ELEMENTS FOR MULTI-CRITERIA MODELING OF URBAN STORM DRAINAGE NETWORK PLANNING

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(Received 9 January 2001 Accepted 16 May 2001)

ABSTRACT

This paper deals with the problem of comparison of urban storm drainage network upgrading alternatives from the economic, operational and environmental point of view. First the conditions required for an accurate comparison are outlined. Then the evaluation of a criterion governing the operation of a storm drainage network is presented. It allows the evaluation of the sensitivity of urban areas to the operation failure of the storm drainage network. This criterion is developed by using an expert system approach based on fuzzy inference. The produced results allow the designer to classify the different network upgrading alternatives according to their impacts on urban areas and to introduce this order in a multi-criteria decision making method. The application of the fuzzy sets theory to characterize the evaluation of alternatives leads to a specific formulation of fuzzy decision problem. A suitable multi-criteria decision making method is then presented. Lastly, a practical application to urban storm drainage network upgrading is given and its applicability is discussed.

Keywords: storm drainage system, evaluation, fuzzy sets, multi-criteria decision making

INTRODUCTION

In order to improve the efficiency of their storm drainage networks (environmental and public health constraints) and optimise their resources (economic constraints), many local authorities have invested in network design software. These tools, which have already demonstrated their usefulness and efficiency, allow the rapid generation of many alternatives to a given problem. However, there exists a lack of software to help the designer to choose between the available alternatives (Kim, 1990).

The multi-criteria decision making (MCDM) approach represents one theoretical solution to this problem (Roy and Bouyssou, 1993; Vincke, 1989). MCDM refers to making a selection among some given and predetermined alternatives in the presence of multiple, usually conflicting criteria. The MCDM approach has been used in establishment of a large group of projects in urban infrastructures planning (establishment of Parisian subway lines (Roy and Hugonnard, 1982), establishment of airport plans (Martel and Aouni, 1992), establishment of highway plans (Mladineo *et al*., 1992), planning of water supply networks (Roy *et al*., 1992) and other applications in urban planning (Gungor and Arikan, 2000; Feng and Xu, 1999; Glover and Martinson, 1987). In fact, in large public investments, the public authorities are confronted with partners having divergent interests. The MCDM approach represents the most favorable tool to establish the "best possible compromise" between these interests.

The MCDM approach has also been used in planning of urban storm drainage systems (Fayolle, 1989; Umbayiha *et al*., 1995). Despite the advantages of these studies, two drawbacks could be noticed which affect the accuracy of their results:
a) these studies do not incorporate the operational viewpoint into the MCDM evaluation,
b) they, as well, do not take into account the uncertainties in quantifying certain elements which contribute to the effectiveness of the proposed alternatives.

In this paper, and in order to avoid the above -mentioned disadvantages, fuzzy sets (Zadeh, 1975) to characterise the evaluation of each alternative with respect to each criterion is used. We also present a method of evaluation of a criterion related to the operation of urban storm drainage network. It is important, in order to establish the choice of an upgrading alternative, to quantify the extent of consequent damage due to flooding for each alternative in urban areas. In fact, an alternative which generates flooding in open space areas is more suitable than an alternative which generates flooding in residential or commercial areas. This method is developed on the basis of an expert system approach.

FORMULATION OF THE COMPARATIVE ANALYSIS

During the planning of an urban development, the urban storm drainage networks are designed with determined capacity of collection, after many years some of these networks become of insufficient capacity or deteriorated that they can not afford their function properly. Therefore, local authorities start to investigate alternatives to upgrade their drainage systems (alternatives could be for example changing some pipes or introducing a retention basin to reduce the flow in pipes of insufficient capacities (Figure1)).

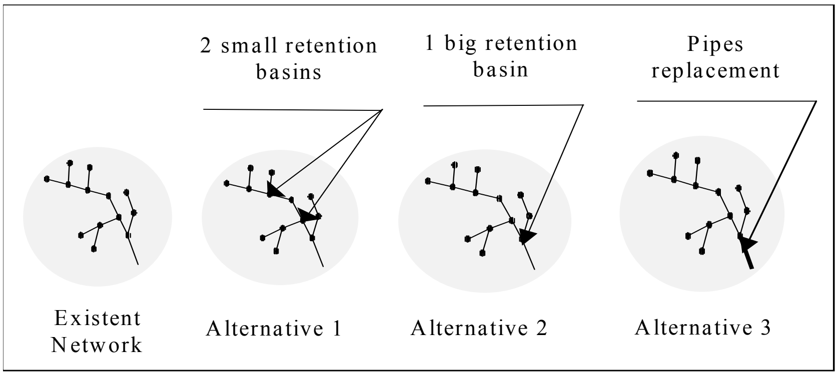

Figure 1. Example of alternatives in Network restructuring.

The choice of criteria

The elaboration of the different criteria to take into account when judging an urban storm drainage alternative depends on the needs or preoccupations of the following three entities: the Employer, the Engineer and the Population. Several studies have investigated the problem of definition of criteria in urban drainage systems (Karnib, 1996; Fayolle, 1989; Bayon, 1990). The defined criteria include functional and economic requirements for some (Fayolle, 1989), others include the environmental aspect (Bayon, 1990; Karnib, 1996).

Despite the difficulty of producing an exhaustive analysis of the preoccupations of entities mentioned above, we have identified three important criteria. They are as follows (Karnib, 1996):

- cost criterion;
- ecological criterion;
- operation criterion.

The choice of these criteria is motivated by the fact that they represent the preoccupations of the several entities which are involved in urban storm drainage planning and they cover the major three aspects mentioned above: economic, environmental and functional.

Presentation of criteria

In this section a resume of the selected criteria mentioned above is given, but for further details on these criteria and their evaluations, see (Fayolle, 1989; Karnib, 1996) and (Blanpain *et al*., 1998). We would like to draw attention to the fact that fuzziness is inherent in the evaluation of these criteria. So, the evaluations of urban storm drainage alternatives are not given in real (crisp) values but in the form of fuzzy numbers. A fuzzy set A is represented by the membership function (Zadeh, 1975):

$$\mu(x) : A \dashrightarrow [0,1] \qquad (1)$$

which measures numerically the degree to which an element x belongs to set A. This function takes values between 0 and 1. The membership function is assessed subjectively, with small values representing a low degree and high values representing a high degree of membership. In this study, fuzzy sets of the trapezoidal type have been used; in this mode of representation, the membership function (μ) is defined by 5 parameters (m, n, α, β, h) and two functions L (left) and R (right) (Figure 2).

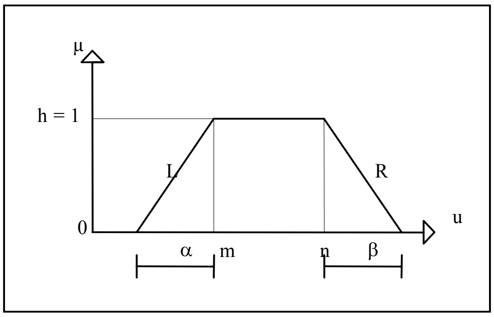

Figure 2. Fuzzy set of trapezoidal type.

The economic criterion

The economic criterion concerns the execution and maintenance costs, only the execution cost can directly be evaluated, but the maintenance cost necessitates more complete statistical studies (Seguin, 1978). We will consider only the execution cost in the evaluation of this criterion ((Figure 3) shows an example of the evaluation of the economic criterion).

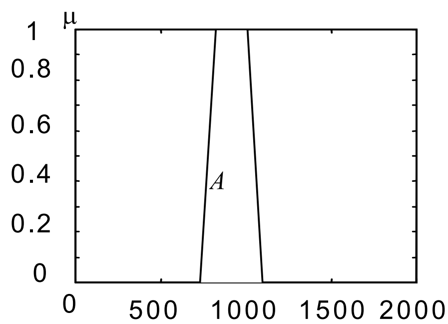

Figure 3. Evaluation of an alternative "*A*" according to the investment cost criterion (in 10^3 FF).

The ecological criterion

This criterion concerns the harmful impacts of the new installations on the environment, It is evaluated in tons/year of the mass of rejected pollution (Fayolle, 1989) ((Figure 4) shows an example of the evaluation of this criterion).

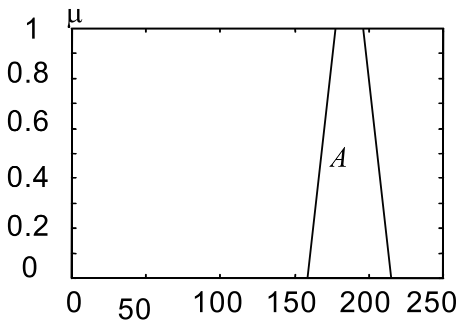

Figure 4. Evaluation of an alternative "*A*" according to the ecological criterion (in tons/year of the mass of rejected pollution).

The operation criterion

This criterion concerns the functioning of the network taking into account the hydraulic operation to prevent flooding. Later on in this paper a method of evaluation of a criterion related to the operation of a storm drainage network is presented. It concerns the sensitivity of urban areas to the functioning failure of storm drainage network. The obtained results are not in themselves significant but they give indications about network functioning and its impact on urban areas when several alternatives are compared.

METHODOLOGY TO COMPARE URBAN STORM DRAINAGE ALTERNATIVES

Formulating of the multi-criteria decision making problem

A problem of multi-criteria decision making (which is described in detail in (Roy & Bouyssou, 1993; Vincke, 1989)) is usually formalised by means of a set of alternatives $K = \{A, B, C, ...\}$ and a set of functions-criteria noted as $\{g_1, g_2, ..., g_n,\}$; here the criteria are real-valued functions defined on set K so that $g_i(A)$ represents the performance or the evaluation of the alternative $A \in K$ on criterion g_i ; the higher the evaluation, the better the alternative satisfies the criterion in question. Consequently, the multi-criteria evaluation of alternative A is the vector $g(A) = [g_1(A), g_2(A), ..., g_n(A)]$ comprised of partial evaluations of n criteria.

There exists a large amount of literature on this problem, dating back to the fundamental work of Fishburn (1964) and earlier. Overviews of methods of multi-criteria decision making are given by MacCrimmon (1973) and also by Vincke (1989), Roy and Bouyssou (1993) and Roubens (1997). In this paper the use of outranking approach is emphasized (Vincke, 1989; Roy and Bouyssou, 1993) due to the following reasons:

- the outranking structure is based on the principle that evaluation of criteria must retain their identity and their properties in the mechanism of a global comparison,
- alternatives are compared two by two with the aid of a valued relation (or preference function) $c_i(A,B)$ which indicates the intensity of preference of the decision-maker for an alternative A with regard to B according to the i^{th} criterion (i = 1, …, n).

These above mentioned properties of the outranking approach makes it preferable over other multi-criteria approaches when applied to urban storm drainage planning where the criteria are difficult to evaluate and conflict in nature.

Every outranking method includes two phases:

- the construction of an outranking relation,
- the exploitation of this relation in order to assist the decision maker.

These two phases may be treated in different ways and many methods have been proposed according to the kind and the concrete cases considered.

One of the most significant methods in this area and easily understood by the decision maker is due to J.P. Brans and PH. Vincke. In the last years, the PROMOTHEE methods have been proposed (Brans & Vincke, 1985; Vincke, 1989). These methods are relatively well known and were successfully used to solve concrete problems.

Principles of the PROMETHEE method

PROMETHEE method (Preference Ranking Organisation METHod for Enrichment Evaluations) is one of the most recent multi-criteria outranking methods. The first mention of the method can be found in (Brans *et al*., 1984). The most complete reference and the most didactic are (Brans & Vincke, 1985; Vincke, 1989). Its applications begin to be numerous : (Mladineo *et al*., 1992; Karkazis, 1989; Briggs *et al*., 1990), *etc*. The principal objective of this method is to be very simple and easily understood by the decision-maker.

Valued outranking degree over all criteria

Adopting the ideas developed in PROMETHEE methods, for each couple of alternatives $A, B \in K$, an outranking degree of A over B for all criteria is defined. It could therefore be written:

$$S(A,B) = \frac{\sum_i p_i \cdot c_i(A,B)}{\sum_i p_i} \qquad (2)$$

Where:

S(A, B) is an outranking degree of *A* over *B*,
$c_i(A, B)$ is the degree of preference associated to each couple of actions according to the i^th^ criterion (i=1,..,n), it takes values between 0 and 1, the closer $c_i(A,B)$ to 1 the greater is the preference.
p_i are weights which translate the relative importance of each criterion.

It is clear that this outranking degree gives a measure of the preference of *A* to *B* for all the criteria: the closer to 1, the greater is the preference.

Exploitation of the valued outranking degree

The valued outranking degree, when obtained, has still to be used in order to rank the alternatives of *K* from the best to the weakest one. In this case the problem consists of using the valued outranking degree to build a total pre-order on *K* (complete ranking without incomparabilities), or possibly a partial pre-order in which some actions are comparable, while others are not. Many methods may be considered to overcome these problems. In this paper PROMETHEE I method is used for solving the ranking problem.

We can therefore write for each node *A*, the outgoing flow

$$\varnothing^{+}(A) = \sum_{B \in K} S(A,B) \qquad (3)$$

and the incoming flow

$$\varnothing^{-}(A) = \sum_{B \in K} S(B,A) \qquad (4)$$

The larger $\varnothing^{+}$(A), the more *A* dominates the other actions of *K*. The smaller $\varnothing^{-}$(B), the less *A* is dominated. The following partial pre-order can then be obtained.

A outranks *B* if $\varnothing^{+}(A) > \varnothing^{+}(B)$ and $\varnothing^{-}(A) < \varnothing^{-}(B)$
or $\varnothing^{+}(A) > \varnothing^{+}(B)$ and $\varnothing^{-}(A) = \varnothing^{-}(B)$
or $\varnothing^{+}(A) = \varnothing^{+}(B)$ and $\varnothing^{-}(A) < \varnothing^{-}(B)$

In all the other cases *A* does not outrank *B*.

The particularity of the problem

In this study the evaluations of urban drainage alternatives are not given in real (crisp) values but in the form of fuzzy numbers. Comparing evaluations, that is, of fuzzy numbers $g_i(A)$ and $g_i(B)$, means that the plausibility value (between 0 and 1) of the assertion " $g_i(A) \geq g_i(B)$" must be made explicit or that an indicator $c_i(A,B)$ related to the comparison $g_i(A)$ versus $g_i(B)$ must be constructed. This implies the necessity to define a degree of preference $c_i(A,B) \in [0, 1]$ of two fuzzy sets $g_i(A)$ and $g_i(B)$.

The notion of the preference index "*c*" descends from the problem of ordering fuzzy sets. A number of authors (Dubois & Prade, 1983; Koczy & Hirota, 1993), (Saade & Schwarzlander, 1992) and others have investigated methods of ordering and calculation of distances between fuzzy sets (Zadeh, 1975; Koczy & Hirota, 1993), despite the advantages of these methods, they were judged optimistic and un-indicative (Saade & Schwarzlander, 1992) (Siskos and Hubert, 1983) and sometimes no distinction in preference is made for small or large deviations between the compared fuzzy sets.

In order to avoid the above-mentioned disadvantages, the method proposed by (Karnib *et al*., 1997) to calculate the preference index $c_i(A,B)$ of two fuzzy sets is used. In this method the comparison of two fuzzy sets is reduced to the comparison of a succession of interval numbers each having a degree of membership α. This degree of membership will be used as a weight to give to each level of comparison of intervals. Hence, this method considers that at each degree of preference $c_\alpha(A_\alpha, B_\alpha)$ of two intervals A_α and B_α produced at α-level of two fuzzy sets A and B has a weight equal to α in the comparison of two fuzzy sets A and B. Therefore, the valued degree of preference of two fuzzy sets is the average of the valued degrees of interval numbers at each level-set α. This may be translated into the following formula:

$$c(A, B) = \frac{\sum_{\alpha} \alpha \cdot c_\alpha(A_\alpha, B_\alpha)}{\sum_{\alpha} \alpha} \qquad (5)$$

where:

$\alpha = \{0.2, 0.4, 0.6, 0.8, 1\}$

$c_\alpha(A_\alpha, B_\alpha)$ represents the degree of preference of the interval A_α to the interval B_α at the level-set α (the α allows to determine $A_\alpha = [a_1(\alpha), a_2(\alpha)]$ and $B_\alpha=[b_1(\alpha),b_2(\alpha)]$).

To calculate the $c_\alpha(A_\alpha, B_\alpha)$, this method use the preference structure introduced by Roy (Roy & Bouyssou, 1993) as follows:

i) When the preferences increase as values of intervals increase

$c_\alpha(A_\alpha, B_\alpha) = 1$ if $b_2(\alpha) < a_1(\alpha)$

$c_\alpha(A_\alpha, B_\alpha) = 0.75$ if $b_1(\alpha) < a_1(\alpha) \leq b_2(\alpha) < a_2(\alpha)$

$c_\alpha(A_\alpha, B_\alpha) = 0.5$ if $[a_1(\alpha), a_2(\alpha)] \subset [b_1(\alpha),b_2(\alpha)]$ or $[b_1(\alpha),b_2(\alpha)] \subset [a_1(\alpha), a_2(\alpha)]$.

$c_\alpha(A_\alpha, B_\alpha) = 0.25$ if $a_1(\alpha) < b_1(\alpha) \leq a_2(\alpha) < b_2(\alpha)$

$c_\alpha(A_\alpha, B_\alpha) = 0$ if $a_2(\alpha) > b_1(\alpha)$

i) When the preferences increase as values of intervals decrease

$c_\alpha(A_\alpha, B_\alpha) = 1$ if $a_2(\alpha) < b_1(\alpha)$

$c_\alpha(A_\alpha, B_\alpha) = 0.75$ if $a_1(\alpha) < b_1(\alpha) \leq a_2(\alpha) < b_2(\alpha)$

$c_\alpha(A_\alpha, B_\alpha) = 0.5$ if $[a_1(\alpha), a_2(\alpha)] \subset [b_1(\alpha), b_2(\alpha)]$ or $[b_1(\alpha), b_2(\alpha)] \subset [a_1(\alpha), a_2(\alpha)]$.

$c_\alpha(A_\alpha, B_\alpha) = 0.25$ if $b_1(\alpha) < a_1(\alpha) \leq b_2(\alpha) < a_2(\alpha)$

$c_\alpha(A_\alpha, B_\alpha) = 0$ if $b_2(\alpha) < a_1(\alpha)$

See (Karnib *et al*., 1997) for more details on this method.

EVALUATION OF THE SENSITIVITY OF URBAN AREAS TO THE FUNCTIONING FAILURE OF STORM DRAINAGE NETWORK

Urban drainage systems have traditionally had the objective of preventing surface flooding during minor storms, the modeling showed that the existing piped storm water systems, designed and installed 30 – 40 years ago, were in many areas capable of carrying the flow from an event of only 5-year returned period, but there is a recent worldwide trend towards extending urban drainage analysis to major storms where surface flooding would happen in one in 50-year return period storm (MacMurray & Barnett, 1996). The return period of a rain storm for which the pipe passes the state of overflow is termed the "return period of failure" (Blanpain *et al*., 1998). The determination of the return period of failure depends on the security level defined by local authorities planners against any failure of the drainage network. In such extreme events, surface flooding is inevitable, so the design objective becomes the maximum reduction of negative impacts on urban areas. Urban development is characterized by a large investment in structures and amenities. In case of flooding, damage costs can be very high. Local authorities drive the upgrading of urban drainage network to ensure that any part of the urban areas would not be flooded by an event having a determined return period of failure. Many upgrading alternatives could be generated (upgrading alternatives from the technical point of view could be for example an increase of the flow capacity of the main sewers, overall accumulation capability of the system or rejection of the flow of part of the system in suitable places). It then falls to the designer to choose among the available alternatives. Many criteria are needed to exercise this choice; it is therefore important, in order to establish the choice of upgrading alternative, to quantify the extent of consequent damage of flooding for each alternative in urban areas. In fact, an alternative which generates flooding in open space areas is more suitable than alternatives which generates flooding in residential or commercial areas. This paper presents a method of evaluation of the sensitivity of urban areas to network failure. This method is developed on the basis of an expert system approach.

Basic Information

The Hydraulic simulation

The evaluation of the sensitivity of urban areas to network failure necessitates that the operational behavior of the network to carry the flow from a rain event of 50-year return period (return period of failure) be known. This could be done using a hydraulic simulation model. To ensure a correct functionality of the simulation model, it is necessary to calibrate the simulation model against real data. Such a model is then able to respond in the same way to the external events as it happens in reality. After the calibration of the model is carried out, simulations based on synthetic rain events could be performed (Karnib & Blanpain, 1996) (Blanpain *et al*., 1998). Many software in urban drainage networks design and management could be used to make hydraulic simulations, to map the results and to show the most overloaded areas and zones where storm water is likely to overflow top of manholes and flood the surface (Rees & Hughes, 1996).

The Identification of ponding areas

The second type of data needed to evaluate the criterion sensitivity of urban areas to network failure is the identification of the "ponding areas" (the ponding area is the area which will be subject to the consequences of the pipe failure). The size of the ponding area depends on the topography and the nature of the soil around the failed pipe. Maps of flooded areas could be generated using suitable software (MacMurray & Barnett, 1996). Figure 5 shows an example of ponding area of a failed pipe.

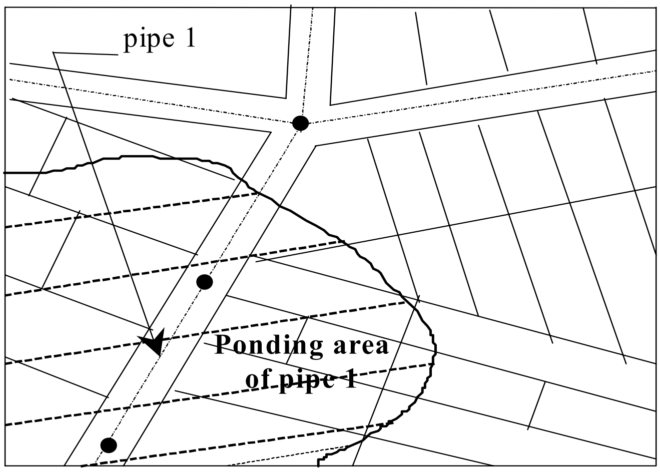

Figure 5. Ponding area of a failed pipe.

The expert system

After the determination of ponding areas, the evaluation of the sensitivity of urban areas to network failure necessitates for each ponding area a good knowledge of the urban fabric. Among this important knowledge, we can identify the density of population, the density of traffic and the density of land use (DLU) (this variable is identified by density of residential land use, density of commercial land use, density of industrial land use and density of public utilities) (Karnib *et al*., 1996; Yan *et al*., 1991). It can then be written

$$s_i = f\,(\text{density of population, density of traffic, DLU}) \qquad (6)$$

where (s_i) is the degree of sensitivity of a ponding area relative to a failed pipe.

Considering the difficulty of the identification of (f), an expert system approach (Kim, 1990) is explored. An expert system is defined as a computer system that consists of a knowledge base for the storage of information and knowledge obtained from experts and an inference engine for the utilization of this knowledge in problem-solving.

The Rules

Knowledge acquisition concerning the representation of conditional rules is the way to obtain groups of rules from experts in a system domain. This is often regarded as a major bottleneck in the development of knowledge-based systems (Han and Tschangho, 1989) because acquisition of knowledge is difficult and very time-consuming with current technology. We will use conditional rules as the basis of knowledge representation in the system to be developed. Then the problem of knowledge acquisition requires one to obtain groups of rules such as those listed in Figure 6. This procedure in system development is called rule making. The simplest way for it to be executed is for us to elicit knowledge directly from experts, rule by rule.

IF	THEN
Density of population is average and density of traffic is average	*The sensitivity degree is average*
Density of population is high and density of commercial land use is average	*The sensitivity degree is average*
....	....

Figure 6. Examples of rules to determine the sensitivity degree.

Rule combining

As one can see from Figure 6 for the example of rules, many imprecise and uncertain statements, such as "density of population is high", "density of traffic is average", "degree of sensitivity is average" and so on, exist in our expert system. In the process of classifying such uncertain knowledge, Yan, Shimizu and Nakamura (1991), characterized them as having two types of uncertainty. If a rule, for example, exists which says below,

IF Density of population is average and density of commercial land use is average

THEN The degree of sensitivity is average

These uncertainties could be identified as follows. The first type of uncertainty is imperfect information. To what degree do we believe that density of population is low? The second type of uncertainty relates to the imperfection of the rule. To what degree does one believe that the degree of sensitivity should be average given that the density of population is average and the density of commercial land use is average? One needs to know how the two types of uncertainty should be handled in the system, how they should be measured, and how they should be combined in inference. These issues are resolved in the following sections.

Fuzzy Sets

Using fuzzy-set theory (Zadeh, 1975), the first type of uncertainty can be expressed in the concept of fuzzy sets themselves. As we mentioned before, a fuzzy set A is represented by the membership function $\mu(x) : A \dashrightarrow [0,1]$ which measures numerically the degree to which element x belongs to set A. This function takes values between 0 and 1. The membership function is assessed subjectively, with small values representing a low degree and high values representing a high degree of membership. In this study, we have used fuzzy sets of trapezoidal type; in this mode of representation, the membership function μ is defined by 5 parameters (m, n, α, β, h) and two functions L (left) and R (right) (Figure 2).

According to this definition, the different levels of the "density of population" (low, average and high) can be represented as shown in Figure 7. In this way, one can express imprecise and subjective premises or conclusions in quantitative form.

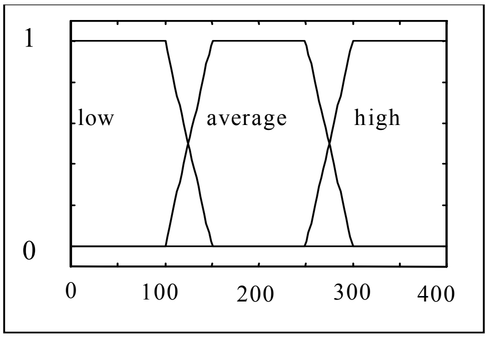

Figure 7. Density of population (persons/ha).

Fuzzy Inference

The second type of uncertainty concerning imperfect rules, is processed by so-called fuzzy inference. In fuzzy inference, imprecise information concerning the premises or the conclusions of rules are represented with membership functions such as those mentioned above. These rules are like: *"If X is A then Y is B"* where X and Y are two linguistic variables, A and B are two qualifying: high, average.... The fuzzy inference allows to determine the output of the system from fuzzy inputs and fuzzy rules. The principle of fuzzy inference is based on Mamdani method (Mamdani, 1976; Tong Tong, 1995). In the following section we present the application of this rules inference method to the evaluation of the degree of sensitivity of urban areas to network failure.

Evaluation of the sensitivity degree of urban areas to network failure

In this section the system that allows the determination of the degree of sensitivity for a ponding area is shown. This system has been implemented in the software 'MATLAB' environment (Roger Jang & Gully, 1995).

For the application of the expert system, knowledge elements and rules were extracted from a bibliographical analysis and limited expertise.

The representation by fuzzy numbers of the different levels (low, average and high) for each knowledge element (density of population, density of traffic, DLU) have to be defined by the planners according the nature and urban development of each city or town.

The knowledge element “sensitivity degree” is expressed by three levels (low, average and high) according to the vulnerability of urban areas to network failure. It takes values between 0 and 1 and it could be represented as shown in Figure 8.

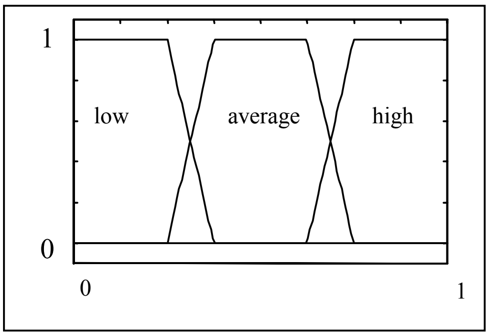

Figure 8. The three levels of the sensitivity degree.

Steps of reasoning

The calculation of the (s_i) value (sensitivity degree of a ponding area) goes through the following steps as shown in Figures 9a and 9b:

1- Fuzzify inputs : the first step is to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions.

2- Apply fuzzy operator and implication method: once the inputs have been fuzzified, we know the degree to which each part of the antecedent has been satisfied for each rule. This step is defined as shaping of consequence (a fuzzy set) for each rule.

3- Aggregate all outputs : this step consists in aggregating into a single fuzzy set each output variable obtained from step 2.

The system presented in this section allows the determination of sensitivity degree for a ponding area. However, for one upgrading alternative of storm urban drainage, hydraulic simulation could show one or several ponding areas. Therefore, the same procedure has to be applied for each ponding area and a degree of sensitivity (s_i) has to be calculated. Finally, the results are aggregated with the following equation:

$$S = \Sigma s_i \qquad (7)$$

where (s_i) is the sensitivity degree for a ponding area and (S) is the sensitivity degree for the ponding areas for one upgrading alternative.

ILLUSTRATIVE EXAMPLE OF APPLICATION

The proposed multi-criteria decision making approach on several problems in planning of urban drainage systems (Karnib, 1996; Blanpain *et al*., 1998) is applied. This section presents a simple example of restructuring of urban storm drainage network to examine the various steps of the methodology on a real case.

The study concerns a restructuring (upgrading) project of the storm drainage network of *Annequin,* a town located in the northern part of France. The population is 4840 people, and the surface is equal to 68 hectares. Following an insufficiency due to saturation of the existent system, a project to upgrade the system has been launched by the local authorities. Three proposals for restructuring have been identified (in the limits of the project budget).

The problem is in deciding which will be executed as a solution.

(Figure 10) shows the town's storm drainage network before and after the proposed upgrading alternatives:

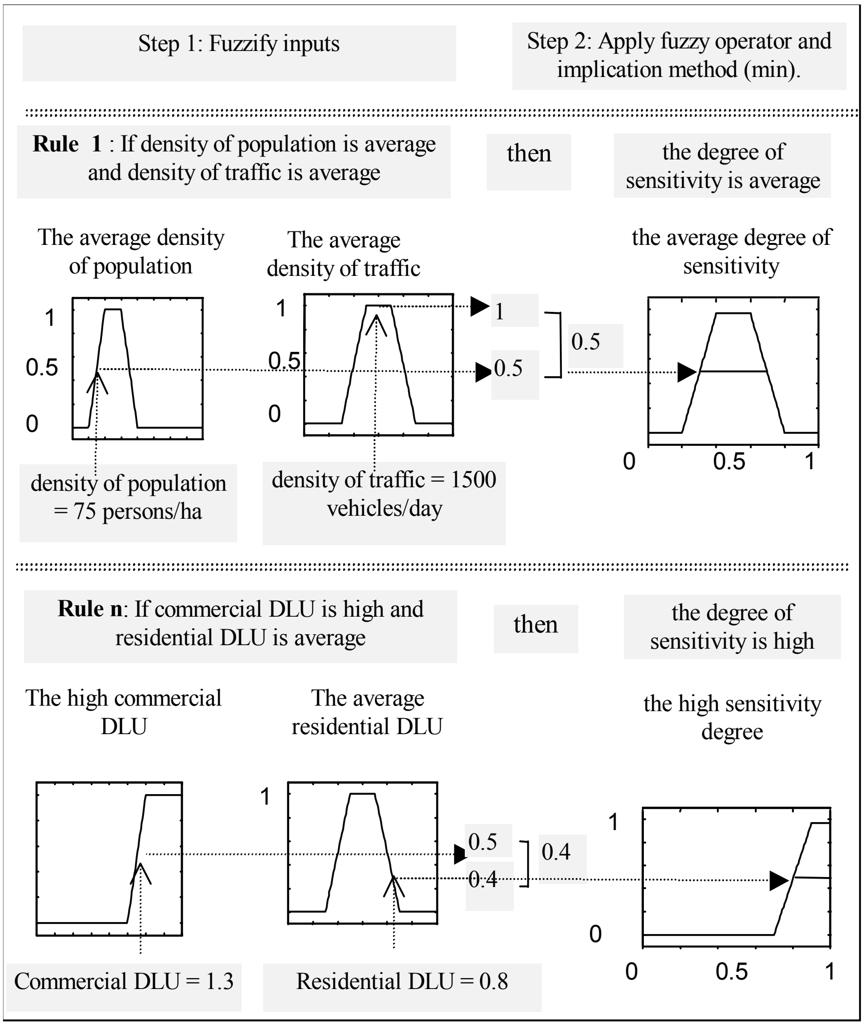

Figure 9a. Illustration of steps 1 and 2 of the proposed expert system to evaluate s_i.

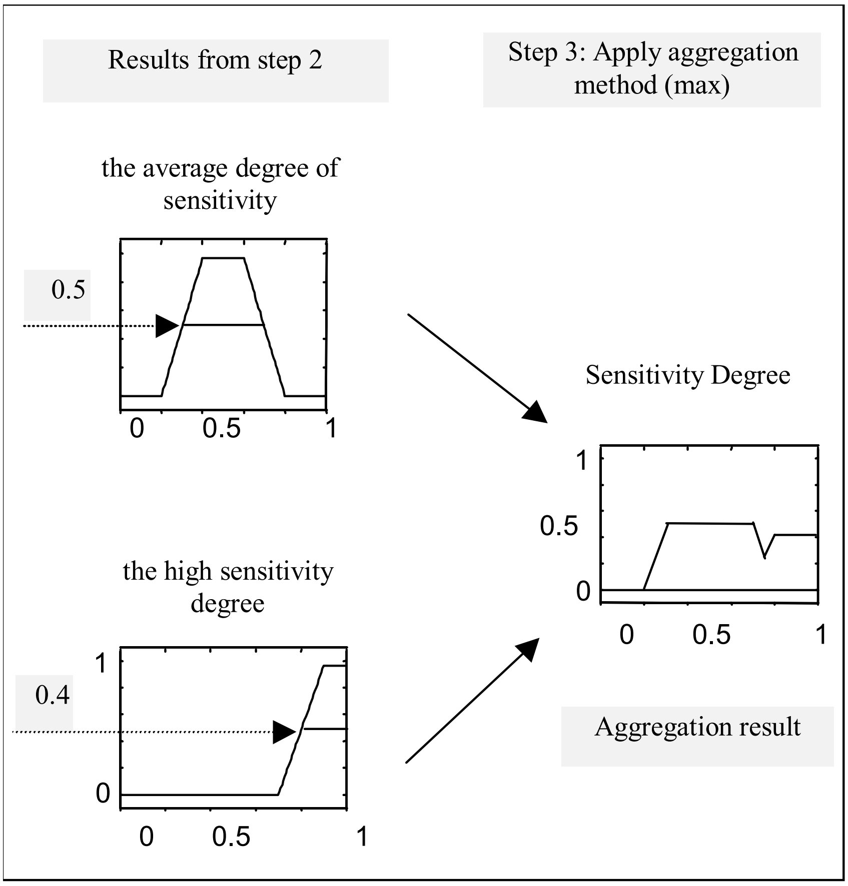

Figure 9b. Illustration of step 3 of the proposed expert system to evaluate s_i.

- alternative A : installation of a retention basin as shown in Figure 10;
- alternative B: installation of a retention basin as shown in Figure 10;
- alternative C : creation of an outflow.

<u>Analysis of the proposed alternatives with regard to "sensitivity of urban areas" criterion</u>

For the application of the expert system for the evaluation of urban areas criterion, knowledge elements were extracted from a bibliographical analysis and limited expertise. By interviewing the planners of the city of Annequin, the rules and the fuzzy representation of knowledge elements levels of the system is defined (low, average and high).

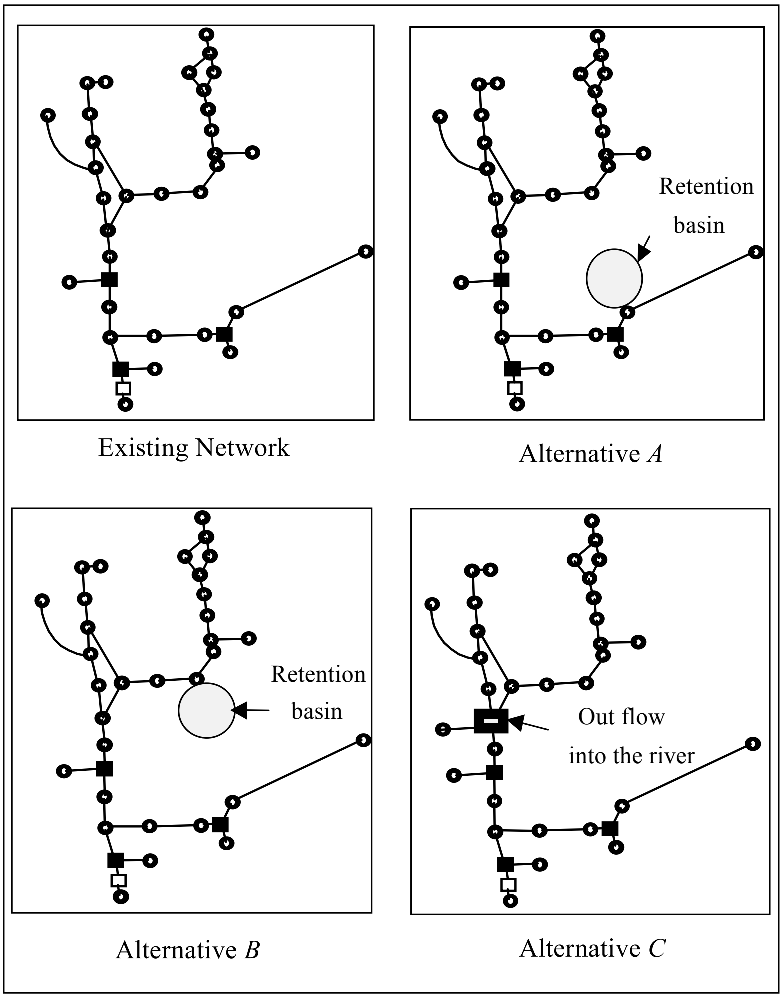

Figure 10. Simplified plan of the different upgrading proposals of the network.

The computer package CEDRE was chosen for the hydraulic simulation (Chocat, 1990) (CEDRE 2, 1990). A 50-year return period rain event was chosen by local authority planners as a return period of failure for this project of network upgrading.
Following hydraulic simulation, the obtained results are shown in Table 1 (only failed pipes are shown).

TABLE 1
Results of Hydraulic Simulations

	Alternative *A*	Alternative *B*	Alternative *C*
Failed pipes	5, 7, 9, 11, 16	5, 9	5, 9, 11, 16

For each failed pipe its ponding area was identified and calculated using the expert system the degree of sensitivity of each area. Then for each alternative the criterion sensitivity of urban areas to network failure was evaluated using equation (7). The results are presented in Figure 11.

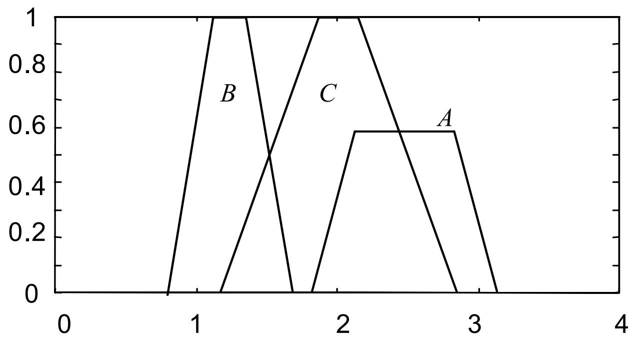

Figure 11. The degrees of sensitivity of urban areas to network failure for Alternatives *A*, *B* and *C*.

Remark : The preferences increase as values decrease for this criterion.

The proposed sensitivity of urban areas to network failure criterion allows the choice of an upgrading alternative that ensure the optimum behavior of the upgraded system and maximum reduction of negative impacts on urban areas. To rank the produced results, the method proposed by (Karnib *et al*., 1997) was used (see section 3) and the following preference degree values were obtained: c(A, B)= 0, c(B, A)= 1, c(A, C)= 0.25, c(C, A)= 0.75, c(C, B)= 0.05, c(B, C)= 0.95. These values could be directly used in multicriteria decision making analysis where c(A, B) gives a measure of preference of alternative A to alternative B: the closer to 1, the greater is the preference.

Inclusion of other relevant criteria in a multi-criteria analysis

The results obtained related to the sensitivity criterion are then used in a multi-criteria decision analysis where other criteria are introduced as investment cost criterion and the ecological criterion (see section 2). (Figures 12 and 13) show the results of the evaluation of these criteria for the proposed alternatives. See (Karnib 1996) for further details on these criteria and their evaluations.

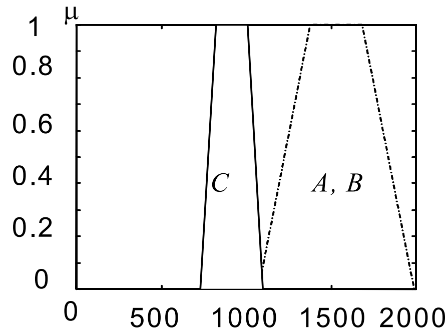

Figure 12. Evaluation of alternatives *A*, *B* and *C* according to the investment cost criterion (in 10^3 francs).

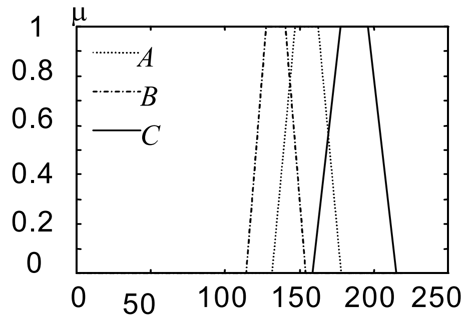

Figure 13: Evaluation of alternatives *A*, *B* and *C* according to the ecological criterion (in tons/year of the mass of rejected pollution).

Remark : Same as the sensitivity criterion, the preferences decrease as values increase for the ecological and investment cost criteria.

Ranking of alternatives

In applying the method proposed by (Karnib, Al-Hajjar & Boissier, 1997) for comparing two fuzzy numbers we obtain the partial valued outranking degrees presented in (Table 2):

TABLE 2
Preference Degrees of Alternatives

	investment cost	sensitivity	ecological
c(A, B)	0.5	0	0.17
c(A, C)	0	0.25	0.9
c(B, C)	0	0.95	1
c(B, A)	0.5	1	0.83
c(C, A)	1	0.75	0.1
c(C, B)	1	0.05	0

Several weights corresponding to each criterion must be defined to make the sensitivity analysis. This part can possibly be determined interactively between the decision-maker and the analyst. We present here an example of these weights :

$P_1 = 1$ weight associated to the investment cost criterion
$P_2 = 0.5$ weight associated to the ecological criterion
$P_4 = 0.8$ weight associated to the sensitivity of urban areas criterion.

Ranking alternatives necessitates the use of information included in (Table 2) and weights associated to each criterion to build a global outranking relationship (*S)*. The results obtained are presented in (Table 3).

TABLE 3
Values of S(A, B), S(A, C), S(B, A), S(B, C), S(C, A) and S(C,B)

S	*A*	*B*	*C*
A		0.246	0.251
B	0.754		0.577
C	0.749	0.426	

We then apply the PROMETHEE technique. According to (3) and (4) formulas we complete the (Table 4).

TABLE 4
Data for Ranking Alternatives According to PROMETHEE Technique

	A	*B*	*C*
$\varnothing^+$	0.497	1.331	1.175
$\varnothing^-$	1.503	0.672	0.828

It is then easy to obtain a complete preorder which is illustrated by:

Alternative B ⟶ Alternative C ⟶ Alternative A

where:

$A \rightarrow B$ means that A outranks B.

DISCUSION

The generation of the three alternatives of network upgrading was proposed by Annequin local authority planners in the limit of their budget to execute this project. Other alternatives could be proposed as for example the increase of the flow capacity of the main sewers or the combination of different proposals of upgrading techniques. In this example, only the three alternatives proposed by Annequin local authority planners to show the applicability of our proposed method on a real case is presented.

The evaluation of each alternative with regard to the "sensitivity of urban areas to network failure" criterion shows that alternative A_2 ensures less uncomfortable situation and less harm on urban areas than alternatives A_1 and A_3. This allows to confirm that alternative A_2 is the best among the proposed alternatives with regard to the sensitivity criterion, but in multi-criteria decision making analysis other relevant criteria must be taken into account and the choice among alternatives necessitates the use of multi-criteria decision making methods, for this purpose we introduced two other criteria and the multi-criteria analysis shows that alternative ***B*** is the best among the proposed alternatives.

CONCLUSION AND FURTHER DEVELOPMENT

The hydraulic analysis showed that the existing piped storm water drainage systems, designed and installed 30-40 years ago, were in many areas capable of carrying the flow from a rain event of only 5-year return period. Local authorities required design of upgrade options in order to improve the operational efficiency of their storm drainage networks. This poses problems of analysis and choice between many alternatives. The multi-criteria decision making approach represents one theoretical solution to choose between the available alternatives. This approach necessitates the definition and assessment of criteria to evaluate the effectiveness of alternatives. One of the criteria needed to exercise this choice is the evaluation of the sensitivity of urban areas to network failure (implications of failure related to flooding). A method has been proposed here which allows the evaluation of this criterion by use of an expert system approach based on the fuzzy inference concepts. The method allows each alternative to be quantified in terms of its impact on urban areas. This allows the designer to choose the alternative which has the least effect of network failure on urban areas. The inclusion of other relevant criteria is presented using a multi-criteria approach.

The concepts of outranking multi-criteria decision making methods were chosen to solve the multi-criteria problem. The outranking structure is based on the principle that alternatives are compared two by two with the aid of a valued preference degree “c” ranging values between 0 and 1.

The method proposed for the evaluation of the sensitivity of urban areas may also be used for other applications such as the improvement of the overall functionality of the existing sewer system taking into account all important interactions and impacts among the existing infrastructure and urban areas. This method allows also a new opening in studying the functioning of the storm drainage systems by taking into account the quality of urban areas surrounding the pipes, it allows also the integration of a qualitative and quantitative knowledge in urban planning process.

ACKNOWLEDGEMENT

The authors wish to thank the local council of 'BETHUNE' and the regional council of 'NORD PAS-DE-CALAIS' (FRANCE) for their help and support in making this study possible.

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