6. Ant colony optimisation

The ant colony optimisation (ACO) is an optimisation method inspired by the behaviour of ant colonies in nature. This still relatively young method was proposed by Marco Dorigo in his doctoral dissertation published in 1992 [99, 100]. The ant colony optimisation algorithm is based on the hypothetical behaviour of an ant colony when searching for food [101-103]. When moving, ants release pheromones. If no pheromones are present, ants move at random; however, if a pheromone trail exists then ants follow this trail [104]. In nature, ants use the shortest possible route to reach their nests, and the concentration of pheromones along the route is higher. As the higher concentration of pheromones means that a lot of ants have used this route, this information is appropriately used by ants to look for food, bypass obstacles, and in everyday activities

[101-103]. The quantity of pheromones released is proportional to the quality of solution [105]. The key to the ACO algorithm success lies in the creation of new solutions [106].

Lukas, Borrmann and Rank [71] use the ACO to optimise inspection planning for various infrastructure facilities, such as bridges and tunnels; however, as earlier mentioned, sewerage systems are also infrastructure facilities, and so the same optimisation could be used for the maintenance of sewerage systems.

4. Conclusion

An overview of expert methods that are used for optimising maintenance of sewerage systems is presented in the paper. The expert methods were selected based on the research conducted by the authors about the expert methods that are most often used, and also based on the literature available at the time this paper was written.

Sewerage system maintenance activities are quite significant, but may sometimes be financially inefficient, which is most often due to system inspection difficulties. Various types of equipment are currently available for recording and inspection of sewerage systems, but this may also be financially inefficient as it is practically impossible to inspect the entire sewerage network. Therefore, the emphasis is placed on those parts of the system that present a higher risk of malfunction or that are older than the remaining parts of the network; here, the experience of maintenance crews is of utmost significance.

It has been established by the analysis of published papers that most of them deal with optimisation of sewerage system maintenance by means of Markov chains; the remaining papers are based on artificial neural networks and expert systems. Genetic algorithms can also be used, while only a limited number of papers base their analysis on decision trees and ant colony algorithm.

Expert methods are used in the optimisation of sewerage system maintenance activities as their use presents numerous advantages. However, the implementation is still inadequate, especially as we know that optimisation in any area is necessary and indispensable, particularly in the maintenance of sewerage systems that are rightfully regarded as significant parts of infrastructure of every community. Their proper functioning is paramount for ensuring adequate sanitary conditions.

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