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DECISION SUPPORT SYSTEM FOR THE MANAGEMENT AND MAINTENANCE OF SEWER NETWORKS

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ABSTRACT

This paper aims to develop a decision support tool to provide solutions to the problems of sewer networks management/maintenance in order to assist the manager to sort sections upon priority of intervention by taking account of the technical, economic, social and environmental standards as well as the managers' strategy. This solution uses the Analytic Network Process (ANP)developed by Thomas Saaty, coupled with a set of tools for modelling and collecting integrated data from a geographic information system (GIS). It provides to the decision maker a tool adapted to the reality on the ground and effective in usage compared to the means and objectives of the manager.

Keywords: Multi-criteria decision support, Maintenance, Geographic Information System, Modelling.

INTRODUCTION

Management of sewer networks is probably one of the most important urban issues at the moment. It is usually related to many financial, technical, social and environmental issues. Over time, the pipes of sewer systems get older, their performance decreases; their degradation can cause dramatic damage.
It is sufficient to perform preventive maintenance to overcome the degradation, ensure a better functioning and achieve a determined or curative technical lifetime manifested by repairs of the failures and unforeseen events (Anthony, 2004; NAFI, 2006).

One recurring question the manager asks about maintenance of sewer facilities is: which of the equipment and structures require intervention and when repairing works should take place? (Saegrov, 2006).
Thus, it is important to maintain the assets in the best technical and economic conditions, and determine when and how to rehabilitate the network elements in the most efficient and most economical way possible (Ibrahim, 2008).
The inspection of sewer networks structures in Algeria and their management have shown a disturbing situation (Benzerra, 2012). The current funding state of infrastructure has a significant imbalance that causes major dysfunctions. The relative financial investment in the field of maintenance in Algeria is about than ten times less than in North America (Djebbar, 2004).
Building infrastructures is not the only important issue that matters, but their functioning, maintenance and control that must be assured, in addition to the implementation of an effective strategy to guarantee their long-term function in a way that meets the objectives of a sustainable development (Bouamrane, 2012).
Nowadays, the major concern for the public sewer services is to measure the levels of the objectives of services rendered to the users, by seeking a cost control of investment, functioning and maintenance of the system under given conditions of operating safety to accomplish a required function (AFNOR, 2001; Granger, 2009).
To achieve this objective, the question that arises is: What strategy should be implemented to ensure an effective management of our networks?
To cope with this situation and optimize rescissory actions, sewer networks maintenance managers need a comprehensive methodology to assist in decision-making within a given period (Aflak, 1994).

In this paper, a decision support tool is proposed to reduce the difficulties and complexities of maintenance managements. It aims to sort the priority sections for intervention taking into account several criteria (social, institutional, environmental, legal, techno-economic, etc.). To provide general information, this includes a set of tools for data collection, analysis, modelling, prioritizing and planning on a particular schedule. All these elements will be integrated into a system for data collecting and managing; in other words, to rehabilitate the appropriate section at the right time using a suitable rehabilitation technique at a low cost (Sægrov, 2006).

APPROACHES TO ORGANIZE THE MAINTENANCE MANAGEMENT OF SEWER NETWORKS

The maintenance management of the sewer networks is an approach that allows tracing the evolution and performance of the sewerage system in order to define a policy ensuring its smooth functioning throughout its lifetime.

So, a maintenance decision must combine a technical, social and economic rational environmental analysis of possible choices.

Several decision support tools are generated from methods and approaches developed to improve decision-making models in maintenance, rehabilitation or renewal (Ahmadi and al., 2014; Laffrechine, 2010). But no one of them can be considered as universal since they all reflect the objectives and priorities set on the basis of the evaluation of the impact of the sewer networks' failure (Manfront, 2007).

Mohamed and al. (2013), Dirksen and al. (2008), Kleiner and al. (2006) Mishalani and Madanat (2002) proposed models for modelling the deterioration of the sewer networks, based on the Markov chain process, to predict the structural state and lifecycle maintenance costs. Some other authors used systems based on fuzzy logic for prioritizing pipes that require maintenance by determining their hydraulic and structural performance systems (Ben Tagherouit and al., 2011).The European CARE-S (Computer Aided Rehabilitation of Sewer and Storm Water Networks) project aims to provide a rational methodology for sewer systems rehabilitation. This methodology is primarily concerned with the technical aspect and its economic consequences (Reboza, 2012).The INDIGAU (Performance Indicators for the asset management of urban drainage networks) is also a project that offers a tool for prioritizing sections to be rehabilitated on a short-term period, based on a Multi-criteria tool and taking into account data about dysfunctions and socioeconomic criteria describing the impacts related to the failures (Cathy, 2012). For that, three main approaches can be used in the maintenance planning of urban infrastructure (Nafi, 2006; Blindu, 2004), namely:

- Models based on economic optimization approaches.
- Models based on lifecycle modelling approaches.
- Decision support models (prototypes or operational) that allow, by using different modules, proposing renewal programs.

REQUIREMENTS FOR THE IMPLEMENTATION OF DECISION SUPPORT TOOLS

The performance of the public sewer networks is a growing concern for public authorities and researchers who show a less worrisome situation to cope with aging and deterioration. This explains the requirements of networks rehabilitation and renewal operations (Ibrahim, 2008). Besides the complexity of urban development, the managers are obliged to act quickly and independently from each other, without effective coordination, with a concern of preserving the infrastructure's quality (Cherrared and al., 2007).

The financing statement in Europe regarding maintenance exceeded 5 billion euros per year with an increasing tendency (Sægrov, 2006).

Algeria is not an exception in front of this challenge that led to the emergence of many gaps and shortcomings in the functioning of the sewerage systems such as: pollution of natural environments, frequent flooding and wastewater contamination.

ADOPTED METHODOLOGY

Our approach focuses on the aspects of the geo-referenced decision problems using bi-univocal integration of GIS, Multi-criteria analysis as well as modelling tools in decision-making process for maintenance of sewerage systems. Their mutual contribution is directed towards the department responsible for the management and maintenance. This approach is concretized in our work through developing a conceptual framework that can be used as a systematic identifier of priority sections for intervention and positioning.

The proposed methodology is characterized by multi-level modelling and treatment (Figure 1):

- Data collection and structuring.
- Implementation of a conceptual model based on modelling:
  - Technical evaluation of networks and their characteristics.
  - Decisional modelling to determine intervention priorities.
  - Determine the emergency levels and category for each section.
- Mapping/cartography of the results on geographic information software.

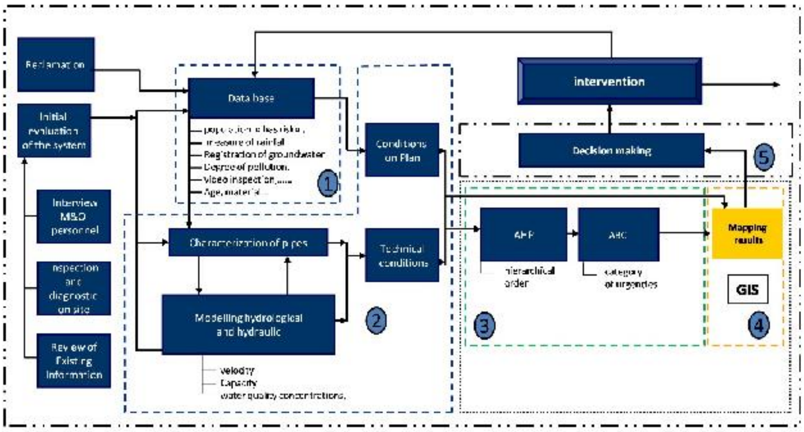

Figure 1: Architecture of the methodology proposed for the management of sewer networks maintenance.

IDENTIFICATION OF DECISION CRITERIA

The decisional problems in the territories refer generally to heterogeneous systems where many social, economic, environmental and technical criteria interact (Laaribi, 2000; Lucien 1994).
According to the adopted methodology, it is necessary to identify criteria to evaluate priorities, which are, in our case, the technical ones characterizing the sewerage system and the ones that contribute to the engagement or the acceleration of the degradation phenomenon. Moreover, socio-economic criteria related to the impacts that become unacceptable for communities and that disturb economic activities and citizens' lives as well as the evaluation criteria of the adverse environmental impact on sustainability objectives to protect the natural environment as well as land use and its vulnerability (type of site, density and type of usage...).

PROGRAMS CONSTRUCTION SUPPORT FOR INVESTIGATION AND REHABILITATION

It is worth remembering that the combination of GIS tools and multi-criteria analysis methods can be done in three integration levels (Laaribi, 2000).

DATA COLLECTION STRUCTURATION

Data collection conducted as part of our work aimed to gather all the raw data and previous or ongoing studies available on the functioning of sewer networks. And like all database management systems, our system is powered by a set of data and information about the network, its environment and the hydraulic and structural performance defined by managers or by the modelling. For this, a decisional database is intended to collect all data and results concerning the decisional modelling.
The data collected about the objective of our work are:

- Various technical features of the system (description plans, functional data, networks and structures, materials, age, etc ...).
- Natural environment of the system (physical environment, geology, climate, local resources, etc...).
- Social and economic environment of the system (concerned human activities and urban areas, municipal boundaries, population, traffic, economic activities etc...).

EVALUATION OF THE HYDRAULIC PERFORMANCE OF SEWER NETWORKS

In this phase, the SWMM model for hydraulic modelling of sewer networks has been adopted. This model has demonstrated its suitability in various applications worldwide (Michael, 2014). The modelling is done to estimate the self-cleansing velocities, the pipes capacity as well as the water quality modelling. To identify the sections that provide no minimum self-cleansing velocity and silting risks, a monthly rainfall frequency is used (Aflak and al., 2007; Bouamrane and al., 2012). Moreover, to define rain flooded sections, a 50-year return period rainfall is used. The application of the model has the advantage, for our prototype, of allowing the assessment of current hydraulic conditions and those after application of rehabilitation interventions or renewal of some or several sections in the sewer network. Figure 2 shows the initial interface SWMM software.

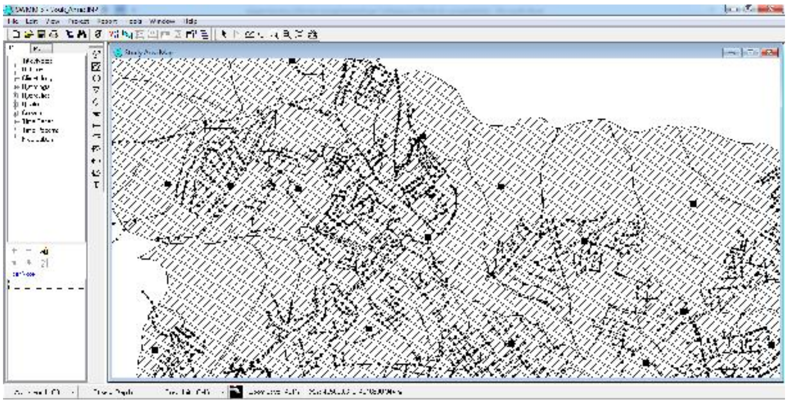

Figure 2: Initial interface of SWMM software.

MULTICRITERIA DECISIONAL MODELLING OF MAINTENANCE PROGRAM:

We used ANP model steps in our case study as a decision-making technique with the ability to involve criteria interactions and dependencies, in order to provide a more accurate approach to model the decision’s complex environment. The model is developed by Thomas Saaty as an extension of the AHP model to solve the problem of its strictly hierarchical design between the decision levels and with no ability to handle all the complexities of the real-world decisions. ANP offered synthetically a logic that presents the problem as a network of criteria and alternatives (sections) and takes in consideration the dependencies and interdependencies among various criteria and sub-criteria.

To use this technique, four main steps are required (Saaty, 1996; Saaty, 2004) as follows:

First step: Define the problem and determine its aim.

The problem should be clearly stated and composed in a reasonable system as a network of criteria and sub-criteria. The structure is defined on the basis of interviews with various interviewers in decision-making and relevant studies for the sewer networks management.

Regarding the model construction, it is necessary to determine the interdependent elements. Indeed, the elements (sub-criteria) of a group (criterion) can influence whether other elements in the same group or in other groups to realize our study problem and looks at the problem of selecting the sections with the priority of intervention. For this, we have built four evaluation groups (criteria).

- Technical group (criteria) with elements (sub-criteria) that are:
  Network type, hydraulic function, external factor, structural sub-criteria
- Economic group (criteria) with elements (sub-criteria) that constitutes it: Disturbing the economic activities, Traffic commoners and the lifecycle of the pipe.
- Social group (criteria) with elements (sub-criteria) that constitutes it: population density, importance of the place and impact of the maintenance.
- Environmental group(criteria) with the elements (sub-criteria) that constitute it: hydrogeological risk, degree of pollution and the site vulnerability.

Figure 3 shows the structure of the network used in our decision problem.

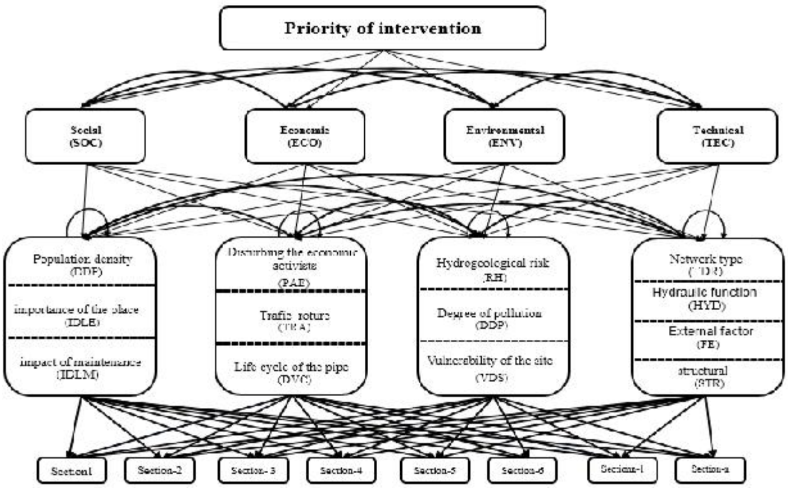

Figure 3: Hierarchical structure of the criteria.

Second step: Pairwise comparisons and priority vectors.

In ANP, like AHP, pairs of decision elements at each cluster are compared with respect to their importance towards their control criteria.
The matrix is the most effective framework for such comparisons in pairs (blindu 2004).
Comparison between all criteria is given by the following matrix:

$$A = [a_{ij}] \text{ of order n} \quad (1)$$

Where: $a_{ij} = w_i/w_j$, w_i and w_j are the relative weights of the criteria g_i and g_j respectively.
The establishment of measures for the criteria is a need for the comparisons to specify the importance degree of one criterion over another.
Table 1 gathers the scales used to make the pairwise comparisons.

Table 1: Pairwise Comparison Scale

Numerical rating	Verbal judgement of preferences
1.0	Equal preference of the two elements
3.0	Moderate preference
5.0	Strong preference
7.0	Very strong
9.0	Absolute preferences
2.0, 4.0, 6.0, 8.0	Intermediate values between two judgements

Determination of weights associated with each criterion.

To calculate the relative importance (weight) of each criterion with regard to its contribution to the objective, the procedure is as follows:

- The values in each column are summed.
- Each element in the matrix is divided by the sum of its column (normalization).
- The average for each element in a row of the matrix is calculated.

The averages represent the weight vector (eigenvector).
The weight associated with the evaluation criteria i is given by the following relationship:

$$wi = \frac{\sum_{i=1}^{n}\left[\frac{a_{ij}}{\sum_{k=1}^{n} a_{ki}}\right]}{n} \qquad (2)$$

With the sum of wi that must be equal to one.

Consistency of judgment

The great advantage of the method is that it allows calculating a consistency index, which evaluates the calculations done. Thus, we can know to what extent our judgments are consistent, since we want to avoid that our decision would be based on little coherent assessments that might seem random.
The coherence index (CI) is determined by the following formula:

$$IC = \frac{\lambda \max - n}{n-1} \qquad (3)$$

Where:
λ max is the matrix biggest eigenvalue.
n: is the number of compared elements.
The larger the consistency index becomes, the more the judgments of the user are inconsistent

Table 2: Random Index

The size of the	2	3	4	5	6	7	8	9	10	11
IA	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Coherence ratio (CR) is given by the following formula:

RC=IC/IA (4)

With:
CR: the consistency ratio.
RI: random index (Table 2).
The assignment of weights is acceptable if CR is less than 10%. In case it exceeds 10%, the assessments may require some revisions.

Third step: Creating the supermatrix

The concept of supermatrix is similar to the Markov chain process (Saaty, 1996). It aims to obtain the overall priority of every criteria and sub-criteria with the interdependent influences. it is necessary to introduce local eigenvectors estimated in step 2 in the homologous columns. Each column in the matrix represents the relative priorities of all elements, compared to a given element. This matrix is called unweighted supermatrix.

$$
W = \begin{array}{cc}
 & \begin{array}{cccc} C_1 & C_2 & \cdots & C_N \\ e_{11}e_{12}\cdots e_{1n_1} & e_{21}e_{22}\cdots e_{2n_2} & & e_{N1}e_{N2}\cdots e_{Nn_N} \end{array} \\
\begin{array}{c} C_1 \begin{array}{c} e_{11} \\ e_{12} \\ \vdots \\ e_{1n_1} \end{array} \\ C_2 \begin{array}{c} e_{21} \\ e_{22} \\ \vdots \\ e_{2n_2} \end{array} \\ \vdots \\ C_N \begin{array}{c} e_{N1} \\ e_{N2} \\ \vdots \\ e_{Nn_N} \end{array} \end{array} &
\begin{bmatrix} W_{11} & W_{12} & \cdots & W_{1N} \\ W_{21} & W_{22} & \cdots & W_{2N} \\ \vdots & \vdots & \cdots & \vdots \\ W_{N1} & W_{N2} & \cdots & W_{NN} \end{bmatrix}
\end{array}
$$

W: unweighted supermatrix.
eij: j th element of the ith group.
Wij: Matrix of relative priorities among the elements of group C and elements of the group Cj.
Ni: elements number in group i.

The supermatrix must be stochastic in column, i.e., the sum of a column is equal to 1. To obtain limited priorities, it needs to multiply each block of the non-weighted supermatrix by the weight of the group (corresponding to the block) in the group matrix, which generates a weighted supermatrix.
For this, the limited supermatrix calculation is present as: the weighted super matrix will reach a steady state until all columns of the weighted supermatrix converge to the same values and each row i of them goes to a consistency αi to complete their convergence. The weighted
supermatrix is raised in power 2k + 1; where k is an arbitrary number. Finally, the obtained final results give us the final weight (Final Priorities) of each criteria.

Fourth step: emergency level Evaluation for each alternative (section):

in case where a limited supermatrix is developed, the last thing is to assess the emergency level (total weight) of each section. The largest among them compared to the emergency level should be one with intervention priority.

APPLICATION AND CASE STUDY

Presentation of the study area

This methodology is applied on the city of Souk Ahras, which is located in Northeastern Algeria. It covers an area of 45 km^2 with a population of 169,162 people with an annual growth rate of 1.8% (source ONA 2014). The city has a sewer network with a connection rate covering currently 94 % of the 290 kml.

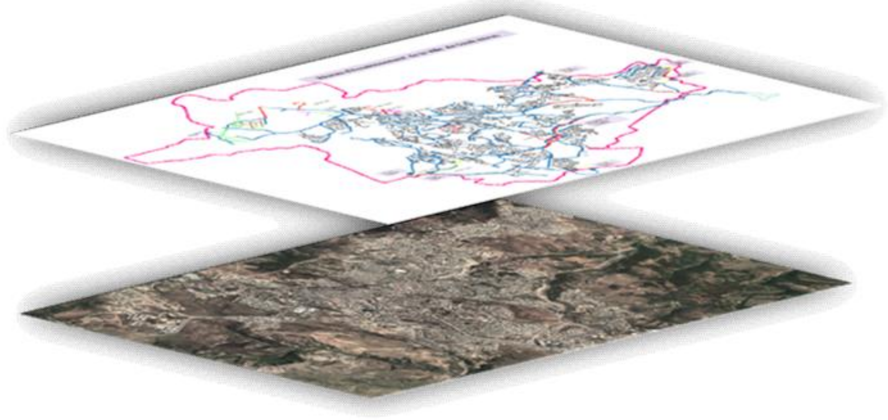

Figure 4: sewer network in the city of Souk Ahras.

Prioritization of sections (alternatives)

After obtaining the evaluation results of the overall relative weights to each criterion or sub-criterion, it is necessary hereafter to proceed with sections hierarchization operation (alternatives) for the maintenance action. The calculation method used is simple: it starts by evaluating the level of urgency for each section that will be calculated by the sum of the relative weight assigned to all the criteria of our grid and present by the following relationship :

$$Pcj = \sum_{j} l_{ij} \tag{5}$$

Where:

Pcj: the overall value of the urgency level for each section

lji: the rate of the overall relative weights for each criterion Cj of section Ii

After having obtained the urgency levels of each section (figure5), the resulting weighted sums sorted in a descending order, which allows carrying out a sections ranking to highlight the position of each one (Figure 6).

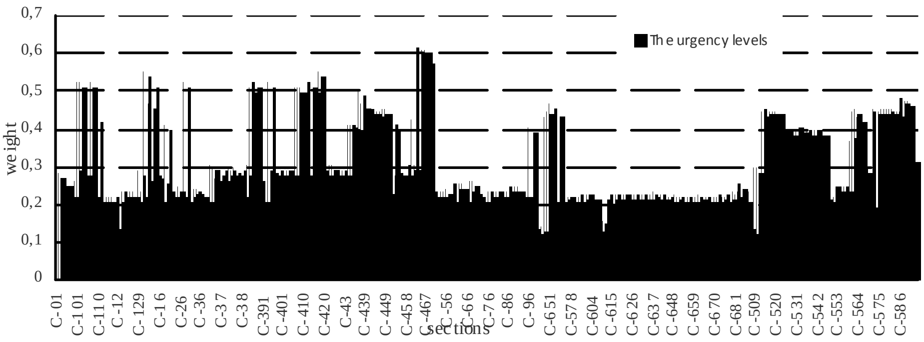

Figure 5: Value of urgency levels

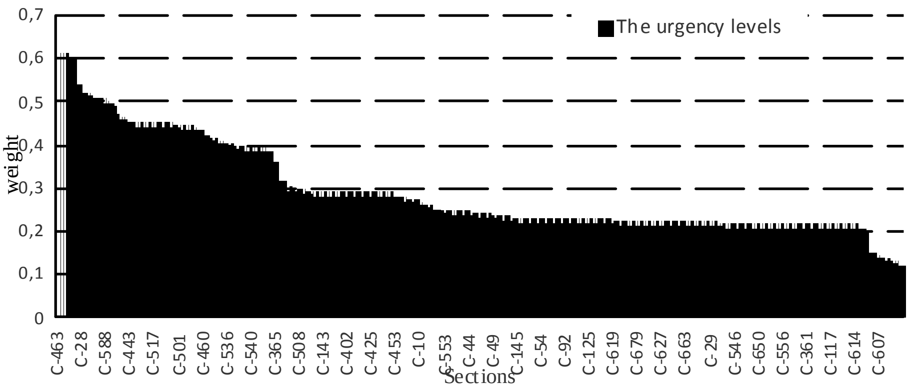

Figure 6: Value hierarchization of the urgency levels and sections

RESULTS ANALYSIS AND EXPLOITATION

Sensitivity/robustness analysis

The sensitivity analysis of the results is a very important step because it helps supporting the validity of the results obtained by specifying the limits in which they allow conclusions that remain robust and stable towards the variation of one or more parameters used (Oumhani, 2006).

- First, we conducted a sensitivity analysis for some criteria individually (hydraulic and structural) to show their influence on the obtained results (assignment 2).
- In a second step, we looked for the capacity of the proposed solution to resist tolerable change in the weight assignment (Assignment 3).

RESULT AND DISCUSSION

The results of the sensitivity analysis showed that the hydraulic criterion should be considered in the same priority as the structural one in the implementation of maintenance decision operations in view of the graphical results that show a small displacement compared to the reference solution (assignment 1) (Figures 7 and 8). This result is supported by the work of Ennaouri (2010).
The sensitivity analysis that was conducted in the second stage shows that the model has excellent robustness in the case where a tolerable weight variation exists. However, there was an emergency decrease of some sections in relation to the others. This decrease causes a slight change in the priority ranking with a simple permutation of the hierarchical order of sections (Figures 7 and 9).

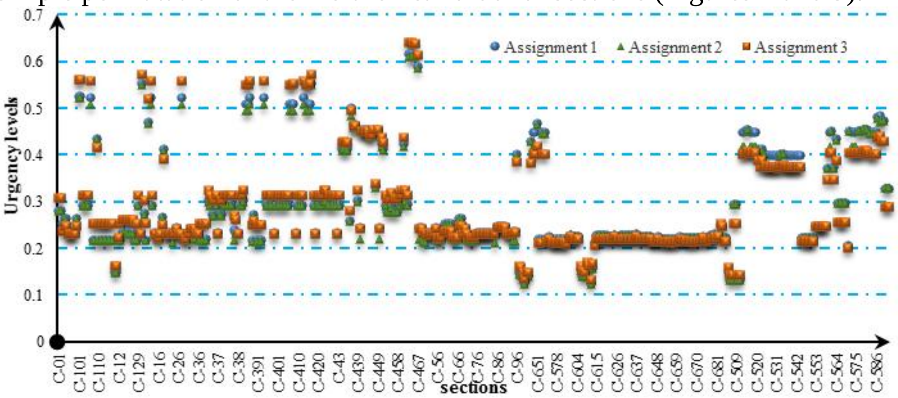

Figure 7: Graphical representations of sensitivity and robustness analysis results.

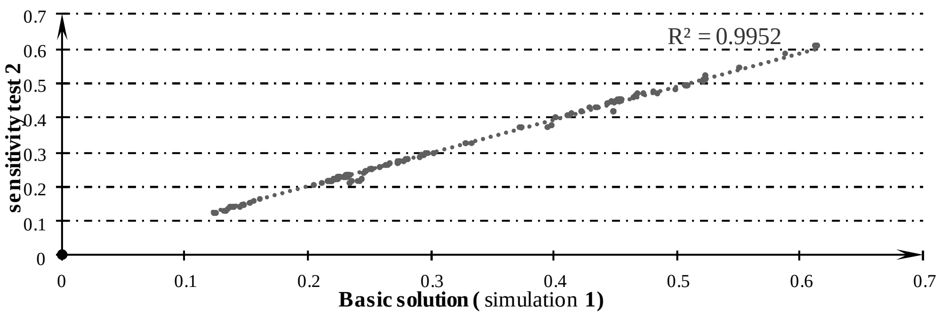

Figure 8: Comparison of the values of the basic solution (assignment 1) and sensitivity test (assignment 2).

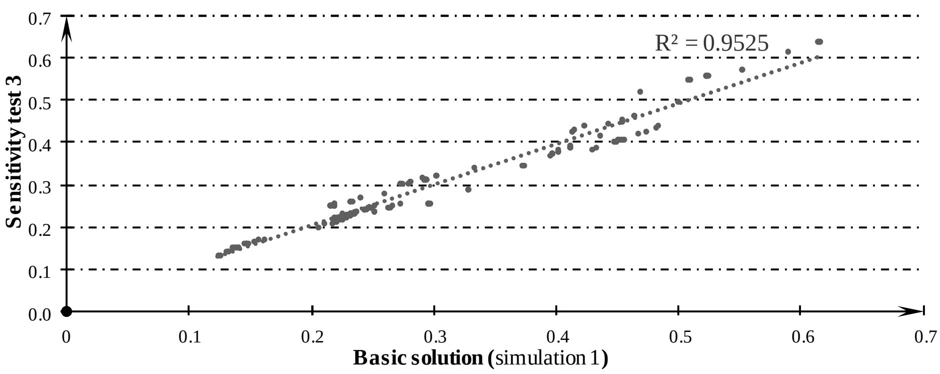

Figure 9: Comparison of the values of the basic solution (assignment 1) and robustness test (assignment 3).

CLASSIFICATION OF PIPES ACCORDING TO THEIR UERGENCY CATEGORY

To provide a better visualization of the previous method results and ensure a smooth reading, and easy understanding, it is necessary to define the urgency categories of each section of the network.

The ABC method called the law 20-80 was developed by the Italian Wilfredo Pareto in the economic field. It was then adopted in many sectors, particularly in the field of maintenance (Zwingelstein, 1996).

The method is the most effective framework for our case to represent the urgency categories. It allows the manager to identify the priority actions' targets, but also to determine the negligible elements to alleviate the study (and Monchy and al., 2010).

The results obtained by the ABC method in our case study are as follows (Table 3, Figure 9):

A. High priority lines: The 20% of the network pipes of high emergency level explain 80% of the interventions. For that, these pipes should be classified as strategic and require increasing number of inspection operations and preventive maintenance interventions to ensure their conditional optimal mission cost and damage.

B. Average priority pipes: The 40% of the network pipes cost approximately 15% of all annual values of the maintenance interventions fees.

C. Low priority pipes: The 40% of the network pipes cost 05% of all annual values of the maintenance interventions fees.

Table 3. Emergency Categories Results

Class	Urgency category	weight
A	High priority	A > 0,3001
B	Average priority	0,3001 > B > 0,2101
C	Low priority	C < 0,2101

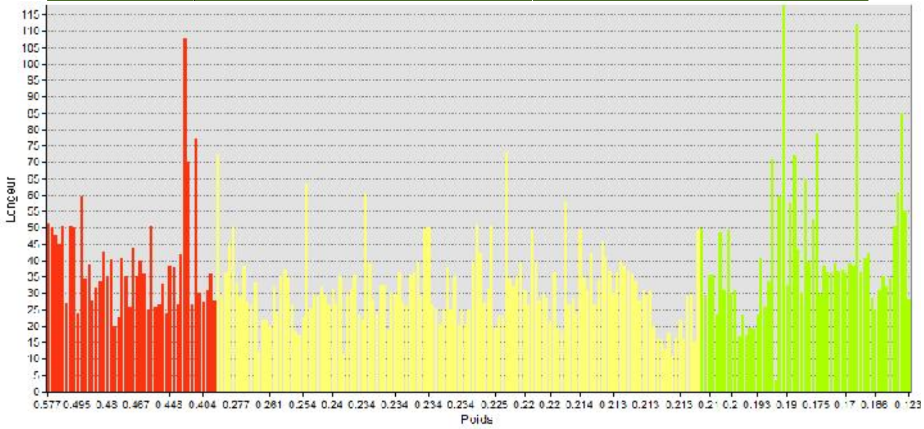

Figure 9: Emergency categories according to section lengths.

Note: These classifications may not be accurate always, but they have proven to be close to the real occurrence of the decision-makers with remarkable accuracy (Swamidass, 2000).

INTEGRATION OF GEOGRAPHIC INFORMATION SYSTEM GIS IN THE DECISION PROCESS

After obtaining assessments and providing intervention priorities and emergency categories for each pipe, we need to apply and execute the final step of the proposed methodology by integrating the geographic information system (GIS) for the maintenance management of the network.

This tool is very powerful in the manipulation, management and analysis of Spatially-referenced data.

It is capable to combine detailed information on the physical structures within the sewer networks as well as the historical information of the networks of pipes and manholes.

The results provided by the previous methods are in the form of notes and emergency categories of maintenance actions. They are not flexible to be exploited, so these results will appear in the form of images to facilitate the manager’s tasks.

Concerning the visualization that is supposed to be one of the strengths of GIS, the results are displayed in terms of priority for each line so that the lines appear on the screen associated with colours that reflect their degree of priority set by the ABC method. Other relevant spatial data such as hydraulic operation of networks, roads, frames, etc... could easily be viewed.

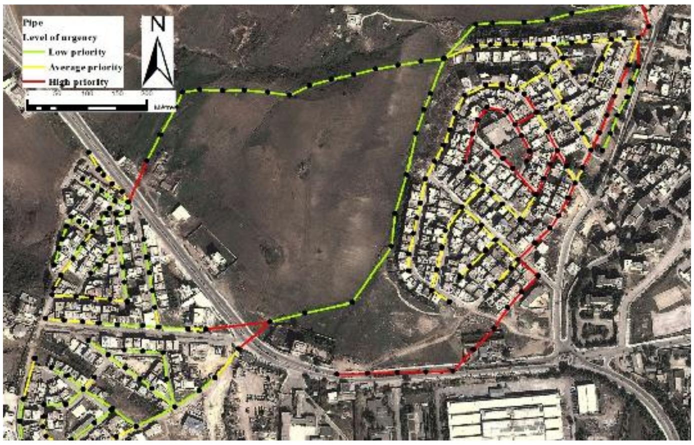

Figure 11: Cartographic Visualization of priority pipes in intervention maintenance.

Figure 12: Cartographic Visualization of priority areas for intervention based on their level of urgency.

CONCLUSION

This work is part of the development of a new generation of tools to support the decision to manage the maintenance of sewer networks. These tools are provided to assist decision-makers defining priority sections for intervention and investigation while considering a set of criteria and sub-criteria for decision-making on various criteria (technical, economic, social and environmental).

The core of this tool is an algorithm of processing and analysis steps exploiting simultaneously the advantages that the integration of GIS, the Analytic Network Process (ANP) method as well as the network modelling tool (SWMM).

They offer a robust tool capable to process and analyze network data quickly and to evaluate its performance. Moreover, the proposed tool provides synthetically a rational multi-annual program of rehabilitation to maximize performance function thanks to the graphical interface of the GIS. It guides decision makers taking the best decisions, which can be considered as a basis for an updated geographic urban database of the managed network, to ensure a better understanding with the advantage of being a tool used for large spread networks.

Future works would focus on the development of a probabilistic model to forecast the pipes degradation in order to optimize the pipes renewal date considering all direct and indirect maintenance costs as well as evaluating the economic and social failures consequences of the network and works implemented to repair them.

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