Multi-criteria model for annual rehabilitation planning of water supply networks: sensitivity analysis and impacts of the quantity of data.

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Abstract

Annual rehabilitation programme of water supply networks requires taking several points of view into consideration. Within the European project CARE-W *(Computer Aided Rehabilitation of Water networks)* a multicriteria tool was defined: Care-W_ARP, dedicated to the selection of the most efficient project for annual rehabilitation programmes. This selection is supported by the use of an outranking method: *ELECTRE Tri.* This model is briefly presented. A sensitivity analysis is proposed in order to assess the impact of data availability on final results. Tests and simulations are carried out with data from Reggio Emilia (I). Four decision contexts have been defined by combining two sets of history (8 or 4 years) with two sets of variables (material, diameter, traffic). Finally, a discussion and an interpretation of programmes obtained regarding the four contexts are presented.

Keywords Water networks, CARE-W, Care-W_ARP, ELECTRE TRI, data, sensitivity analysis.

1. INTRODUCTION

Rehabilitation of water supply networks requires tools to support the managers. During the last years, several research projects have been established in the world as WARP *(water mains renewal planner)* in Canada (Rajani and Kleiner, 2001), WiLCO (*Whole life costing*) in the UK (Engelhard et al., 2002), CARE-W *(Computer Aided Rehabilitation of Water networks)* in Europe, etc. Within the European project CARE-W (Herz, 2002), three complementary approaches are developed to support the management of water networks: the definition of a set of performance indicators (Alegre et *al.,* 2000), the calculation and evaluation of long-term strategic planning (Herz and Lipkow, 2002), and the prioritisation of projects for annual rehabilitation programmes (Le Gauffre *et al.* 2002a, 2002b). This third issue is addressed in the CARE-W_ARP module (Le Gauffre *et al.,* 2003). This module uses information from various sources: predicted failure rates (calculated with CARE-W_PHM or CARE-W_Poisson) (Eisenbeis et al., 2002), performance indicators, and parameters or indices representing the consequences of pipe failures.

Within the CARE-W_ARP software, defining an annual rehabilitation programme consists of ranking and selecting pipes according to various criteria (§2.1). To prioritise pipes, the decision support uses a multiciteria model (§ 2.2): ELECTRE Tri (Yu, 1992), (Rogers *et al.* 2000), (Mousseau *et al.*, 2001).

The calculation of annual rehabilitation programme is depending on the availability of data: failure history, variables used to represent the assets and their surrounding environment. This paper presents first results of a study dedicated to the behaviour of the CARE-W tools and to the benefits of using these tools within several contexts. It discusses the sensitivity of the model and the impacts of the quantity of the data.

2. CARE-W_ARP: MAIN PRINCIPLES

2.1. Points of view & Criteria

The decision problem is depending on different points of view: repair costs, water quality, water interruptions, water losses, etc. For each point of view, one or more criteria have been defined.

Criteria used in CARE-W_ARP are presented in the following table. Depending on the available data each pipe will be assessed with n out of these 14 criteria, providing a multicriterion profile.

Table 1: Points of view and criteria used in CARE-W_ARP (Le Gauffre *et al*. 2002a)

Point of view	**Criterion**	
Co-ordination	COS	Co-ordination score
Repair costs	ARC	Annual Repair Costs
Water losses	WLI	Water Losses Index
Water interruptions	PWI	Predicted Water Interruption
	PCWI	Predicted Critical Water Interruption
	PFWI	Predicted Frequency of Water Interruption
Damages and	DFH	Damage due to Flooding ...in Housing areas
disruptions	DFI	…in Industrial or Commercial areas
(induced by bursts)	DSM	Damage due to Soil Movement
	DT	Traffic Disruptions
	DDI	Damage and/or Disruption on other Infrastructure
Water quality	WQD	Water Quality Deficiencies index
Hydraulic reliability	HCI	Hydraulic Criticality Index
Rehabilitation cost	AUCR	Annual Unit Cost of Rehabilitation

2.1.1. Example of calculation of criteria:
To assess the criterion "Damages due to Flooding in Housing areas" (DFH) 3 types of information are considered:

$$DFH(i) = PBR(i)\, P(i)\, D(i)^2\, SFH(i) \qquad \text{(eq. 1)}$$

where *i* is the pipe id., *PBR(i)* is the predicted burst rate calculated with failure prediction tools according to available data (failure history and variables used to define pipe categories, such as material, diameter, soil type, traffic, etc.), *P(i),* pressure and *D(i),* diameter, are aggravating factors, and *SFH(i)* is an index expressing the vulnerability of the urban environment (sensitivity to flooding in housing areas).

2.2. Multicriteria procedure: ELECTRE Tri
The ELECTRE Tri method (Yu, 1992), (Rogers *et al.* 2000), (Mousseau *et al.*, 2001) allows to prioritise pipes by comparing each multicriterion profile with k reference profiles. In CARE-W_ARP, 2 reference profiles (b1&b2) are used, allowing to delimit three categories ordered from category C3 (high priority) to category C1 (low priority) (figure1).

For the assignment of a pipe *a* to a category, the multicriterion profile of the pipe is compared to the two reference profiles. This comparison is done according to two complementary procedures: an "optimistic procedure" (OP) and a "pessimistic procedure" (PP). The combination between the two procedures gives six categories: *Cxy,* where C*x* is the result of the optimistic procedure and C*y* ($y \leq x$) is the result of the pessimistic procedure.
Category C33: pipes with the highest priority level, assigned to C3 with the both procedures.
Categories C32 and C31: pipes assigned to C3 with the "optimistic" procedure and to C2 or C1 with the "pessimistic" procedure. These pipes can be seen as good candidates for annual rehabilitation programme.
Categories C22, C21 and C11: categories of pipes with a medium or low priority level.

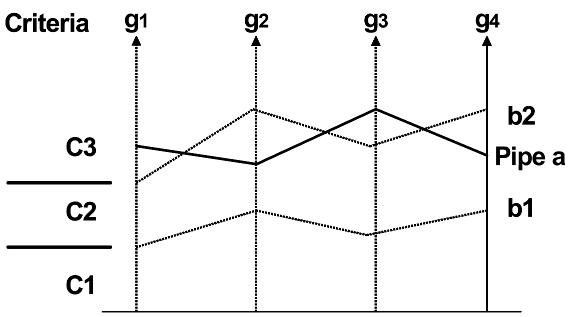

Figure 1. Two reference profiles (b1, b2) delimiting three hierarchical categories. The multicriterion profile of pipe *a* represents the performance deficiencies according to 4 criteria (g1, g2, g3, g4).

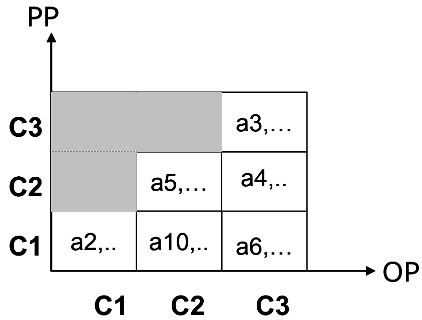

Figure 2. Assignment of pipes to one of 6 categories according to two complementary procedures: an "optimistic" (OP) and a "pessimistic" (PP).

The following figure is a typical result of a simulation obtained with ELECTRE Tri.

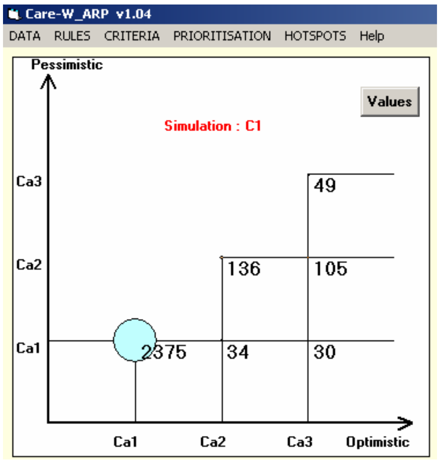

Figure 3. Ranking obtained with ELECTRE Tri. In this example, 49 pipes (out of 2729) are assigned to C33, 105 to C32, 30 to C31, etc.

2.3. How to calculate the annual rehabilitation programme in Care-W_ARP

The Calculation of the annual rehabilitation programme with ELECTRE Tri requires following several steps in Care-W_ARP:

- Import of data, like: Pipe Id, diameter, length, predicted failure rate, codes of category (e.g. C-SFH or C-SR) for the definition of parameters (e.g. SFH or SR "Sensitivity of the Road"),
- Definition of "local rules": these rules are used to define parameters and sensitivity indices by the user (figure 4),
- Calculation of criteria,
- Definition of weight for each criterion,
- Definition of reference values and ELECTRE Tri parameters.

Finally, result of calculation is saved in a text file. In this file, each pipe is assigned in one of six possible categories (figure 2).

2.4. Case study: Reggio Emilia (AGAC)

2.4.1. Network and data sources

The city of Reggio Emilia has a network of 2729 pipes, with a total length of 632 km. Data come from various sources: flow measurements and active leakage control (water losses), the call center (failures & complaints), customer consumption database, yellow pages, etc.

2.4.2. Knowledge bases and criteria available in Reggio Emilia

Rules applied in Reggio Emilia have been determined in June /July 2003 (Schiatti et *al.*, 2003) and stored in corresponding "knowledge bases". An example of a knowledge base is given below.

Code of category	Hours	Description
1	4	Diameter <= 110 & FIB
2	7	Diameter <=200 & FIB
3	10	Diameter >200 & FIB
4	3	Diameter <= 110 & other material
5	6	Diameter <=200 o& ther material
6	8	Diameter>200 & other material
7	0	

Figure 4. KB7: definition of EDI "Expected Duration of Interruption" (hours), used to calculate criteria PWI, PCWI and PFWI. Six cases have been defined by AGAC according to the diameter (3 classes) and the pipe material (Asbestos Cement vs other materials).

In this experiment, 8 criteria are available: COS, ARC, WLI, PWI, PCWI, PFWI, DT, WQD.

2.4.3. Calculation of PFR (Predicted Failure Rate)

CARE-W_Poisson is used for the calculation of the Predicted Failure Rate (PFR). Splitting the asset stock in pipe categories and using failure records, the individual failure rate is given by:

$$PFR(i) = Max\ (FR(i), FR(j)) \quad \text{(eq. 2)}$$

where *FR(i)* denotes the individual failure rate observed over a chosen period for pipe *i*, and *FR(j)* the failure rate observed for the corresponding pipe category *j*.

Pipes categories are defined in using available data and statistical tests may be performed in order to validate this definition (Le Gauffre *et al.,* 2000). For each variable, several classes are defined: material (2 classes), diameter (3 classes), and type of road (3 classes). The number of categories can be obtained by multiplying the number of classes chosen. For example with all variables available or without the road type, the asset stock has been divided successively into 18 or 6 pipe categories (figure 5).

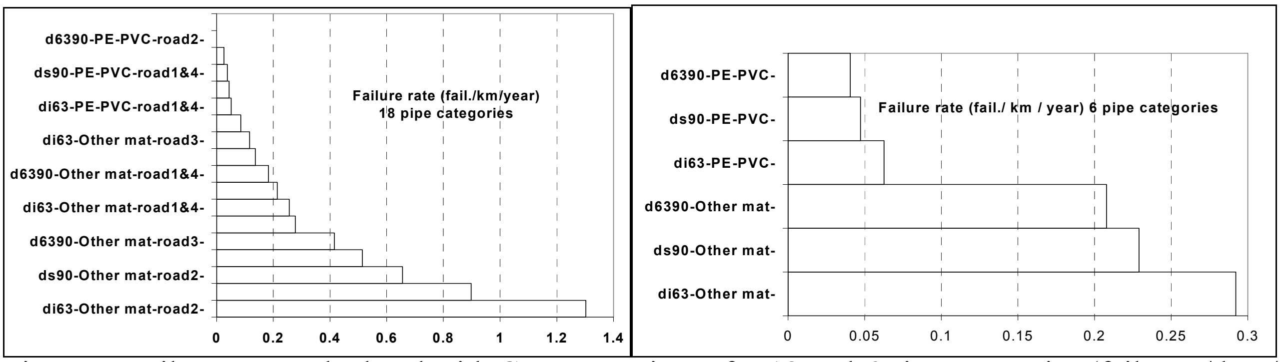

Figure 5. Failure rates calculated with Care-W_Poisson for 18 and 6 pipe categories (failures / km / year)

Removing the “road type” data decreases the number of categories and leads to a lower ability to deferentiate failure risks.

3. IMPACTS OF INPUT DATA ON OUTCOMES: SENSITIVITY ANALYSES

3.1. Sensitivity analyses

The impact on project outcomes of changing one or more key input values can be evaluated by sensitivity analyses. It allows studying the instability of the model. In other terms, sensitivity analyses can be used to investigate the impact various input parameters have on the final output "predictions" (Marshall H. E., 1999). Here, sensitivity analyses show how the annual rehabilitation planning is affected by changing the data (failure history, number of variables available for defining pipe categories) or by modifying the values of the parameters used in the ELECTRE TRI procedure: q(k), p(k) and v(k), indifference- preference- veto-threshold associated to criterion k. If a model is sensitive to a certain parameter, small changes will have large effects on the annual rehabilitation programmes. In this study, the sensitivity analysis will be focussing on the effect of data. A methodology has been applied to realize that.

3.1.1. Characteristics of input data

Numerous inputs can be influencing the annual rehabilitation programme. Firstly, failure records and pipe description data (diameter, material, etc.) which are used to calculate failure rates. Moreover, rules used in Care-W_ARP to express the pipe environment and to calculate criteria, for example (SR: sensitivity of the road indexed between 0 and 1), parameters (q, p & v) and criteria weights.

3.1.2. Methodology

3.1.2.1. Construction of contexts and definition of a reference context

Two set of historical data have been defined (8 years "1994-2001"; 4 years "1998-2001"). Thus, 2 set of variables (set 1: material, diameter, traffic; set 2: material, diameter). The combination of the sets gives four contexts. To measure the impact of change of history and variables, C1 has been considered as reference.

Table 2: The four contexts used to experiment Care-W_ARP

Variables / History	Material, Diameter, Traffic	Material, Diameter
8 years : 1994-2001	C1 (reference)	C3
4 years : 1998-2001	C2	C4

3.1.2.3. Calculation and simulations in Care-W_ARP

Eight criteria have been calculated and were available. Four simulations was been done regarding the four context. For all the simulations, a set of criterion weights and a set of reference values has been fixed (table 3).

Table 3: Criterion weights and reference values g (b2) and g (b1) used in ELECTRE Tri

Criterion	COS	ARC	WLI	PWI	PCWI	PFWI	DT	WQD
weights	0	0.2	0.2	0.12	0.18	0	0.3	0
g(b1)	-	100	0.4	65	0.05	-	0.020	-
g(b2)	-	170	0.8	110	0.100	-	0.040	-

3.2. First results

The results presented below are obtained regarding the four contexts defined.

C1: 49 pipes (out of 2729) are assigned to C33, 105 pipes to C32, 30 pipes to C31, etc.

C2: 57 pipes (out of 2729) are assigned to C33, 118 pipes to C32, 31 pipes to C31, etc.

C3: 42 pipes (out of 2729) are assigned to C33, 91 pipes in C32, 28 pipes in C31, etc.

C4: 41 pipes (out of 2729) are assigned to C33, 98 pipes in C32, 30 pipes in C31, etc.

The four results show the impact of each context. This impact appears clearly when we compare the number of pipes assigned to categories C33 and C32.

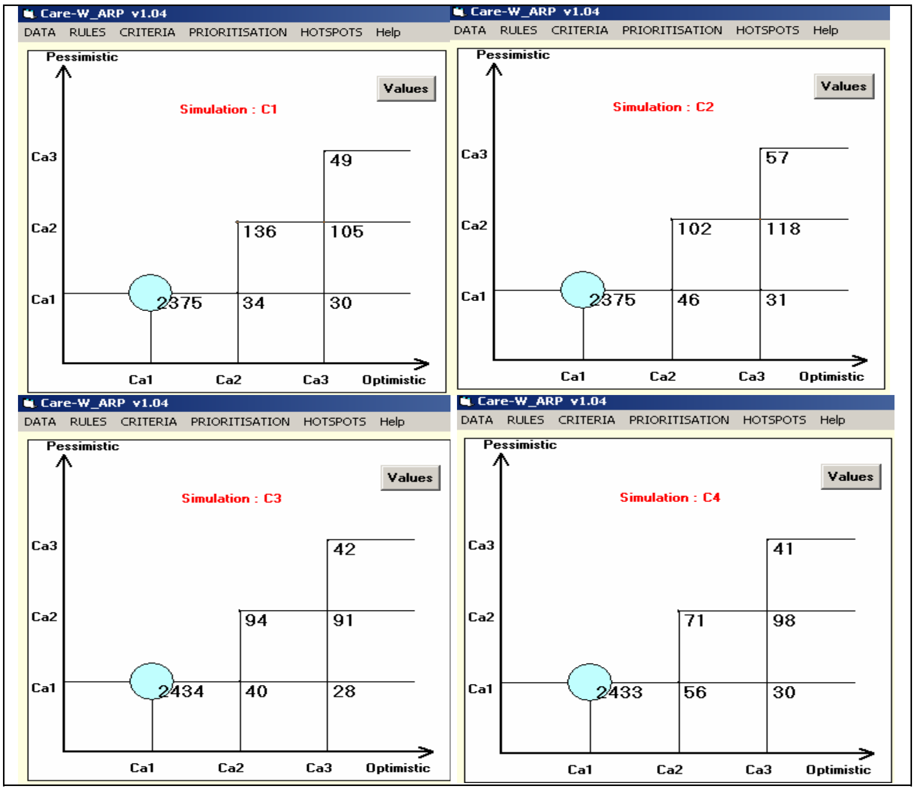

Figure 6. Outranking obtained regarding successively context C1, C2, C3 & C4.

In Care-W_ARP, quantifying the impact of each context by comparison with context C1 can be done in using the option PRIORITISATION / SENSITIVITY ANALYSIS. This option shows the number of pipes assigned to Cxy with one simulation and to Ckl with another simulation. The table displayed by figure 7 presents a comparison between simulation C2 (context C2) and simulation C1 (context C1): 37 pipes are assigned to C33 with both simulations, 4 pipes assigned to C33 with C1 are assigned to C32 with C1, etc.

Synthesis table

-C2- ; ; ; AGAC-C1 ; REGGIOR2

Reference -C1- AGAC-C1 REGGIOR2

	Total	C33	C32	C31	C22	C21	C11
C33	49	37	4	1	0	2	5
C32	105	9	60	4	5	4	23
C31	30	0	5	15	0	0	10
C22	136	11	42	0	34	0	49
C21	34	0	3	6	3	16	6
C11	2375	0	4	5	60	24	2282

Figure 7. Simulation C2 versus simulation C1

3.3. How to compare results or outcomes – first conclusions

The comparison of results makes it possible to understand the impact of each context in the annual rehabilitation programme. A first way of making this comparison is to quantify and analyse the changes and the stability concerning the number of pipes assigned to category C33, C32, etc.

Table 4 shows the number of pipes assigned to category C33 with two simulations (C1: reference and C2 or C3 or C4). Successively, with the new contexts (C2, C3, C4), by comparison with C1, (12, 7, 20) pipes pass to other categories with a lower priority level.

Table 4: Pipes assigned to C33 with C1 and C2 or C3 or C4

Context	C1	C2	C3	C4
Number of pipes in C33 regarding C1	49	37	42	29

Within context C2, the changes can be explained by the loss of information: pipes with failures recorded in 1994-1997 and no failures during 1998-2001. Table 5 shows the passing of the pipe to C31 with the context C2 related to the decreasing of PFR.

Table 5: Predicted failure rate of pipe 2410 in two contexts: C1 and C2

I1	pipe_id	Failures 1994-2001	Priority level in C1	Priority level in C2	PFR (C1)	PFR (C2)
2410	Tassoni A. *_2	10	C33	C31	0.178	0.036

Within context C3, 6 pipes with no previous breaks and 1 pipe with only one break during 8 years (1994-2001) are now assigned to other categories than C33. Within C1, these pipes belong to pipe categories with a high failure rate. Within C3, failure rates are predicted using 6 pipe categories instead of 18 within context C1. Removing the "road type" data decreases the number of categories and leads to a lower ability to deferentiate failure risks. Within C1, pipes assigned to C33 are good candidates for corrective rehabilitation or for preventive rehabilitation (7 pipes with no or 1 previous failure but with a high predicted failure rate combined with high potential consequences). Within C3 this preventive part of a rehab programme is disappearing.

Within context C4, results appear as a combination of the results obtained with context C2 and C3: reduction of the corrective part of a rehabilitation programme, and no preventive rehabilitation.

3.4. Further work

A second step in analysing the impact of a decision context consists of assessing the changes in terms of benefits: the benefits can be evaluated dividing the history records in two parts, one to calibrate the model and the other one to see the real benefits obtained (impacts avoided by rehabilitation) if the model has been applied in the first part with a decision for rehabilitation taken on the beginning of the second part of history. Table 6 summarises the process of the study.

Table 6: assessment of rehab benefits within 4 decision contexts

	Step 1 – period 1 (94-98 for C1 & C3) (96-98 for C2 & C4))	Step 2 – period 2 (1999-2001)
For each context (C1 to C4)	1a) Calibration of CARE-W_Poisson or CARE-W_PHM (2 cases) → PFR (i) 1b) Criteria calculation with CARE-W_ARP → predicted impacts 1c) ELECTRE TRI → Pipes assigned to C33, C32, etc	2a) Observed failures → FR(i) 2b) Criteria calculation in using FR(i) → real impacts during period 2 2c) Benefits (avoided impacts) if pipes previously assigned to C33 (+C32, etc.) have been rehabilitated before period 2

4. CONCLUSIONS

A methodology to study the sensitivity of the multicriteria procedure CARE-W_ARP has been applied by using the data coming from the network of Reggio Emilia in Italy. To be able to see the sensitivity of the model to the quantity of data, four contexts have been defined. Results obtained regarding the four contexts demonstrate the importance of the quantity of data. A good indicator of this impact on the annual rehabilitation appears in the number of changes in category C33 "pipes with the highest priority level". With a short historical data "C2: four years of failure records" pipes which have had breaks before 1998 pass to other categories with a lower priority level. Without knowing the traffic type (C3), the model looses the preventive ability. These important impacts of data relate to the dependence of three criteria (out of five selected in case of Reggio Emilia) on the PFR. This strong dependence makes it necessary to study the impact of the model used for the calculation of PFR on the annual rehabilitation programme. Furthermore, it will be necessary to repeat this study with another model for the calculation of PFR and compare its corresponding results with results obtained here.

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