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Research Paper

Prioritization of maintenance work in wastewater networks using decision support methods

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ABSTRACT

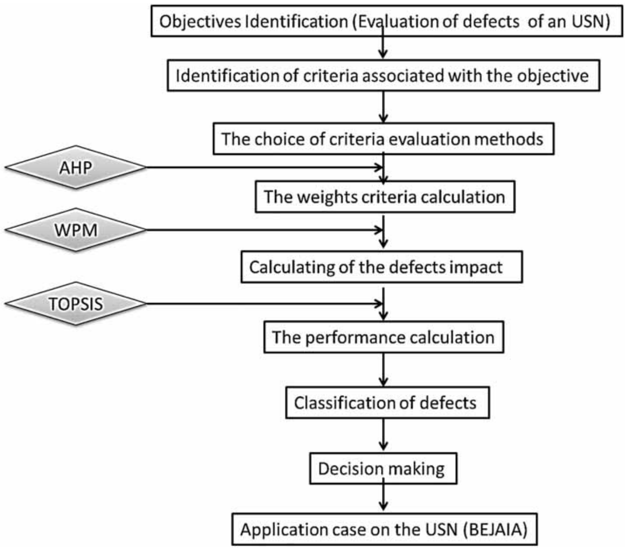
Sanitation networks are extremely important infrastructures because of their function and capital-intensive nature. Indeed, network knowledge is essential for a reliable prioritization of maintenance work. In this context, this research work is interested in the evaluation and the prioritization of the defects of an Urban Sanitation Network (USN), taking into account the criteria of the FMECA method (failure mode and effects and criticality analysis), namely the probability of defect occurrence (*P*), the defect's detectability (*D*) and the defect impact (*I*). The methodology adopted is based on the combination of three methods: the analytic hierarchy process (AHP) used to assign weights to FMECA criteria, the weighted product model (WPM) method to determine the defect impact and the technique for order of preference by similarity to ideal solution method (TOPSIS) to classify sanitation defects in descending order in order to prioritize maintenance interventions. A case study of a real sewerage project in the city of Bejaia (Algeria) essentially composed of eight non-visitable sections evaluated from television inspections was used to illustrate and validate the proposed model. The results show that the following defects: collapse, chemical attack, pipe surface degradation, and abrasion are considered as critical defects requiring immediate intervention due to their significant influence on the section performance rate, which is between $0\% \leq P < 50\%$, contrary to the other studied parameters which present a performance rate of $P > 50\%$. These results prove that the combination of AHP–WPM–TOPSIS methods can be used to design an effective management and maintenance system.

Key words: AHP, maintenance, sanitation defect, TOPSIS, urban sanitation network, WPM

HIGHLIGHTS

- A new model has been proposed to prioritize the defects of urban sanitation networks.
- Detailed analysis of sewer pipe malfunctions.
- Combination of AHP/WPM /TOPSIS methods to prioritize maintenance interventions on sanitation networks.
- The developed model is applied for a real network of an Algerian city. The proposed methodology could be applied to developing countries.
- The validation of the judgments was done in coordination between experts in the field and university teacher–researchers.

GRAPHICAL ABSTRACT



INTRODUCTION

Decision support is an extremely broad field. Its objective is to support decision-makers in the construction of a satisfactory decision when the choice of an optimal solution is difficult. In recent years, multi-criteria methods have provided important solutions to evaluation problems from several contradictory points of view. Indeed, it seems important to integrate these methods into the management and maintenance of the Urban Sanitation Network (USN). In Algeria, this service is managed by the National Sanitation Office (ONA) which is currently facing major problems in the field of sanitation, the consequences of which on the health and environment of citizens can be significant (Bedjou *et al.* 2019; Igroufa *et al.* 2020).

In Algeria, very few studies have been dedicated to this management issue. However, Benzerra *et al.* (2012) have developed a hierarchical structure of objectives, criteria and indicators to measure the sustainability of Algerian urban drainage systems and thus contribute to improving their management and development. A model for prioritizing rehabilitation work in a sanitation network has been developed by Kessili & Benmamar (2016). The latter was applied in Algeria with the aim of classifying collectors according to their state of deterioration using the AHP-PROMETHEE II multi-criteria methods. Another numerical model has recently been developed by Igroufa *et al.* (2020) to improve infrastructure asset management of urban drainage systems. This model is mainly based on a participatory methodology for the selection of objectives, criteria and performance indicators, as well as the multi-criteria fuzzy analytical hierarchy process (FAHP) method to determine criteria weights, and also the weighted sum method (WSM) for the aggregation of indicators and criteria.

Several scientists seek to assess the deterioration of the USN using mathematical decision support models. These include the network rehabilitation planning model, which takes into account the future deterioration of pipelines (Timothy *et al.* 1993). The software called CARE-S (Computer-Aided Rehabilitation of Sewer network) was developed with the aim of prioritizing sewer rehabilitation projects (Saegrov 2006). The idea of the model is to identify rehabilitation projects promising high-cost efficiency, since not all identified critical sewers can be rehabilitated at the same time due to budgetary constraints. Zhen & Georges (2020) proposed a new method to analyze the selection problems of sewer networks. The approach they developed is based on the comparison of four multi-criteria decision-making methods, namely the analytic hierarchy process (AHP), the technique for order of preference by similarity to ideal solution (TOPSIS), ELimination Et Choix Traduisant la REalité (ELECTRE III) (ELimination And Choice Translating Reality) and the Preference Ranking Organization METHods for Enrichment Evaluations II (PROMETHEE II).

Recent research uses the principle of the FMECA method to assess remediation risks and predict pipe degradation. Baah *et al.* (2015) proposed a new approach based on a risk matrix and a multi-criteria weighted sum decision matrix which aims to assess the consequences and risks of sewer pipe defects. A risk assessment model has been proposed by Anbari *et al.* (2017). The latter makes it possible to calculate the probability of defect as well as the consequences of defect using the weighted average method. A Bayesian geo-additive regression model has been developed by Balekelayi & Tesfamariam (2019) to assist urban water utility managers in prioritizing inspections, maintenance and replacement. This model makes it possible to predict the risks of deterioration of sewerage pipes from a set of predictors classified into physical, maintenance and environmental data. A new approach to sewer pipe assessment has been proposed by Ghavami (2019). The technique used is based on the combination of three models: AHP, data envelopment analysis (DEA) and geographic information system (GIS) to identify critical risks that require maintenance actions.

Several indexes are designed to evaluate the sustainability of a sanitation system. So, Lundin *et al.* (1999) studied the sustainability of an urban water system through the application of a set of indicators that focus on environmental issues, efficiency and performance of the technical system. The proposed indicators were tested on the municipality of Gothenburg (Sweden), which showed that the water supply and sanitation system in this municipality has evolved to a more sustainable. On the other hand, Iribarnegaray *et al.* (2015) developed a sustainability index in collaboration with the local water company. This index was initially tested in the province of Salta, in northern Argentina, and then validated in three smaller cities (San Ramón de la Nueva Orán, Joaquín Víctor González, San Antonio de los Cobres) in different climatic, geographic and demographic contexts. An online interface has been developed to facilitate the use and dissemination of the tool developed which will aim to monitor water and sanitation systems and promote more transparent and sustainable water policies. Furthermore, a new Sanitation Sustainability Index (SSI) has been suggested by Hashemi (2020). This index has sub-indices that consider technical, social and economic aspects of the sanitation system, and all variables are dimensionless and highly dependent on the current state of the community where the sanitation system is going to be implemented. The applicability of the SSI was demonstrated by evaluating the implementation of two on-site sanitation systems including a septic tank system and a resource-based sanitation system in South Korea. Analyzing the indexes proposed in the literature with the obtained results in our research, we found that the probability of defect occurrence, the defect detectability, the impact of sanitation defects on the structural quality of the pipe, the impact of defects on the cost and time of pipe repair can be considered as important indexes which have a considerable influence on the evaluation of sanitation systems as well as the prioritization of maintenance works.

The present research paper is interested in the prioritization of maintenance interventions by evaluating the deterioration of the USN. The proposed model is based on the combination of three decision support methods: the AHP multi-criteria method used to determine the relative importance of the criteria, the weighted product model (WPM) aggregation method, which makes it possible to calculate the defect impact, and the TOPSIS method, which makes it possible to classify the defects of each section in order of degradation. The final ranking of the TOPSIS method will allow us to prioritize maintenance interventions and design an efficient management and maintenance system. A case of a real sanitation project in the Bejaia city (Algeria) is studied to illustrate and validate the proposed model.

METHODS

We have developed a methodological tool to help the management and maintenance of the USN. This methodology is applied to a real case of a sanitation network of Bejaia city (Algeria) containing eight sections of different diameters (200, 400, 1,000 and 1,200 mm), where these sections are evaluated according to the criteria of the FMECA method (failure mode and effects and criticality analysis). Each section can contain up to nine defects which are infiltration/exfiltration, decrease in hydraulic capacity (DHC), sand, collapse, clogging, degradation of pipe surfaces (DPS), chemical attack, root intrusion and abrasion (ABR). The proposed model is based on the combination of three methods: the AHP, the WPM and the TOPSIS. The model process is characterized by five main steps: (1) the selection of criteria, (2) the AHP calculation, (3) the WPM calculation, (4) the TOPSIS calculation and (5) the decision-making.

Selection of criteria of the FMECA method to assess sanitation defects

The FMECA is a method of predictive reliability analysis that systematically identifies potential defects of a system and then estimates the risks associated with the occurrence of these defects in order to initiate corrective actions to the system. Its purpose is to evaluate the impact, or criticality, of the failure modes of the components of a system on the reliability, maintainability, availability and safety of this system. The FMECA method depends on three criteria, namely:

1. The probability of defect occurrence (P): this represents the occurrence probability of defect cause and the probability that this cause will lead to failure.
2. The defect's detectability (D): this represents the detection probability of the defect or the defect cause.

3. The defect impact (I): this represents the evaluation of the effect of the potential defect. In the case of a sanitation network, it represents the following three impacts:
   - The defect impact on the structural quality of the pipe (I_q).
   - The defect impact on the cost of repairing the pipes (I_c).
   - The defect impact on pipe repair time (I_t).

The defects identified in each section will be evaluated according to the previous criteria. The purpose of this assessment is to prioritize the defects to avoid real failures in the sanitation network.

Analytic hierarchy process

The AHP method is one of the most popular techniques for resolving complex decision-making problems. It allows a problem to be broken down in a logical way by moving from a higher to a lower level. In the application of the AHP method, the weight of the criterion is determined after consultation with experts using a qualitative or quantitative assessment approach that corresponds to the decision-maker's preference for one criterion over another. In general, the Saaty scale is recommended for comparison, it is detailed in Table 1 (Saaty 1986; Benzerra *et al.* 2012; Kessili & Benmamar 2016).

In this study, the choice of the AHP method is due to its ability to mix quantitative and qualitative criteria within the same decision-making framework. The proposed model uses the AHP method over two steps:

- Calculate criteria weights of defect impact (I) which are the following:
  - The defect impact on the structural quality of the pipes (I_q).
  - The defect impact on the cost of repairing the pipe (I_c).
  - The defect impact on pipe repair time (I_t).

  The weights found by the AHP method will later be used in the WPM method to calculate the defect impact (I).

- Calculate the weights of criticality criteria which are as follows:
  - The Probability of defect occurrence (P).
  - The defect's detectability (D).
  - The defect impact (I).

The weights found by the AHP method will be used in the TOPSIS method to classify the defects of sanitation pipes in degradation order.

The AHP method steps are as follows:

Step 1: We define the square matrix $M = a_{ij}$ according to Table 1 where the weight of criterion i compared to the component j is assigned to the (i, j)th position of the comparison matrix by pairs and the inverse of the assigned number is

Table 1 | Pair-wise comparison scale for AHP preferences

Scale	Verbal judgments of preferences	Explanation
1	Equally preferred	i and j are equally preferred
2	Equally to moderately	i and j are equally moderately preferred
3	Moderately preferred	i is moderately preferred over j
4	Moderately to strongly	i is moderately to strongly preferred over j
5	Strongly preferred	i is strongly preferred over j
6	Strongly to very strongly	i is strongly to very strongly preferred over j
7	Very strongly preferred	i is very strongly preferred over j
8	Very strongly to extremely	i is very strongly to extremely preferred over j
9	Extremely preferred	i is extremely preferred over j

associated with the (j, i)th position according to the following rule:

$$\mathrm{M} = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ 1/a_{1n} & 1/a_{2n} & \ldots & 1 \end{bmatrix}, \quad a_{ij} = 1, \quad a_{ji} = 1/a_{ij}, \quad a_{ij} \neq 0 \tag{1}$$

Step 2: After the completion of the binary comparisons, the weights are determined for the different criteria. The procedure steps are as follows:

1. The first step would be to sum up the values of each row in the comparison matrix M.

$$S_i = \sum_{j=1}^{n} a_{ij} \tag{2}$$

2. The second step would be to calculate the total sum of the row sum by the following formula:

$$T = \sum_{i=1}^{n} S_i \tag{3}$$

3. The row sum is then divided by the total sum; the weight for each row is given by the following formula:

$$W_i = \frac{S_i}{T} \tag{4}$$

Step 3: In this hierarchical classification model, consistency can be checked by calculating the consistency ratio (CR):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{5}$$

where CI is the consistency index and RI is a random index. The consistency index is calculated as follows:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{6}$$

where $\lambda_{\max}$ is the maximum eigenvalue, and n is the number of criteria.

$\lambda_{\max}$ is evaluated from the arithmetic mean of the components of the vector u which is defined as follows (Igroufa *et al.* 2020):

$$\mathrm{u} = \sum_{i=1}^{n} \mathrm{M}_{ij} W_j / W_i \tag{7}$$

where M_{ij} is the decision matrix used to compute the set of n weights W_i (i=1, …, n).

RI is a value that depends on the matrix dimension. The values of RI are detailed in Table 2.

The maximum admissible value of the coherence rate for a matrix of order 3 is 5% (n=3; CR<5%).

Table 2 | Random index (RI) (Igroufa *et al.* 2020)

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58	1.59

Weighted product model

The weighted product method is a multi-criterion decision-making method in which there will be multiple alternatives and we have to determine the best alternative based on multiple criteria. The overall weight of an alternative is calculated by the following formula (Vygantas *et al.* 2013):

$$R(A_k) = \prod_{j=1}^{n} (a_{kj})^{W_j}, \quad k = 1, 2, 3, \ldots, m \tag{8}$$

where $R(A_k)$ is the overall weight of an alternative, n is the number of criteria, m is the number of alternatives, a_{kj} is the actual value of the kth alternative in terms of the jth criterion and W_j is the weight of importance of the jth criterion. In our study, the WPM method is used in order to calculate the defect impact (I) which represents the effect caused by the defects; it is calculated by the following equation (Marcelino-Sádaba *et al.* 2014):

$$I = (I_t)^{W_{I_t}} \times (I_c)^{W_{Ic}} \times (I_q)^{W_{Iq}} \tag{9}$$

where I_t is the defect impact on pipe repair time. I_c is the defect impact on the cost of repairing the pipe, I_q is the defect impact on the structural quality of the pipes, W_{I_t} is the weight of criteria (I_t), W_{I_c} is the weight of criteria (I_c) and W_{I_q} is the weight of criteria (I_q).

Technique for order of preference by similarity to ideal solution

The TOPSIS method was first developed by Hwang & Yoon (1981). According to this technique, the best alternatives are found by minimizing the distance to the positive ideal solution and maximizing the distance to the negative ideal solution. All alternative solutions can be classified according to their proximity to the ideal solution. In our case, this method is used to classify the defects of a sanitation section by order of degradation in order to prioritize maintenance interventions in the USN. The TOPSIS method consists of the following steps (Dashore *et al.* 2013; Vasiliki *et al.* 2018):

- Construct the decision matrix and determine the criteria weights: Let $X = x_{ij}$ a decision matrix and $W_i = [W_1, W_2, \ldots, W_n]$ a weight vector, where $x_{ij} \in \mathcal{R}$, W_i is the weight of the ith criterion such that $\sum_{i=1}^{n} W_i = 1$.
- Construction of the standardized decision matrix.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^2}} \quad for\ j = 1, \ldots, m; \quad i = 1, \ldots, n \tag{10}$$

- Calculate the weighted normalized decision matrix by multiplying the normalized decision matrix by its associated weights. The calculation method is as follows:

$$v_{ij} = W_i r_{ij} \ \text{ for } j = 1, \ldots, m; \ i = 1, \ldots, n \tag{11}$$

- Determine positive and negative ideal solutions
  - The positive ideal solution A^+ has the following form:

$$A^+ = (v_1^+, v_2^+, \ldots, v_i^+) = \left\{ \left(\max_j v_{ij} \,|i \in I' \right), \left(\min_j v_{ij} \,|i \in I'' \right) \right\} \tag{12}$$

  - The negative ideal solution A^- has the following form:

$$A^- = (v_1^-, v_2^-, \ldots, v_i^-) = \left\{ \left(\min_j v_{ij} \,|i \in I' \right), \left(\max_j v_{ij} \,|i \in I'' \right) \right\} \tag{13}$$

where I' is associated with the benefit criteria and I'' is associated with the cost criteria.

• Calculate the separation measurements from the positive ideal solution and the negative ideal solution.
  ○ Positive ideal separation:

$$S_j^+ = \sqrt{\sum_{i=1}^{n} (v_{ij} - v_i^+)^2} \; ; \; j = 1, 2, \ldots, m \tag{14}$$

  ○ Negative ideal separation:

$$S_j^- = \sqrt{\sum_{i=1}^{n} (v_{ij} - v_i^-)^2} \; ; \; j = 1, 2, \ldots, m. \tag{15}$$

• The last step is to rank the alternatives according to the values of performance (P_j). The minimum performance value is the most critical value that requires immediate intervention.

$$P_j = \frac{S_j^-}{S_j^+ + S_j^-} \; ; j = 1, 2, \ldots, m \tag{16}$$

Decision-making

After ranking the performance values (P_j) in descending order, the performance scale adopted in our work is that of Igroufa *et al.* 2020) which is presented in Table 3.

Application case: sanitation network in the Bejaia city (Algeria)

In order to highlight the presented model, we propose an illustrative example relating to a real sanitation network of the Bejaia city, which is located northeast of the capital Algiers, with about 185,000 inhabitants and an area of around 120.22 km^2 (ONA 2017).

Presentation of sanitation network

According to the diagnostic study carried out by the French company 'Société Coopérative Européenne (SCE)' on the sanitation network of the Bejaia city (Algeria) for the ONA benefit during a 3-year period (2014/2017), it is noted that the total length of the network identified during the television inspections is about 74.609 km. 99.4% of pipes inspected operate in gravity mode. 91.9% of pipes have a diameter between 200 and 650 mm, which are evaluated using the French project method: Rehabilitation of Urban Sanitation Networks 'RERAU'. This latter is based on information from television inspections carried out according to standard NF-EN 13508 (Le Gauffre *et al.* 2004). The major problem with Bejaia's sanitation networks is the level of obstruction of the manholes (ONA 2017). We opted for the sanitation network of the Bejaia city following the availability of diagnostic data at the ONA. The television inspection team retained the nine indicators of major and relevant defects in the Algerian context which are infiltration/exfiltration (INF/EXF), DHC, presence of sand in the pipe (SAN), collapse (COL), clogging (CLO), DPS, chemical attacks on the pipe (CHA), root intrusion into the pipe (ROO) and abrasion of pipe inside (ABR).

A qualitative scale was proposed by experts in the sanitation field who are the ONA service team which is made up of the agency director, engineers specializing in the USN and the team of the Applied Hydraulics and Environment Research Laboratory (LRHAE) of the University of Bejaia. The purpose of this scale is to assess the defect impact, the probability of defect occurrence and the defect's detectability (D).

Table 3 | Performance scale

Range values	0–25%	25–50%	50–75%	75–100%
Performance	Bad	Weak	Good	Very good

Table 4 | Criteria scales (I_q/*P*/*D*)

I_q	*P*	*D*	I_q	*P* (%)	*D*
Very low damage to pipes and none to the environment	Impossible	Very easy to detect the defect or the cause of defect	1	1	1
Low damage to pipes and no damage to the environment	Possible	Easy to detect the defect by investigation	2	25	2
Moderate damage to pipes and possible damage to the environment	Probable	Detectability is validated manually	3	50	3
Critical damage to pipes and moderate to the environment	Likely	Detection not validated (manual or automatic)	4	75	4
Catastrophic damage to pipes and serious damage to the environment	Very probable	It is almost impossible to detect the defect or the cause of the defect	5	99	5

1. *Scale of the defect impact on the structural quality of the pipes (I_q)*: This scale is an extrapolation of the score proposed by the television inspection team, which is based on the French method 'REREAU' (scales 1–4, from the best condition to the most degraded) with an extrapolation scale from 1 to 5.
2. *Scale of the Probability of defect occurrence (P)*: The probability of defect occurrence increases with increasing defect impact on the structural quality of the pipe.
3. *Scale of defect detectability (D)*: This represents the detection probability of the defect or the defect cause. Based on the distribution of several questionnaires to ONA experts on the detectability of sanitation defects using existing means, a qualitative scale was proposed by the research team to assess the detectability of sanitation defects. Table 4 shows the proposed scales.
4. *Scale of the defect impact on the time* (I_t) *and cost* (I_c) *of repairing the pipe*: According to ONA experts, the defect impact on the time and cost of pipe repairing generally depends on four main criteria: The pipe's depth, the pipe's location, the defect impact on the structural quality of the pipes and the pipe diameter. Each section is evaluated according to the four preceding criteria; the sum of the scores presents the final score of the impact on the time (I_t) and cost (I_c) of repairing the pipe. The proposed scale is presented in Table 5.

Table 5 | Scale of defect impact on the time and cost of repairing the pipe (I_t/I_c)

Pipe criteria		I_t	I_c
Depth (m)	0–1	1	1
	1–3	2	2
	3–6	3	3
	>6	4	4
Location	Road	1	4
	Sidewalk	2	3
	Built	3	2
	Vegetation	4	1
Defect impact on the structural quality of the pipes (I_q)	I_q=1	1	1
	I_q=2	2	2
	I_q=3	3	3
	I_q=4	4	4
	I_q=5	5	5
Diameter (mm)	200–300	1	1
	400–500	2	2
	600–700	3	3
	800–900	4	4

RESULTS AND DISCUSSIONS

Calculate criteria weights of defect impact (*I*) which are I_t, I_c and I_q

Using questionnaires, sewer managers were asked to compare the criteria and determined relative values for the criteria using the Saaty (1986) rating scale of Table 1. Information gathered from the questionnaires are shown as a pair-wise comparison matrix in Table 6. The criterion (I_q) in the first row and the criterion (I_q) in the first column are equally preferred and have been assigned a value of 1; criterion (I_q) in the first row is very strongly preferred to the criterion I_c in the second column and the value assigned is 7; criterion (I_q) in the first row is moderately to strongly preferred to the criterion (I_q) in the third column, the value assigned is 4 and so on. This can be expressed mathematically as $a_{11} = (I_q, I_q) = 1$; $a_{12} = (I_q, I_c) = 7$; $a_{13} = (I_q, I_t) = 4$.

Calculate the weights of criticality criteria which are *P*, *I* and *D*

Table 7 gives the pair-wise comparison matrix for the criteria *P*, *I* and *D*.

After calculating the weights, it is important to check the consistency of the judgments. The values of the CR, CI, maximum eigenvalue (λ_{max}) and randomized index (RI) obtained for the two matrices are, respectively, (CR_1=4.7%, CI_1=0.024, λ_{max1}=3.049 and RI_1=0.52) and (CR_2=2.62%, CI_2=0.014, λ_{max2}=3.027 and RI_2=0.52). We conclude from the previous results that the judgments made are consistent because the values of CR do not exceed the authorized value (CR<5%).

Application of the WPM method

After having obtained the criteria weights, we use Equation (9) of the WPM method to calculate the defect impact. This method has been tested on eight sections of the Bejaia sanitation network (Algeria). In this article, we present the results of section No. 1 of 1,000 mm in diameter with a length of 30.6 m and a depth of 1.85 m; it is located on the road. The obtained results are presented in Table 8. The calculation method has been proposed by the authors using the scales presented in Tables 4 and 5. A calculation example for the INF/EXF defect of section No. 1 is given as follows:

- The values of the defect impact on the structural quality of the pipe (I_q) are extracted from the television inspection data of section No. 1. In our study, the obtained overall score was extrapolated from the overall score introduced by the televisual inspection team using the REREAU method (scales 1–4) [$I_{q(\mathrm{INF/EXF})} = 3$].
- The value of the defect impact on the cost and pipe repair time is calculated according to Table 6. The calculation method is as follows (The significance of the bold values in the display mathematics refers to the results shown in Tables 8–10):

$$
\begin{aligned}
I_{c(\mathrm{INF/EXF})} &= \text{the grade of the depth} + \text{the grade of the location of the pipe} + \text{the grade of } I_q + \text{the grade of diameter} \\
&= 2 + 4 + 3 + 4 = \mathbf{13}
\end{aligned}
$$

Table 6 | Pair-wise comparison matrix for the criteria ($I_q/I_c/I_t$)

Criteria	I_q	I_c	I_t	Row sum	Weight (W_i)
I_q	1	7	4	12.000	**0.677**
I_c	1/7	1	1/3	1.476	**0.083**
I_t	1/4	3	1	4.250	**0.240**
Total row sum	/	/	/	17.726	

Bold denotes the final results of the AHP method.

Table 7 | Pair-wise- comparison matrix for the criteria (*P/I/D*)

Criteria	*P*	*I*	*D*	Row sum	Weight (W_i)
P	1	1/3	1/6	1.500	**0.095**
I	3	1	1/3	4.333	**0.274**
D	6	3	1	10.000	**0.632**
Total row sum	/	/	/	15.833	

Bold denotes the final results of the AHP method.

Table 8 | Defect impact (I)

Defects	I_q $W_{I_q} = 0.677$	I_c $W_{I_c} = 0.083$	I_t $W_{I_t} = 0.240$	I
INF/EXF	**3**	**13**	**10**	**4.524**
DHC	2	12	9	3.330
SAN	1	11	8	2.010
COL	2	12	9	3.330
CLO	3	13	10	4.524
DPS	2	12	9	3.330
CHA	2	12	9	3.330
ROO	2	12	9	3.330
ABR	1	11	8	2.010

Bold refers to the examples of calculations presented in this article.

$$I_{t(\mathrm{INF/EXF})} = \text{the grade of the depth} + \text{the grade of the location of the pipe} + \text{the grade of } I_q + \text{the grade of diameter}$$
$$= 2 + 1 + 3 + 4 = \mathbf{10}$$

$$I_{(\mathrm{INF/EXF})} = (I_q)^{W_{I_q}} \times (I_c)^{W_{I_c}} \times (I_t)^{W_{I_t}} = 3^{0.677} \times 13^{0.083} \times 10^{0.240} = \mathbf{4.524}$$

Application of the TOPSIS method

After having obtained the defect impact (I), we used the scales in Table 4 to determine the probability of defect occurrence as well as the defect's detectability based on the opinions of ONA experts [$P_{(\mathrm{INF/EXF})}$=50%; $D_{(\mathrm{INF/EXF})}$=3]. Once the I/P/D matrix is obtained, the TOPSIS method is used to rank the defects of the sanitation sections. According to Dashore *et al.* (2013) and Vasiliki *et al.* (2018), the calculation procedure for the TOPSIS method can be expressed in several steps. The first step is the normalization of the values by Equation (10). The results are shown in Table 9. A calculation example is given below:

$$I = \sqrt{\sum_{j=1}^{9} x_{ij}^2} = 4.524^2 + 3.330^2 + 2.010^2 + 3.330^2 + 4.524^2 + 3.330^2 + 3.330^2 + 3.330^2 + 2.010^2 = \mathbf{10.221}$$

$$r_{11} = \frac{x_{11}}{\sqrt{\sum_{j=1}^{9} x_{ij}^2}} = \frac{4.524}{10.221} = \mathbf{0.443};\ r_{12} = \frac{x_{12}}{\sqrt{\sum_{j=1}^{9} x_{ij}^2}} = \frac{0.50}{0.901} = \mathbf{0.555};\ r_{13} = \frac{x_{13}}{\sqrt{\sum_{j=1}^{9} x_{ij}^2}} = \frac{3}{10.817} = \mathbf{0.277}$$

Table 9 | Normalized decision matrix

	Standardized decision matrix			Normalized decision matrix		
Defects	I	P	D	I	P	D
INF/EXF	4.524	50%	3	**0.443**	**0.555**	**0.277**
DHC	3.330	25%	2	0.326	0.277	0.185
SAN	2.010	1%	3	0.197	0.011	0.277
COL	3.330	25%	5	0.326	0.277	0.462
CLO	4.524	50%	2	0.443	0.555	0.185
DPS	3.330	25%	4	0.326	0.277	0.370
CHA	3.330	25%	4	0.326	0.277	0.370
ROO	3.330	25%	3	0.326	0.277	0.277
ABR	2.010	1%	5	0.197	0.011	0.426
$\sqrt{\sum_{j=1}^{m} x_{ij}^2}$	**10.221**	0.901	10.817	/	/	/

Bold refers to the examples of calculations presented in this article.

The weighted normalized value is calculated by Equation (11). The results of the TOPSIS method for the following steps are presented in Table 10. An example of the calculation for the weighted normalized value is given as follows:

$$V_{11} = W_I r_{11} = 0.274 \times 0.443 = \mathbf{0.121}$$

$$V_{12} = W_P r_{12} = 0.095 \times 0.555 = \mathbf{0.053}$$

$$V_{13} = W_D r_{13} = 0.632 \times 0.277 = \mathbf{0.175}$$

The positive ideal alternative (V^+) is calculated by Equation (12), and the negative ideal alternative (V^-) is calculated by Equation (13), for example:

$$V^+_{(I)} = \text{Min}\ (0.121; 0.089; 0.054; 0.089; 0.121; 0.089; 0.089; 0.089; 0.054) = \mathbf{0.054}$$

$$V^-_{(I)} = \text{Max}\ (0.121; 0.089; 0.054; 0.089; 0.121; 0.089; 0.089; 0.089; 0.054) = \mathbf{0.121}$$

The separation of each alternative from the positive ideal solution (S^+) and the negative ideal solution (S^-) is calculated by Equations (14) and (15), respectively. The calculation method is given as follows:

$$S^+_{1(\text{INF/EXF})} = \sqrt{(0.121 - 0.054)^2 + (0.053 - 0.001)^2 + (0.175 - 0.117)^2} = \mathbf{0.103}$$

$$S^-_{1(\text{INF/EXF})} = \sqrt{(0.121 - 0.121)^2 + (0.053 - 0.053)^2 + (0.175 - 0.292)^2} = \mathbf{0.117}$$

Finally, Equation (16) is used to calculate the performance score. It is important to rank the obtained results in descending order in order to determine critical defects that require immediate maintenance actions. Defects that have a low-performance score are given the highest priority for maintenance actions. The results of the TOPSIS method are shown in Table 10. An example of a performance score calculation is given by Equation (16):

$$P_{(\text{INF/EXF})} = \frac{S_1^-}{S_1^+ + S_1^-} = \frac{0.117}{0.103 + 0.117} = \mathbf{53\%}$$

The performance results of the eight studied sections grouped according to pipe diameters are presented in Figure 1.

Table 10 | Results of the TOPSIS method for section No. 1

Defects	*I* W_I=0.274	*P* W_P=0.095	*D* W_D=0.632	S^+	S^-	P_j (%)
INF/EXF	**0.121**	**0.053**	**0.175**	**0.103**	**0.117**	**53**
DHC	0.089	0.026	0.117	0.043	0.180	81
SAN	0.054	0.001	0.175	0.058	0.144	71
COL	0.089	0.026	0.292	0.180	0.041	19
CLO	0.121	0.053	0.117	0.085	0.175	67
DPS	0.089	0.026	0.234	0.125	0.072	36
CHA	0.089	0.026	0.234	0.125	0.072	36
ROO	0.089	0.026	0.175	0.073	0.124	63
ABR	0.054	0.001	0.292	0.175	0.085	33
V^+	**0.054**	0.001	0.117	/	/	/
V^-	**0.121**	0.053	0.292			

Bold refers to the examples of calculations presented in this article.

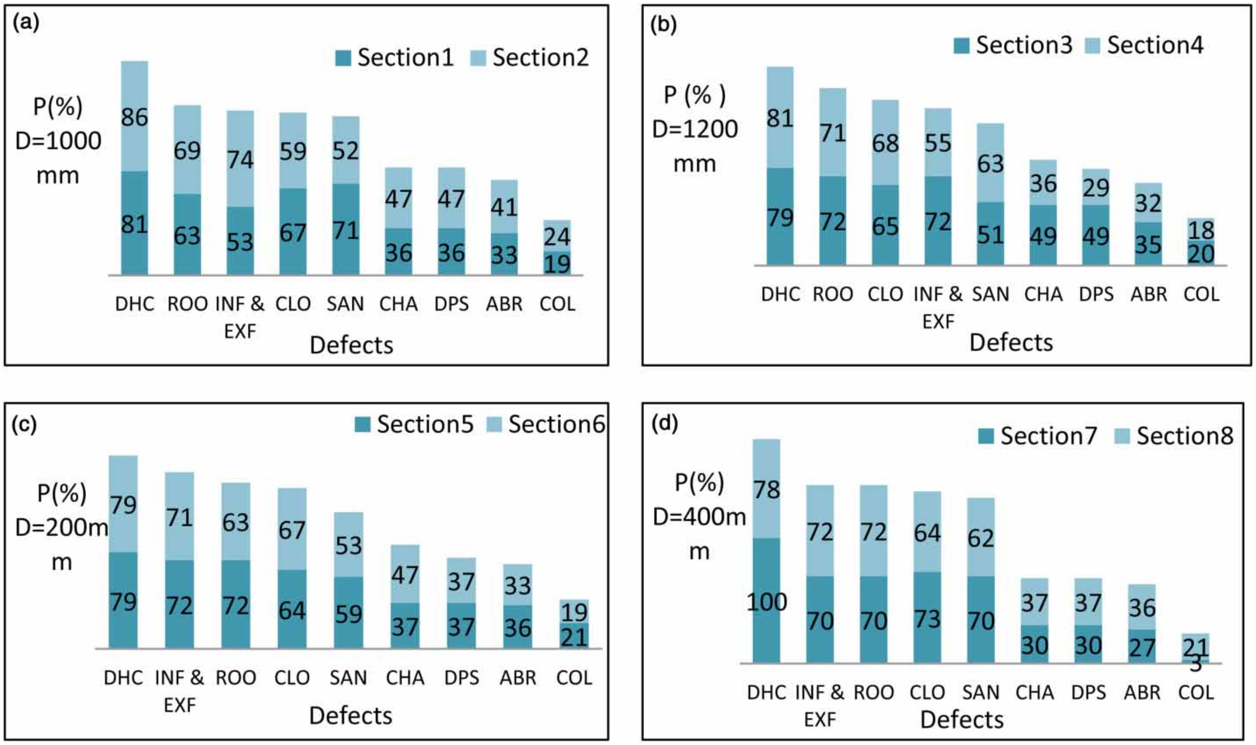


Figure 1 | Performance of diameter sections [(a) 1,000 mm, (b) 1,200 mm, (c) 200 mm and (d) 400 mm] for different defects.

Decision-making

It is seen from the obtained results in Table 9 and illustrated in Figure 1 that the sections studied show a very good performance with regard to the DHC, with a performance rate between ($75\% \leq P \leq 100\%$), which means that the totality of the studied sections do not have any problem of DHC and this is due to their low probability of occurrence ($P_{\mathrm{DHC}}=0.25$), the low impact ($I_{\mathrm{DHC}}=3.33$) and their high detectability ($D_{\mathrm{DHC}}=2$). Similar to the defects root intrusion into the pipe (ROO), INF/EXF, CLO and the presence of sand in pipes (SAN) are considered as weak defects due to the good performance of the pipes ($50\% < P \leq 75\%$).

The results show that the following defects: CHA, DPS and ABR are considered to be critical defects requiring immediate intervention because of their considerable influence on the performance rate of the sections, which is between ($25\% \leq P < 50\%$). This observation is similar to the COL, which is considered in our case the major defect in all the pipes studied. Consequently, the pipe performance following this defect is very low ($0 \leq P < 25\%$). This is particularly due to the priority assigned by the weighting of the AHP method to the criteria: the defect's detectability and the defect impact on the structural quality of the pipe, respectively (63.2–67.7%).

Bejaia city is characterized by an important industrial zone that generates the presence of aggressive effluents in the wastewater network, which favors the presence of defects (CHA, DPS and ABR). To this effect, the results thus found confirm those encountered by the ONA service during systematic inspections of the Bejaia sanitation network (Algeria). The major problem encountered in the network studied is the collapse defect which requires emergency treatment actions, followed by the DPS as well as the ABR of sanitation pipes.

CONCLUSION

The presented model in this paper is based on the combination of three methods: AHP, WPM and TOPSIS. This model has been integrated to support the ONA in its decision-making challenge on priority defects for maintenance work. An application case on the sanitation network of Bejaia city (Algeria) was used to show and prove the relevance of the proposed model. The AHP method was used to calculate the weights of the selected criteria. The results show that the defect impact on the structural quality of pipe is the most important criterion ($W_{I_q} = 0.677$), followed by the defect impact on pipe repair time ($W_{I_t} = 0.240$) and the defect impact on the cost of repairing the pipe ($W_{I_c} = 0.083$). The value of the CR found for the impact matrix is verified ($CR_1 = 4.7\%$). The obtained weights by the AHP method are used in the WPM method to calculate the defect impact.

The application of the AHP method on the criticality criteria identified the defect's detectability as a very important criterion with a weight of $W_D = 0.632$, followed by the defect impact (W_I=0.274) and the probability of defect occurrence (W_P=0.095). The consistency index has also been checked here (CR_2=2.62%). The weights obtained from AHP are used in the TOPSIS method to prioritize the defects of sanitation pipes.

By applying the TOPSIS method on a set of sections of the USN of the Bejaia city (Algeria), it has been noticed that the absolute priority is assigned to the COL defect which causes the low performance of pipes ($0 \le P < 25\%$). Defects CHA, DPS and ABR are also considered as critical defects requiring immediate maintenance actions due to the low performance of the sections ($25\% \le P < 50\%$).

The defects (ROO, INF/EXF, PLU and SAN) are considered as weak defects following the good performance of the studied sections ($50\% < P \le 75\%$). Finally, the DHC defect is very low due to the good performance of the pipes ($75\% < P \le 100\%$). It can be concluded that the developed multi-criteria decision-making (AHP–WPM–TOPSIS) is an important tool envisaged helping sanitation managers to evaluate and prioritize maintenance interventions in the USN.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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