A RESEARCH PROJECT SUPPORTED BY THE EUROPEAN COMMISSION UNDER THE FIFTH FRAMEWORK PROGRAMME AND CONTRIBUTING TO THE IMPLEMENTATION OF THE KEY ACTION "SUSTAINABLE MANAGEMENT AND QUALITY OF WATER" WITHIN THE ENERGY, ENVIRONMENT AND SUSTAINABLE DEVELOPMENT

EVK1-CT-2000-00053

REPORT

No. 3.2 - June 2002

CARE-W: WP 3 – Decision support for annual rehabilitation programmes.
D7 – Survey of multi-criteria techniques and selection of relevant procedures

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CARE

COMPUTER AIDED REHABILITATION OF WATER NETWORKS

RESEARCH AND TECHNOLOGICAL DEVELOPMENT PROJECT OF EUROPEAN COMMUNITY

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CARE – W

Computer Aided REhabilitation of Water networks. Decision Support Tools for Sustainable Water Network Management

WP 3 - Decision support for annual rehabilitation programmes

Tasks 3.3 – Survey of multi-criteria techniques and selection of relevant procedures

D7 – deliverable [1]

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Lyon (F), June 2002

[1] *Reference*:
LE GAUFFRE P., R. BAUR, K. LAFFRÉCHINE, M. MIRAMOND (2002) Survey of multi-criteria techniques and selection of relevant procedures. D7 report. CARE-W (Computer Aided Rehabilitation of Water networks), EU project under the 5th Framework Program, contract n°EVK1-CT-2000-00053, 31p. + Appendices, June 2002.

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1 - INTRODUCTION

The CARE-W project aims to develop methods and software that will enable engineers of water undertakings to establish and maintain an effective management of their water supply networks, rehabilitating the right pipelines at the right time. The results shall be disseminated as a manual on Best Management Practice (BMP) for water network rehabilitation.

This project is organised in the following Working Packages (WP):

- WP1: Construction of a control panel of performance indicators for rehabilitation;
- WP2: Description and validation of technical tools;
- WP3: Elaboration of a decision support system for annual rehabilitation programmes;
- WP4: Elaboration of long-term strategic planning and investment;
- WP5: Elaboration of CARE-W prototype;
- WP6: Testing and validation of CARE-W prototype;
- WP7: Dissemination;
- WP8: Project management.

INSA Lyon is responsible for WP3, which is divided into 4 Tasks:

- Task 3.1: Criteria for selecting rehabilitation projects – technical concerns and technical costs
- Task 3.2: Criteria for selecting rehabilitation projects – external points of view
- Task 3.3: Survey of available multi-criteria techniques and selection of relevant methods
- Task 3.4: Multi-criteria procedure for annual rehabilitation programmes

The previous report D6 referred to tasks 3.1 and 3.2. **This report refers to task 3.3.**

Table 1: Planning

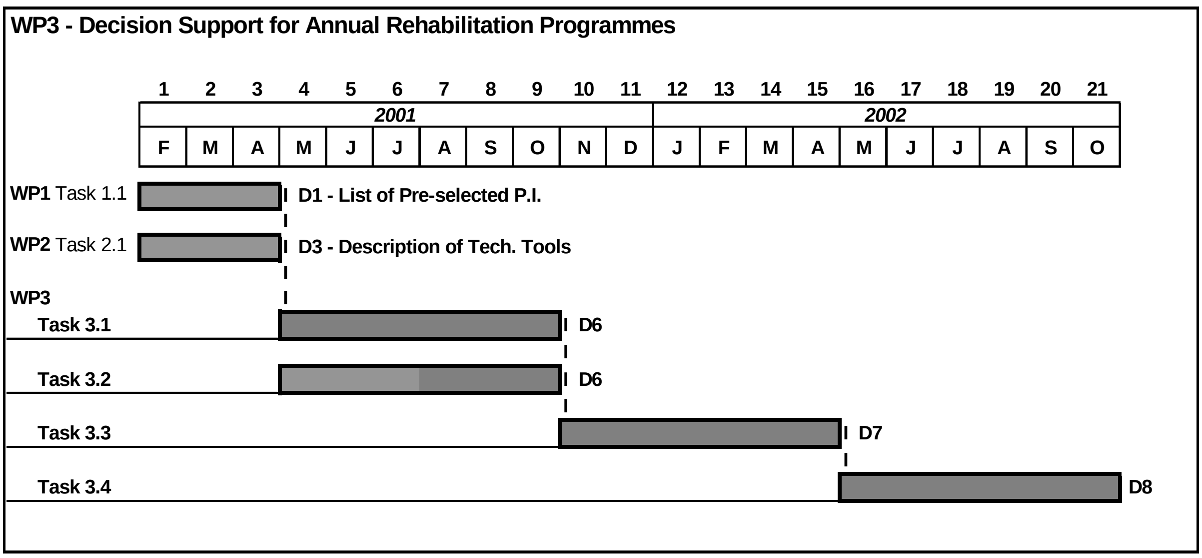

Table 2: Deliverables

Deliverables	Delivery date	Nature	Dissemination level
D6 – Criteria for evaluating potential actions Criteria relative to technical concerns and technical costs *(Task 3.1.)* Criteria relative to the effects on social impacts *(Task 3.2.)*	+10	Th (theory) Re (report)	PU (public)
D7 – Survey of multi-criteria techniques and selection of relevant procedures *(Task 3.3.)*	+16	Th (theory) Re (report)	PU (public)
D8 – Multi-criteria procedure for annual rehabilitation programmes *(Task 3.4.)*	+22	De (demonstrator)	RE (Restricted)

2 - PREVIOUS WORK (SUMMARY OF TASK 3.1 AND 3.2)

The decision problem can be regarded from different points of view corresponding to particular concerns (technical, economic, social). The comparison of rehabilitation projects, which are the potential candidates of the decision problem, according to a particular point of view is enabled by criteria, or criterion functions (Rogers et al 2000).

Actions (candidates = pipes)	Criteria					
	g_1	g_2	..	g_j	..	g_M
a_1	a_{11}	a_{12}		a_{1j}		a_{1M}
a_2	a_{21}	a_{22}		a_{2j}		a_{2M}
..						
a_i	a_{i1}	a_{i2}		a_{ij}		a_{iM}
..						
a_N	a_{N1}	a_{N2}		a_{Nj}		a_{NM}

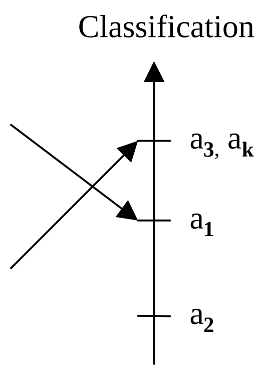

Figure 1: Performance matrix with N candidates and M criteria

The definition of an annual rehabilitation plan can be considered as a classification procedure of the different potential actions.

Each potential action (rehabilitation of pipe i) is characterised according to several criteria. In order to sort or rank these actions, a performance matrix has to be calculated (Figure 1), where $a_{ij} = g_j(a_i)$ is the score (or performance) of action i according to criterion j.

2.1 Survey of practice

In order to study the current practices and the expectations of water utilities, a questionnaire has been submitted to the end-users where the practices have been studied with two levels of detail:

- Main objectives of rehabilitation in the network
- Criteria used for prioritisation of projects

Utilities were asked to assign the relative importance to each of a proposed set of objectives (Table 1) and to a proposed set of more than 20 criteria: “of overriding importance”, “important”, “of minor importance” or “not important” for the priority setting of rehabilitation projects (Le Gauffre et al. 2002).

Table 3: Objectives of rehabilitation projects, according to survey among 12 European water utilities (Le Gauffre et al 2002)

Objectives	1	2	3	4	data or tools missing (to take into account this objective)
Improve hydraulic performance	1	**6**	3	1	2
Improve water quality	**5**	**5**	2	0	3
Reduce operation and maintenance costs	3	**7**	2	0	**6**
Reduce water losses	2	**7**	3	0	3
Reduce the number of mains failures and their consequences	**6**	**5**	1	0	**4**
Reduce the age of water at the customer tap	0	3	**5**	4	**5**
Maintain or improve the average condition of the network	3	**6**	1	1	**6**

1 - of overriding importance, 2- important, 3 - of minor importance, 4 - not important

The identified objectives of network rehabilitation are rearranged into nine "points of view" which split up into two types. "Internal" points of view refer to the view of the operator and are focussing on technical concerns and their corresponding costs. "External" points of view refer to the view of the customer and affected third parties, such as road users, who in most cases will be represented by the responsible local authorities. These "external" points of view are corresponding to social concerns or social costs. Each point of view is rendered more precisely by a number of criteria contributing to the criteria set and the corresponding sub-criteria with their particular measurement rules. The calculated criteria can be represented by detailed cost functions (e.g. in [euro/(100m•year)]), quantification of current deficiencies (e.g. frequency of water interruptions), assessment of risks or assessment of the pipe's potential contribution to a zonal problem (e.g. high, medium, low estimated contribution to water quality problems).

An additional aspect, potential co-ordination with work on parallel infrastructure networks, such as waste water and gas, or road rehabilitation was considered:

- co-ordination with other utilities and roadway rehabilitation programmes
- co-ordination with service connection replacement programmes

Both aspects are closely interrelated with the points of view "rehabilitation costs" and "disruptions associated with a particular rehabilitation method". Usually, the cost savings from co-ordination will vary from project to project and an individual cost saving factor (CSF) for the particular project is proposed to be taken into account. In general, co-ordination will reduce the costs and disruptions associated with open trench techniques.

2.2 Definition of decision criteria

In detail, the definitions and measurement rules of criteria are explained in the D6 report (Le Gauffre et al, 2002).

Table 4 gives an overview of the criteria, and the information used for their calculation. PI, UI and EI mean <u>Performance Indicators</u>, <u>Utility Information</u> and <u>External Information</u>, respectively (Baptista & Alegre, 2002).

Table 4: Points of view, criteria, and required information

Point of view	Criteria[2]	Information	corresponding PI	UI	EI
Rehabilitation costs	AUCR(i;h)	Annual Unit Cost of Rehab.			
		• Material		X	
		• Pipe depth		X	
		• Seasonal variation			X
		• Density of fittings		X	
		• Soil type			X
		• Diameter		X	
	CSF(i;h)	Co-ordination cost saving factor (project specific)			
Co-ordination	COS(i)	Co-ordination score			
		• Schedule of service connection rehab		X	
		• Schedule of road work			X
		• Schedule of other utility rehab			X
Repair costs	ARC(i)	Annual Repair Costs			
		• Cost table, mean costs	Knowledge Base	(X)	
		• Street category			X
		• Failure rate	Op5_link Op26_link		
Water losses and relative costs	WLI(i)	Water losses index			
		• Failure rate observed	Op5_zone Op26_zone		
		• Leakage cost		X	
		• Failure rate	Op5_link Op26_link Op27_link		
Disturbances induced by rehab measure	DRM(i;h) DS(h)	Disturbance index			
		• technique scoring table	KB		
		• Service connection density		X	
		• Street category			X
		• Sensitive customer		X	
		• Coordination with road work			X
		• Coordination with other utility			X
Water interruptions	PWI(i) PCWI(i)	Predicted Water Interruption Pr. Critical Water Interruption			
		• Predicted Burst rate	Op26aa_link		
		• Duration of interruption		X	
		• No of people supplied by the link		X	
		• (No of) Sensitive Customers supplied by the link		X	
	PFWI(i)	Predicted Frequency of WI			

[2] The indices **i** and **h** stand for the corresponding pipe and the rehab technique respectively.

Point of view	Criteria[2]	Information	corresponding PI	UI	EI
Damages and disruptions	DFH(i) DFI(i)	Damage due to Flooding in Housing areas, or Industrial or Commercial areas resp.			
	DSM(i)	Damage due to soil movement			
	DT(i)	Traffic Disruptions			
	DDI(i)	Damage and/or Disruption on other Infrastructure			
		• Diameter		X	
		• Pressure		X	
		• Slope			X
		• Risk of landslide			X
		• Street category			X
		• Basement			X
		• Ground Floor above soil			X
		• Type of housing			X
		• Type of activities			X
		• Sensitive infrastructure close to the link			X
		• Failure rate	Op5_link, Op26_link		
		• Burst rate	Op26aa_link Op27a		
Water quality Deficiencies	WQD(i)	Water quality deficiencies			
		• Quality of water	QS15_zone, …		
		• Customer complaints	QS22_zone, …		
		• Material		X	
		• Installation date		X	
Hydraulic reliability	HCI(i)	Hydraulic criticality index			
		• Mean duration of repair		X	
		• Failure rate	Op5_link Op26_link		

2.3 Conclusions

At the conclusion of tasks 3.1 and 3.2 we had identified nine points of view and proposed 15 criteria and their measurement rules. However, available information and preferences may vary from utility to utility and will change over time. It was therefore agreed that the final decision matrix be flexible to allow the integration of additional criteria. This should be considered when configuring the decision support tool.

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Le Gauffre P., Laffréchine K., Baur R., Di Federico V., Eisenbeis P., König A., Kowalski M, Sægrov S.,Torterotot J.P., Tuhovcak L., Werey C. (2002) CARE-W: WP3 – Decision support for annual rehabilitation programmes. D6 - Criteria for the prioritisation of rehabilitation projects. CARE-W (Computer Aided Rehabilitation of Water networks), EU project under the 5th Framework Program, contract n°EVK1-CT-2000-00053. Lyon (F): INSA-URGC, June 2002, 72 p.

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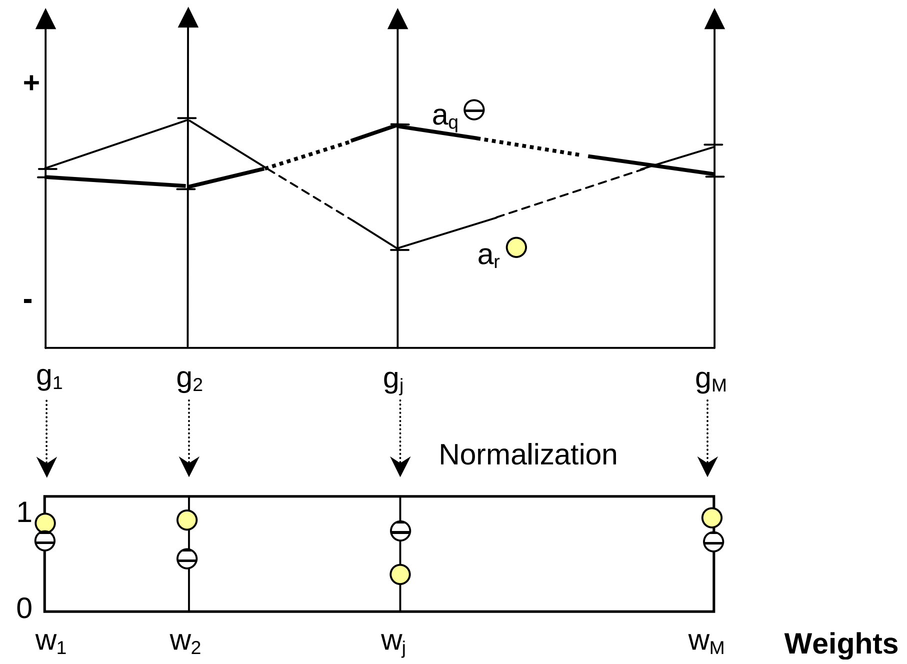
3 - MULTI-CRITERIA TECHNIQUES – DESCRIPTION OF METHODS

3.1 Aggregation: Scoring models

The most popular multi-criteria technique is represented by the method of average weighting. The method requires a - a priori existing - global preference structure that can be expressed by a utility function. The preference structure should express the amount or ratio of compensation of criteria values that is accepted by the decision maker. The aim of the methods is, to find analytically a solution, which is closest to the optimum solution, and corresponds to the preferences of the decision-maker.

Due to their easy handling, once they are set up, compensatory aggregation methods are widely used in decision support practice.

Firstly, the calculated criteria values have to be *normalized* by a transformation function $U_j(g_j)$. This can be done by calculating cost equivalents, like in a cost benefit analysis, or by transformation to a point-scale, in the most elementary case this is a linear transformation to a scale between 0 and 1.



- Aggregation with utility function, e.g. $U(a_i) = \sum_{j=1}^{M} w_j \cdot U_j(a_i)$

- Ranking of candidates by score

action	score	rank
…	…	1.
34587 ○	0,73	…
33978 ⊖	0,67	…
...	...	...

Figure 2: Aggregation method

After normalization, the *weights* w_i have to be assigned to each criterion. The weights aim to quantify the decision-maker's preference structure. As mentioned above, the weights should represent the measure of compensation, to which the decision-maker would accept less desired or undesired values at one criterion if the values are better at another criterion. The weights are the trade-offs between these criteria values, so the normalized criteria values must be multiplied by the weights. Finally, the normalized and weighted criteria values are aggregated by the *utility function*, which, again in the simplest case, is the addition of the normalized and weighted criteria values. This gives a *score* for each candidate, by which all of them can be *ranked*.

The result of aggregation procedures depend on two components, which are not obvious, or at least not transparent in their inter-dependencies to the decision-maker, when applying the expert-designed decision making tool: (1) the influence of the definition of the transformation function and (2) the influence of the definition of the utility-function, sometimes called a "super-goal-function" (Strassert 1984), and their inter-action with the subjectively by the decision-maker distributed weights, on the final result.

In general, the assignment of weights (giving a relative importance to criteria) is the only interaction between the decision-maker and the aggregation procedure. In some cases, enormous effort is required to estimate criteria weights using analytical tools (Hastak et al. 2000, Saaty 1990, Zimmermann and Gutsche 1990). In practice, criteria weights are mostly chosen by the "experienced" decision-maker (Dyksen et al. 2000; DVGW 1997).

In more sophisticated applications of aggregation methods for decision making, the focus is on the construction of appropriate transformation functions. Instead of the linear transformation of criteria to a scale between 0 and 1, any kind of transformation-function could be applied, such as step-functions, decreasing or increasing exponential functions, functions with or without threshold, all to give more attention to the nature of the criteria values and their measured range.

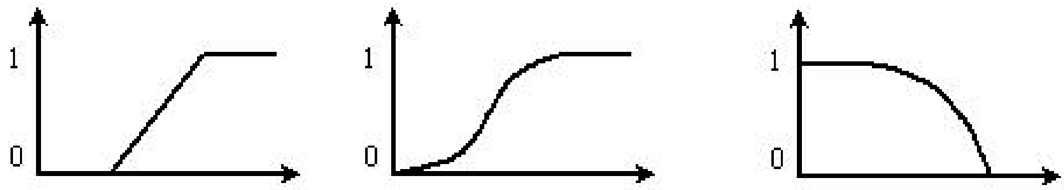


Figure 3: Examples for normalization functions $U_j(g_j)$

These procedures might improve the final result. However, the main drawback of aggregation models is their lack of transparency in the decision process (Strassert 1984, Vincke 1992)

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3.2 Outranking method: ELECTRE TRI

The *outranking* methods have been developed in the last 30 years by a “European school” in decision theory, mainly in francophone universities (Roy 1996).

3.2.1 Principles and definitions

Definition: action *a* **outranks** action *b* if there are enough arguments to decide that *a* is **at least as good as** *b*, while there is no essential reason to refute that statement (Vincke 1992).

Sorting procedure

The ELECTRE TRI method is designed for the assignment of potential actions a_i according to their specific characteristics to one of NC pre-defined *categories*, which are defined in a hierarchical order. There is no distinction among actions that are assigned to the same category.

By the outranking approach of ELECTRE methods, actions are compared in pairs according to a number of criteria. Within ELECTRE TRI, for the assignment of an action *a* to a category Ca_k, *a* is compared successively to *reference profiles*. The NC categories are defined in a hierarchical order by (NC+1) reference profiles from category Ca_{NC}, for the best options, to category Ca_1, the category for options which are “not so good” (Figure 4)[3].

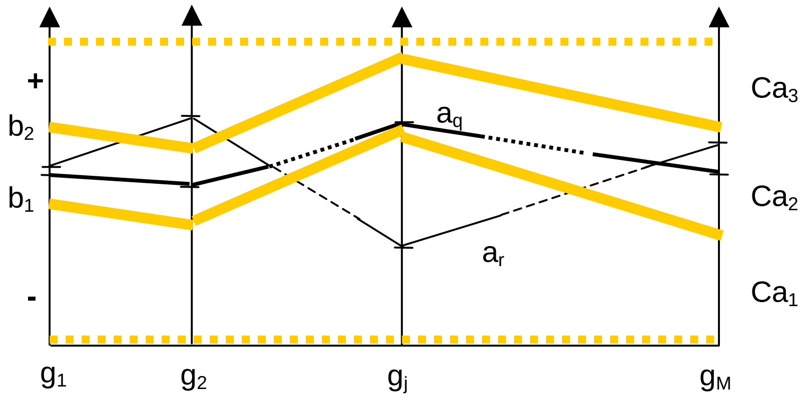

Figure 4: Hierarchy of categories with reference profiles

[3] Two notional reference profiles are the upper and lower boundary of the solution corridor: The upper reference profile is, by definition, better than the best action; the least desired action is, by definition, better than the lowest reference profile.

The general scheme of the ELECTRE TRI procedure is outlined in Figure 5.

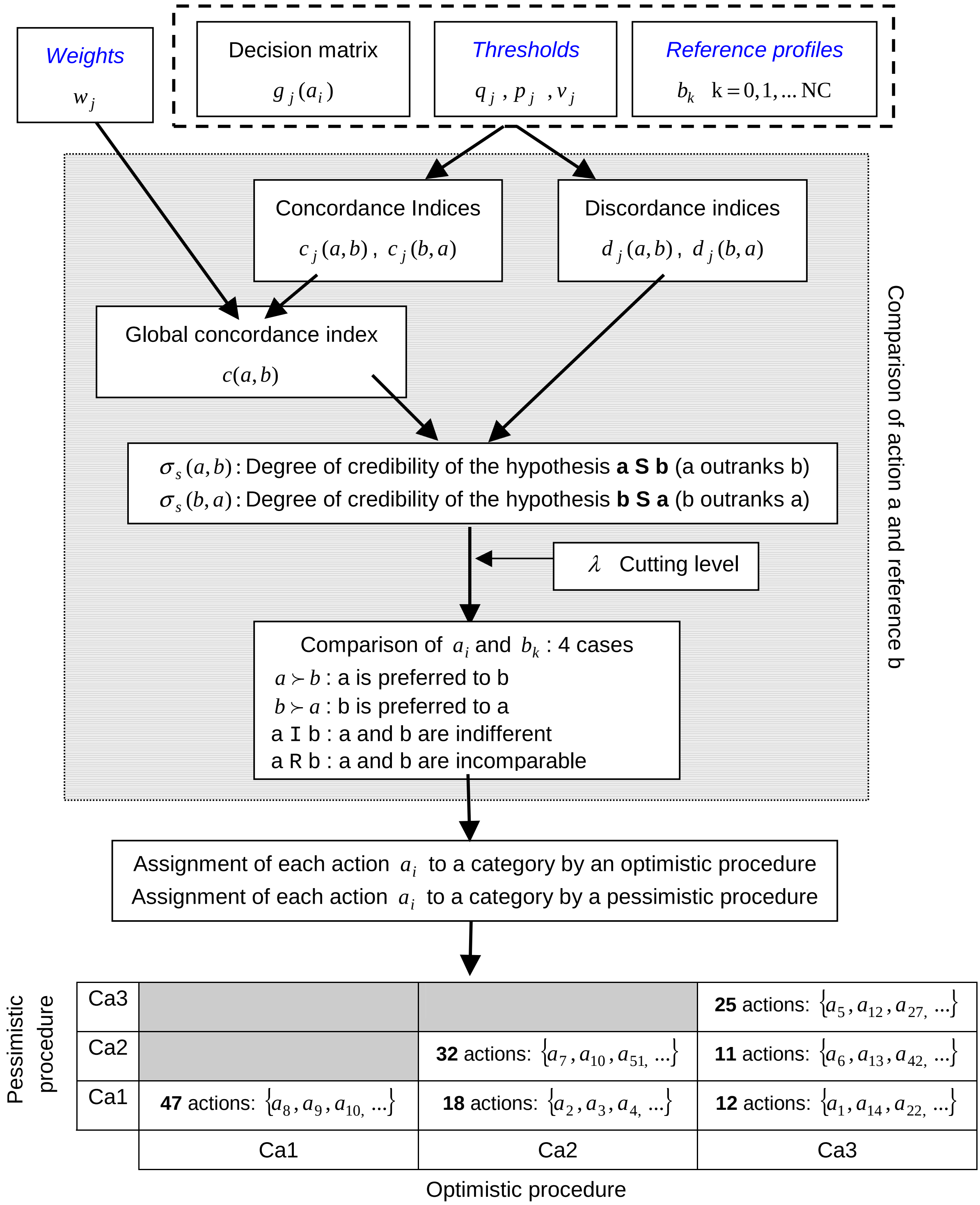

Figure 5: Scheme of the general ELECTRE TRI procedure

Notations and definitions:

Notation	Concept	Definition
$g_j(a_i)$	Decision matrix	Performance of actions a_i in considering criteria g_j. Here, all criteria functions g_j are defined such that a higher value on it indicates the preference to a lower one.
q_j	Indifference threshold for criterion g_j	q_j is used in the calculation of the <u>*concordance indices*</u> $c_j(a,b)$ and $c_j(b,a)$ [see 3.2.2] Remark: q_j could be a constant or a function of b, $q_j(b)$
p_j	Preference threshold for criterion g_j ($p_j > q_j$)	p_j is used in the calculation of the <u>*concordance indices*</u> $c_j(a,b)$ and $c_j(b,a)$ [see 3.2.2], and in the calculation of the <u>*discordance indices*</u> $d_j(a,b)$ and $d_j(b,a)$ [see 3.2.3]. Remark: p_j could be a constant or a function of b, $p_j(b)$
v_j	Veto threshold for criterion g_j ($v_j > p_j$)	This threshold allows criterion g_j to express a veto on the statement: <u>*a outranks b*</u> (aSb), that could have been established in considering the other criteria. If $g_j(a) < g_j(b) - v_j$, then a will not outrank b (veto from g_j) v_j is used in the calculation of the discordance indices $d_j(a,b)$ and $d_j(b,a)$ [see 3.2.3]. Remark: v_j could be a constant or a function of b, $v_j(b)$
b_k	Reference profile	The reference profile b_k is the upper boundary for category Ca_k and the lower boundary for category Ca_{k+1}, respectively.
$c_j(a,b)$ $c_j(b,a)$	Partial concordance index for criterion g_j	$c_j(a,b)$ gets a value between 0 and 1, and measures the strength of the statement "action *a* outranks action b", in considering criterion j only.
w_j	Weight of criterion g_j	
$c(a,b)$ $c(b,a)$	Global concordance index	$c(a,b)$ gets a value between 0 and 1, and measures the strength of the statement "action *a* outranks action b", in considering all the criteria. $c(a,b)$ is calculated in using partial concordance indices $c_j(a,b)$ and weights w_j [see 3.2.2].
$d_j(a,b)$ $d_j(b,a)$	Discordance index for criterion g_j	$d_j(a,b)$ gets a value between 0 and 1, and measures the extent to which a particular criterion j opposes the statement that "action *a* outranks action b".
a S b	"a outranks b"	"a outranks b" means that there are enough arguments to decide that a is <u>at least as good as</u> b, while there is no essential reason to refute that statement.
$\sigma_s(a,b)$	Degree of credibility	$\sigma_s(a,b)$ quantifies the relationship (aSb) and is calculated in using $c(a,b)$ and $d_j(a,b)$ [see 3.2.4].
λ	Cutting level	λ is used to transform a quantified relationship into a binary statement: if $\sigma_s(a,b) \geq \lambda$, then aSb; else Non(aSb). The value of λ is usually set to 0.75.
$a \succ b$	a is preferred to b	If aSb and non(bSa), then: $a \succ b$
$b \succ a$	b is preferred to a	If bSa and non(aSb), then: $b \succ a$
a I b	a and b are indifferent	If aSb and bSa, then: a I b
a R b	a & b are incomparable	If non(aSb) and non(bSa), then: a R b

3.2.2 Concordance indices

The global concordance index c(a,b) is calculated by the weighted sum of the partial concordance indices $c_j(a,b)$:

$$c(a,b) = \frac{1}{\sum_{j=1}^{M} w_j} \cdot \left(\sum_{j=1}^{M} w_j \cdot c_j(a,b) \right)$$

with w_j: weight of criterion g_j

and $c_j(a,b)$: concordance index for criterion g_j.

The partial concordance $c_j(a,b)$ indices are calculated by:

$$c_j(a,b) = \begin{cases} 0, \ldots \text{if } g_j(a) \leq g_j(b) - p_j \\ 1, \ldots\text{if } g_j(a) \geq g_j(b_i) - q_j \\ \text{else } \ldots \dfrac{g_j(a) - \left(g_j(b) - p_j\right)}{p_j - q_j} \end{cases}$$

Figure 6 shows the graphical interpretation of the concordance index.

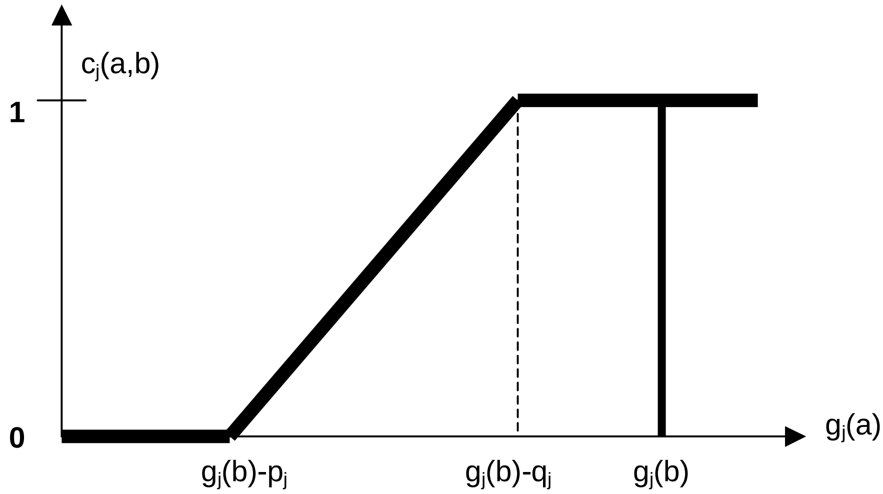

Figure 6: Illustration of the construction of the concordance index

Weights

In the outranking methods, weights w_j are not used for aggregating criteria values to a single score, but are used to calculate the global concordance index which represents the degree of consensus concerning the statement “a outranks b”.

Rogers et al. (2000) mention four ways of determining the weights in ELECTRE methods:

- “direct” weighting applied by Hokkanen and Salminen (1994), based on experts’ opinion on criteria’s absolute ranks and relative distances the weights are assigned to criteria.
- the method developed by Mousseau (1993) is characterised as rigorous, and a “real weighting-aid for criteria” (Maystre et al. 1994). It is based on the pair-wise comparison of the importance of the criteria by the decision maker. The method is rather complex.

- the "Pack of Cards" technique, proposed by Simos (1990) and revised by Roy and Figuera (1998), in general, is based on a similar expert's opinion like in the direct weighting applied by Hokkanen and Salminen
- the "Resistance to Change" grid: Rogers and Bruen (1996) themselves put forward this method from personal construct theory in human psychology. The authors are in favour of the method however, they admit that "the method has certain operational drawbacks".

All proposals rely on experts' opinion.

3.2.3 Discordance indices

The discordance index $d_j(a,b)$ measures the extent to which the comparison of a and b according to criterion g_j is discordant with the statement "a outranks b".

The discordance index is calculated by:

$$d_j(a,b) = \begin{cases} 0, \ldots \text{if } g_j(a) \geq g_j(b) - p_j \\ 1, \ldots \text{if } g_j(a) \leq g_j(b) - v_j \\ \text{else } \ldots \dfrac{g_j(b) - p_j - g_j(a)}{v_j - p_j} \end{cases}$$

Figure 7 illustrates the construction of the discordance index.

Case 1: performance of action a is very low compared to the performance of b, so criterion j expresses a veto to the statement "a outranks b" ($d_j(a,b) = 1$).

Case 2: performance of action a is quite low compared to the performance of b, so criterion j expresses a certain opposition to the statement "a outranks b" ($0 \leq d_j(a,b) \leq 1$).

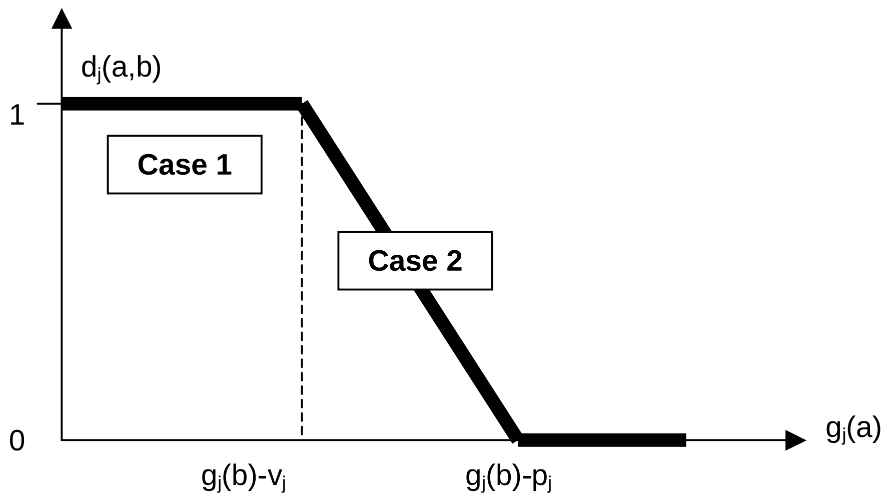

Figure 7: Construction of the discordance index.

3.2.4 Degree of credibility

From the global concordance index and the discordance indices, $\sigma_S(a,b)$, the degree of credibility of the statement "a outranks b", can be calculated.

If there is no criterion discordant to the statement that *action "a" is outranking b* (aSb) the degree of credibility σ_S(a,b) is equal to the global concordance index c(a,b). If a veto is expressed by any criterion, then the degree of credibility σ_S(a,b) is zero.

In any other case, the degree of credibility σ_S(a,b) is calculated by:

$$\sigma_S(a,b) = \prod_{j \in \overline{F}} \frac{1 - d_j(a,b)}{1 - c(a,b)}$$

$$\text{with} \quad \overline{F}(a,b) = \left\{ j \in \overline{F} \,\middle|\, d_j(a,b) > c(a,b) \right\}$$

3.2.5 Outranking relation

Action a outranks reference action b, if the degree of credibility σ_S(a,b) of the outranking relation meets or exceeds the user-defined "*cutting level*" λ:

$aSb \Leftrightarrow [\sigma_S(a,b) \geq \lambda]$

In the literature the value of λ is generally set to 0.75.

In comparing a to b and b to a, four final statements can be distinguished:

	$\sigma_S(a,b) \geq \lambda$ aSb	$\sigma_S(a,b) < \lambda$ non(aSb)
$\sigma_S(b,a) \geq \lambda$ bSa	a I b **a and b are indifferent**	$b \succ a$ **b is preferred to a**
$\sigma_S(b,a) < \lambda$ non(bSa)	$a \succ b$ **a is preferred to b**	a R b **a and b are incomparable**

3.2.6 Assignment of actions to categories

The comparison of actions to the reference profiles is split into two procedures, which must be run through: an "optimistic" one (bottom-up) and a "pessimistic" one (top-down).

By the "pessimistic" procedure, action a is assigned to category Ca_{k+1} if b_k, starting from b_{NC} to b_0, is the first reference profile which is outranked by a (aSb_k).

By the "optimistic" procedure, action a is assigned to category $Ca_{k'}$ if $b_{k'}$, starting from b_0 to b_{NC}, is the first reference profile that is preferred to a ($b_{k'} \succ a$).

The assignment of actions to categories by the two procedures, the pessimistic and the optimistic one, is demonstrated in three examples (Figure 8).

Pessimistic & optimistic procedures: example 1

Reference profile	Categories	Pessimistic procedure		a ? b		
b_6			Not (a S b_6)	<	b_6 S a	
	Ca_6					
b_5			Not (a S b_5)	<	b_5 S a	**a < b_5**
	Ca_5					$a \in Ca_5$
b_4			Not (a S b_4)	R	Not (b_4 S a)	
	Ca_4					
b_3			Not (a S b_3)	R	Not (b_3 S a)	
	Ca_3	$a \in Ca_3$				
b_2		**a S b_2**	a S b_2	>	Not (b_2 S a)	
	Ca_2					
b_1			a S b_1	>	Not (b_1 S a)	
	Ca_1					
b_0			a S b_0	>	Not (b_0 S a)	
						Optimistic procedure

Pessimistic & optimistic procedures: example 2

Reference profile	Categories	Pessimistic procedure		a ? b		
b_6			Not (a S b_6)	<	b_6 S a	
	Ca_6					
b_5			Not (a S b_5)	<	b_5 S a	
	Ca_5					
b_4			Not (a S b_4)	<	b_4 S a	**a < b_4**
	Ca_4	$a \in Ca_4$				$a \in Ca_4$
b_3		**a S b_3**	a S b_3	>	Not (b_3 S a)	
	Ca_3					
b_2			a S b_2	>	Not (b_2 S a)	
	Ca_2					
b_1			a S b_1	>	Not (b_1 S a)	
	Ca_1					
b_0			a S b_0	>	Not (b_0 S a)	
						Optimistic procedure

Pessimistic & optimistic procedures: example 3

Reference profile	Categories	Pessimistic procedure		a ? b		
b_6			Not (a S b_6)	<	b_6 S a	
	Ca_6					
b_5			Not (a S b_5)	<	b_5 S a	**a < b_5**
	Ca_5	$a \in Ca_5$				$a \in Ca_5$
b_4		**a S b_4**	a S b_4	I	b_4 S a	
	Ca_4					
b_3			a S b_3	>	Not (b_3 S a)	
	Ca_3					
b_2			a S b_2	>	Not (b_2 S a)	
	Ca_2					
b_1			a S b_1	>	Not (b_1 S a)	
	Ca_1					
b_0			a S b_0	>	Not (b_0 S a)	
						Optimistic procedure

Figure 8: Three examples of the assignment results

3.2.7 Example

a) Performance matrix and parameters:

criteria:	g_1	g_2	g_3	g_4	g_5	
weights:	25%	45%	10%	12%	8%	
actions						
a_1	-120	-284	5	3,5	18	
a_2	-150	-269	2	4,5	24	
a_3	-100	-414	4	5,5	17	
a_4	-60	-596	6	8,0	20	
a_5	-30	-1321	8	7,5	16	
a_6	-80	-734	5	4,0	21	
a_7	-45	-982	7	8,5	13	
b_2	-50	-500	7	7	20	(reference profile between Ca3 and Ca2)
b_1	-100	-1000	4	4	15	(reference profile between Ca2 and Ca1)
q	15	80	1	0,5	1	
p	40	350	3	3,5	5	
v	100	850	5	4,5	8	

b) Profiles of seven actions and two references

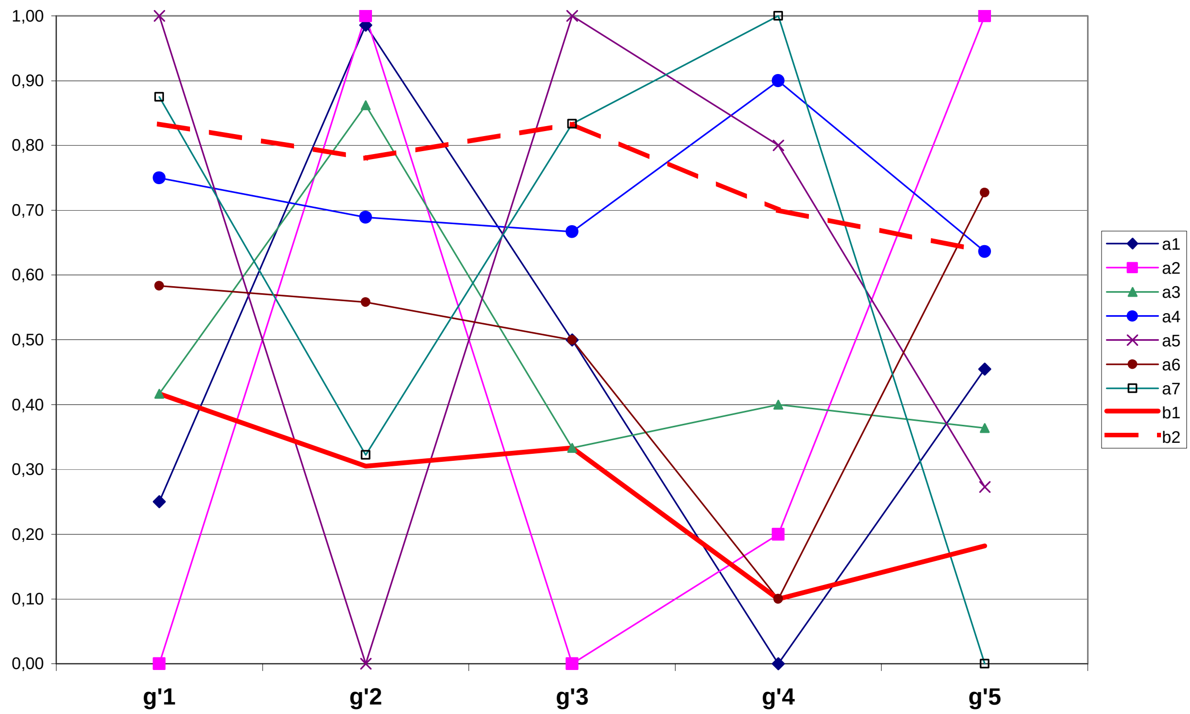

Figure 9: Profiles

c) Partial concordance indices and discordance indices

	Cj(a , b2)					Cj(b2 , a)				
	g1	g2	g3	g4	g5	g1	g2	g3	g4	g5
a1	0	1	0,50	0	0,75	1	0,50	1	1	1
a2	0	1	0	0,33	1	1	0,44	1	1	0,25
a3	0	1	0	0,67	0,50	1	0,98	1	1	1
a4	1	0,94	1	1	1	1	1	1	0,83	1
a5	1	0	1	1	0,25	0,80	1	1	1	1
a6	0,40	0,43	0,50	0,17	1	1	1	1	1	1
a7	1	0	1	1	0	1	1	1	0,67	1

	Cj(a , b1)					Cj(b1 , a)				
	g1	g2	g3	g4	g5	g1	g2	g3	g4	g5
a1	0,80	1	1	1	1	1	0	1	1	0,50
a2	0	1	0,50	1	1	1	0	1	1	0
a3	1	1	1	1	1	1	0	1	0,67	0,75
a4	1	1	1	1	1	0	0	0,50	0	0
a5	1	0,11	1	1	1	0	1	0	0	1
a6	1	1	1	1	1	0,80	0,31	1	1	0
a7	1	1	1	1	0,75	0	1	0	0	1

	dj(a , b2)					dj(b2 , a)				
	g1	g2	g3	g4	g5	g1	g2	g3	g4	g5
a1	0,5	0	0	0	0	0	0	0	0	0
a2	**1**	0	**1**	0	0	0	0	0	0	0
a3	0,17	0	0	0	0	0	0	0	0	0
a4	0	0	0	0	0	0	0	0	0	0
a5	0	0,94	0	0	0	0	0	0	0	0
a6	0	0	0	0	0	0	0	0	0	0
a7	0	0,26	0	0	0,67	0	0	0	0	0

	dj(a , b1)					dj(b1 , a)				
	g1	g2	g3	g4	g5	g1	g2	g3	g4	g5
a1	0	0	0	0	0	0	0,73	0	0	0
a2	0,17	0	0	0	0	0	0,76	0	0	**1**
a3	0	0	0	0	0	0	0,47	0	0	0
a4	0	0	0	0	0	0	0,11	0	0,50	0
a5	0	0	0	0	0	0,50	0	0,50	0	0
a6	0	0	0	0	0	0	0	0	0	0,33
a7	0	0	0	0	0	0,25	0	0	**1**	0

d) Global concordance index

	C (ai , b2)	C (b2 , ai)	C (ai , b1)	C (b1 , ai)
a1	0,56	0,77	0,95	0,51
a2	0,57	0,69	0,70	0,47
a3	0,57	0,99	1,00	0,49
a4	0,97	0,98	1,00	0,05
a5	0,49	0,95	0,60	0,53
a6	0,44	1,00	1,00	0,56
a7	0,47	0,96	0,98	0,53

e) Degree of credibility

	σ (a , b2)	σ (b2 , a)	σ (a , b1)	σ (b1 , a)
a1	0,56	0,77	0,95	0,28
a2	**0,00**	0,69	0,70	**0,00**
a3	0,57	0,99	1,00	0,49
a4	0,97	0,98	1,00	0,02
a5	0,06	0,95	0,60	0,53
a6	0,44	1,00	1,00	0,56
a7	0,30	0,96	0,98	0,00

Comments:
$\sigma(a_2, b_2) = 0$, since $d_1(a_2, b_2) = d_3(a_2, b_2) = 1$: Criteria 1 and 3 express a veto to "$a_2 \, S \, b_2$".
$\sigma(b_1, a_2) = 0$, since $d_5(b_1, a_2) = 1$: criterion 5 expresses a veto to "$b_1 \, S \, a_2$".
These two results can easily be understood in looking at the profiles in Figure 9.

f) Preference relationships

	a S b_2	**b_2 S a**	**a S b_1**	**b_1 S a**	**a ? b_2**	**a ? b_1**
a_1	No	Yes	Yes	No	**<**	**>**
a_2	No	No	No	No	**R**	**R**
a_3	No	Yes	Yes	No	**<**	**>**
a_4	Yes	Yes	Yes	No	**I**	**>**
a_5	No	Yes	No	No	**<**	**R**
a_6	No	Yes	Yes	No	**<**	**>**
a_7	No	Yes	Yes	No	**<**	**>**

Comments: "Yes" indicates that $\sigma(x, y) \geq 0.75$, and that xSy.

g) Assignments according to the pessimistic and optimistic procedures

Pessimistic procedure				
	Ca3			$\{a_4\}$
	Ca2		$\{a_1, a_3, a_6, a_7\}$	/
	Ca1	/	$\{a_5\}$	$\{a_2\}$
		Ca1	Ca2	Ca3

Optimistic procedure

Comments:

→ Since action **a_2** is incomparable with references **b_1** and **b_2** then this action appears in the cell Ca3-Ca1, which outlines the pattern of the performance profile. (see Figure 9).

→ Action **a_4** has a performance profile that is very close to the reference **b_2**. This action is assigned in Ca3 with both the optimistic and pessimistic procedures.

3.2.8 References

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3.3 Interactive elimination

In an interactive elimination procedure with effect control (Gero et al. 1982, Hochstrate 1986, Baur 2000) a sensitivity analysis is carried out for the attributes and criteria of each pipe that is within the total set of potential rehabilitation actions. The procedure requires no utility function and uses criteria and attributes of actions on their original scale. The elimination process consists in general of three elementary steps:

1. Setting a threshold value at criterion C_1 from the elimination of actions
2. Observing the consequences at all other criteria
3. Confirming (or rejecting) the elimination-threshold and setting the next threshold at the next criterion

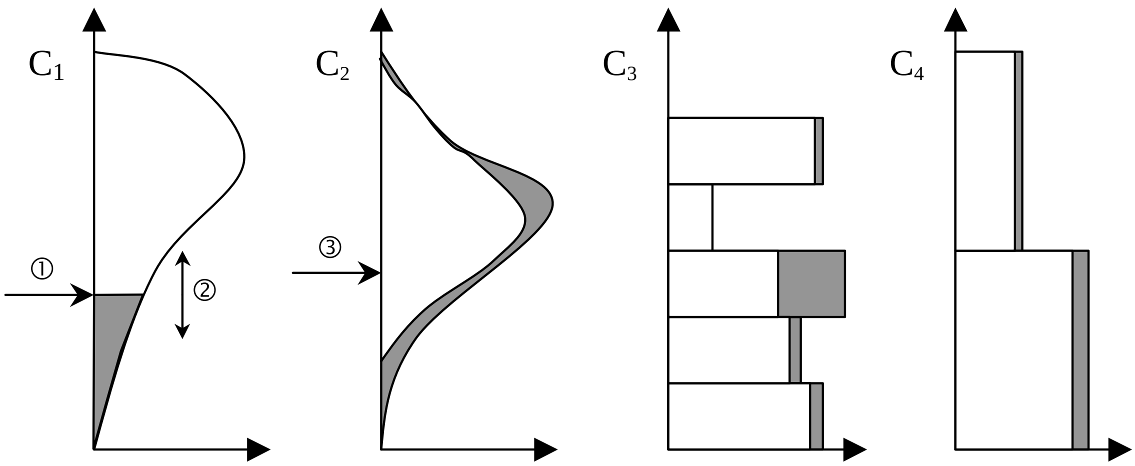


Figure 10: Elimination and observation of consequences by distribution-curves of criteria values

The principle of elimination and effect control is outlined by drawing the distribution of values for four different criteria in Figure 10. In the first elimination step, a threshold (1) is set for criterion C_1, and the eliminated options are drawn on the distribution curves of all the other criteria. The second step would be the modification of the threshold or its confirmation (2). After confirmation of the elimination of actions, the next threshold at the next criterion would be set (3).

The procedure starts with the presentation of the total network and all criteria ranges, from the lowest (less desired) to the highest (most desired) value, defined as the initial solution corridor. By the definition of a reference solution, the elimination process can be supported through the reduction of required comparison of actions (Kropp and Baur 2002). For the observation of the effects of an elimination-threshold, tables, charts, distribution curves of criteria values and maps can be used. It is not necessary, that values at all criteria are available for all actions. Even incomplete information can be used and can improve the decision process. By combination of attributes criteria limits can be linked (e.g. elimination of all ductile iron pipes laid after 1985). The number of projects will be reduced step-by-step by setting limits for particular criteria values until a break-off value at a pre-defined criterion is reached. In most cases this will be the budget limit, where the elimination process comes to an end. Thus the interactive elimination procedure with effect control works like a funnel where each elimination step has the function of a refining screen for the most efficient rehabilitation projects. In Figure 11, the formal structure of the elimination process is outlined in a flow chart.

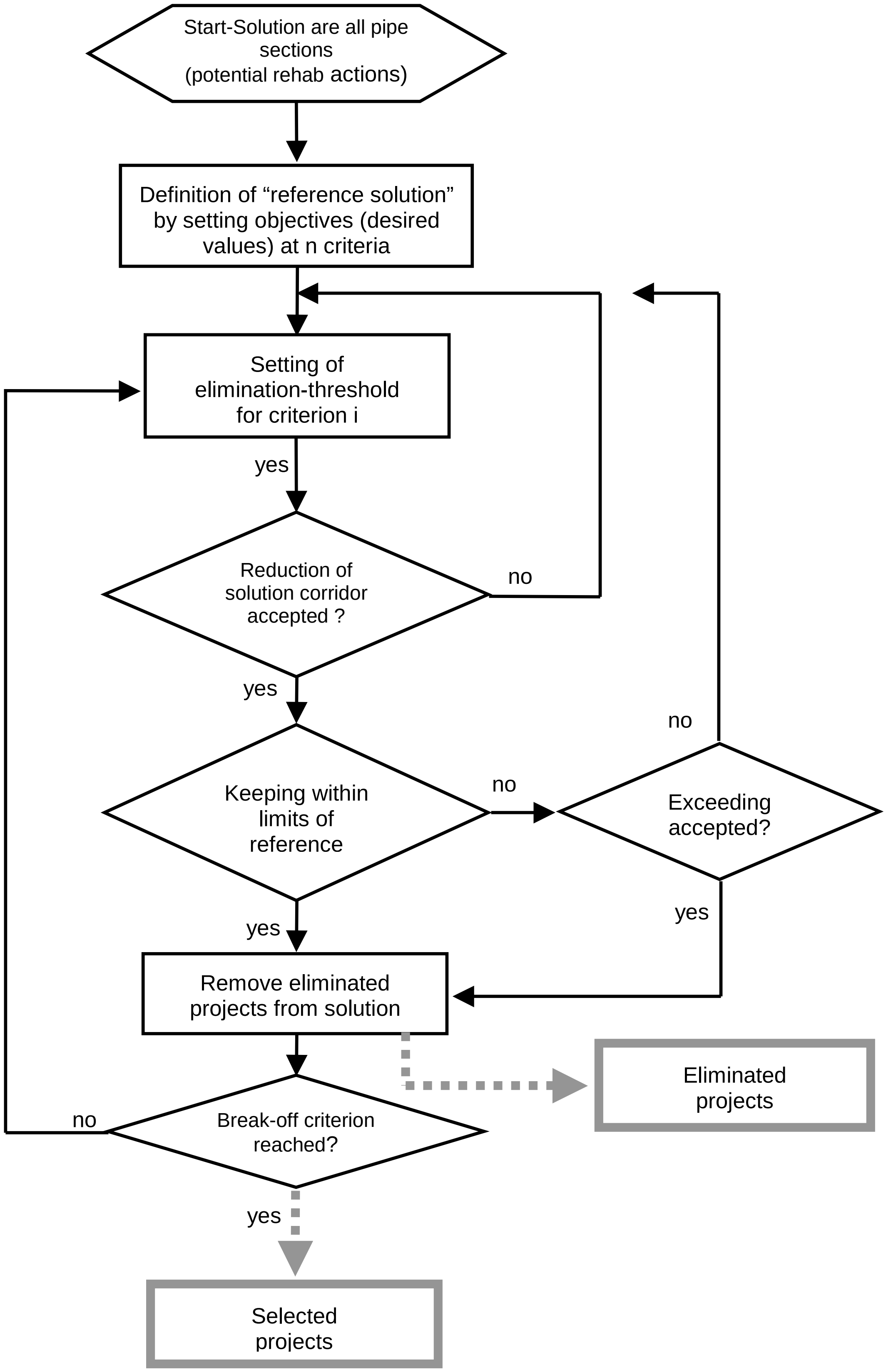
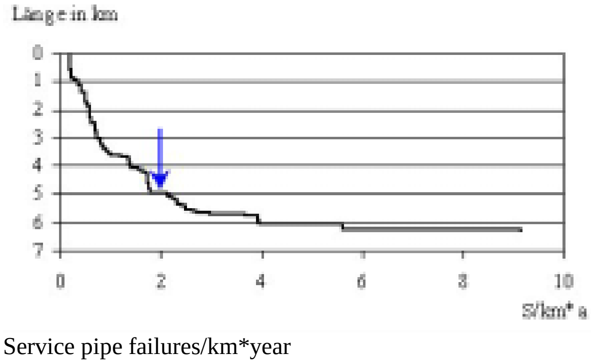


Figure 11: Flow chart of the interactive elimination procedure (Kropp and Baur 2002)

Thresholds are preferably chosen with the aid of sensitivity curves, which show the relative distribution of attribute values. This way, potential gaps that would be appropriate for a threshold setting could be identified. In Figure 12 one of these gaps can clearly be identified for the failure rate of service pipes in the remaining set of potential rehab projects between 2.3 and 2.6 failures per km of distribution pipe and year. For the subsequent effect control, absolute distribution curves are used. In the example of Figure 13 the reduction in the distribution of the diameter after the elimination of all pipe sections for which no failures are recorded to date is shown. Additionally, elimination steps are documented on a network map (Figure 14).



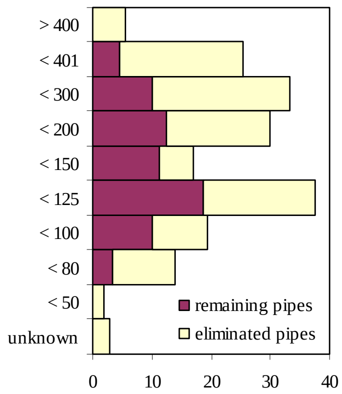


Figure 12: Sensitivity curve for failure rate of service pipes

Figure 13: Effect control with distribution curve for remaining and eliminated length of pipes by diameter

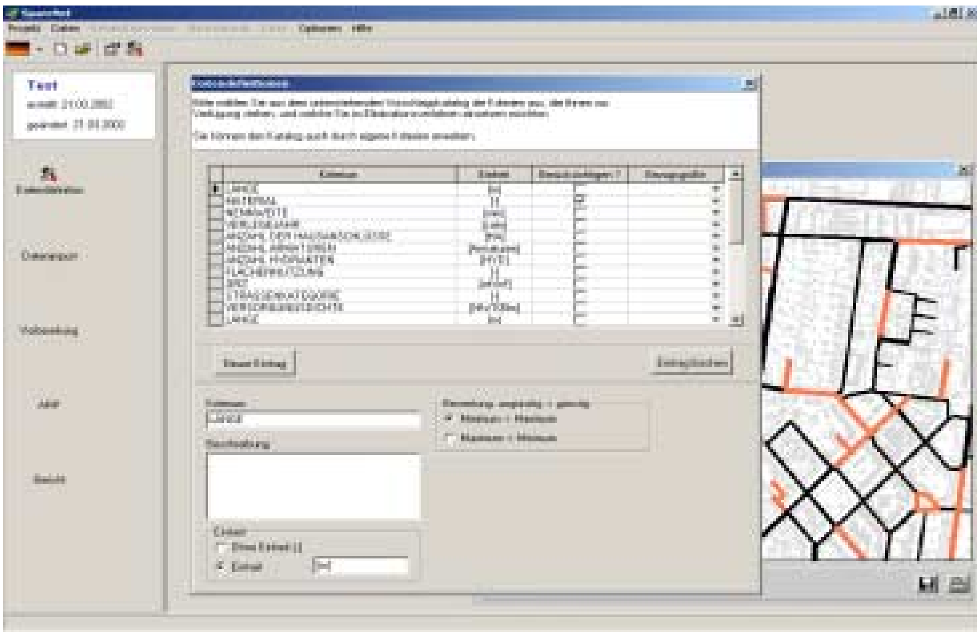


Figure 14: Application screen for the interactive elimination procedure (Kropp and Baur 2002)

The order, in which the criteria are chosen for the elimination steps, is free. Mathematically, the result will not be influenced by the order, due to the conjunctive nature of the thresholds (Zimmermann and Gutsche 1990). However, different preferences might be expressed by the decision maker, in the case of a changing order of decision criteria. In general, the decision maker would start the elimination with thresholds at those criteria that are easy to determine for selection (e.g.: elimination of all ductile iron pipes installed after 1985). This way, the decision maker's understanding of the elimination process and of the nature of the decision problem's trade-offs will be improved.

The procedure will not necessarily lead to results in the sense of a mathematical optimum such as aggregation methods like the weighted sum-rules suggest, but it will give a better understanding of the problem (data availability and requirements) and it will stimulate a learning process, which should be the objective of any method of decision-aid.

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4 - ONGOING WORK

4.1 Application

The methods will be applied and tested with realistic example data. Partners from Italy, Czech Republic and France were asked to fill an example data sheet with information required for the elaboration and calculation of criteria developed in Task 3.1 and 3.2 (Le Gauffre et al. 2002). Meanwhile, a comprehensive database is available from Reggio (I) (see Appendix 2), Brno (CZ) and three villages in the region of Bologna and Ferrara (I). Data mining in Lyon (F) and Reggio is still ongoing. The current state of information availability is outlined in Table 5. In an additional column data availability in the German research project of TU Dresden (Gotha) is mentioned.

Table 5: Information required and data availability (June 2002)

Information	Lyon (ongoing)	Reggio (ongoing)	Bologna/ Ferrara	Brno *(sample)*	Gotha
No. of pipes	47052 3000 km	1400 n.a.	380 17.4 km	59 16.7 km	6177 190 km
Pipe ID	✓	✓	✓	✓	✓
Length	✓	mean	✓	✓	✓
Material	~ 60%	377	✓	✓	✓
Diameter	✓	371	✓	✓	✓
Pressure	n.a.(*)	n.a.	simplified	n.a.	n.a.
Number of people supplied by link	n.a.(*)	by street	by street	✓	n.a.
Sensitive customer *Special customer*	n.a.	✓ ✓	n.a.	✓	n.a.
Customer complaints	n.a.	n.a.	n.a.	n.a.	n.a.
Predicted burst rate PBR	-	n.a.	n.a.	n.a.	n.a.
Predicted failure rate PFR	obs. 93-01	obs. 94-00	n.a.	n.a.	90-01
Hydraulic criticality index	n.a.	1/0	n.a.	✓	n.a.
Co-ordination score	partial	n.a.	n.a.	✓	✓
Unit Cost of Repair UCRp	✓	by diameter	uniform	n.a.	uniform
Unit Cost of Rehabilitation UCRh	✓	by diameter	✓	n.a.	uniform
Contribution to leakage	n.a.	by zone	n.a.	n.a.	n.a.
Cost factor CF	n.a.(*)	n.a.	n.a.	✓	n.a.
Co-ordination cost saving factor in %	n.a.(*)	n.a.	n.a.	n.a.	n.a.
Expected duration of repair	n.a.(*)	n.a.	uniform	n.a.	n.a.
Sensitivity of housing areas due to flooding SFH	n.a.	n.a.	uniform	n.a.	n.a.
Sensitivity of industrial areas due to flooding SFI	n.a.	n.a.	uniform	n.a.	n.a.
Risk of landslide LS	✓	n.a.	uniform	n.a.	partial
Street category factor SR	✓	✓	uniform	✓	✓
Parallel infrastructure factor SI	n.a.	n.a.	uniform	n.a.	n.a.
Intensity factor IFH	n.a.(*)	n.a.	uniform	n.a.	n.a.
Vulnerable values in housing areas factor VFH	n.a.	n.a.	✓	✓	n.a.
Vulnerable values in industrial areas factor VFI	n.a.	n.a.	n.a.	n.a.	n.a.

.(*) ongoing studies.

4.2 Outlook

The development of a computer programme for the application of ELECTRE TRI is in progress. For the interactive elimination procedure, a computer programme is under development by TU Dresden in the course of a German research project (Kropp and Baur 2002). The methods and procedures will be tested for the result's robustness against data availability, incomplete data sets, variation of parameters such as weights and thresholds and the sensitivity to variation of criteria values.

Beside programming the ELECTRE tool, a main objective of task 3.4, *development of a multi-criteria procedure for annual rehabilitation programmes*, will be the interpretation of the parameters (weights and thresholds) used in the different procedures. We aim to investigate the inter-dependencies between data accuracy (criteria uncertainties) and threshold setting, and between the distribution of weights and the consequences for the selection of pipes with their contribution to particular problems in the network (hotspots).

A further aspect will be the appropriate presentation of results of the multi-criteria decision-aid in tables, graphs and maps.

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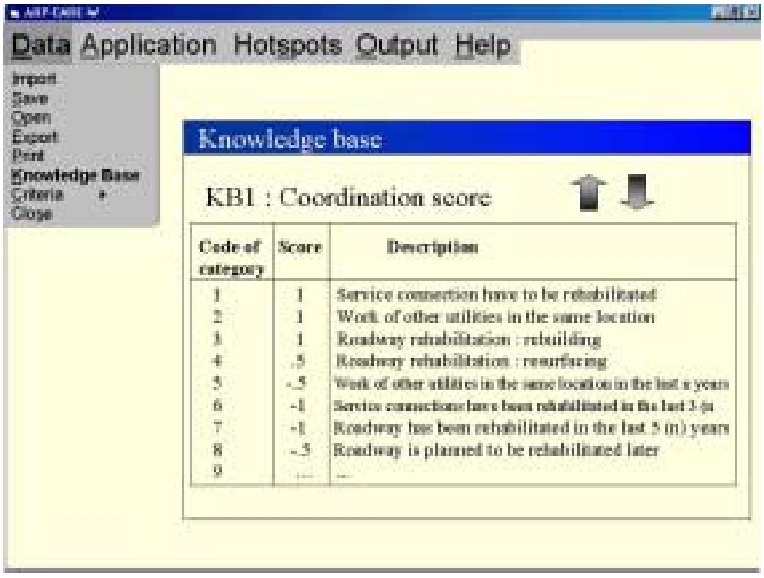
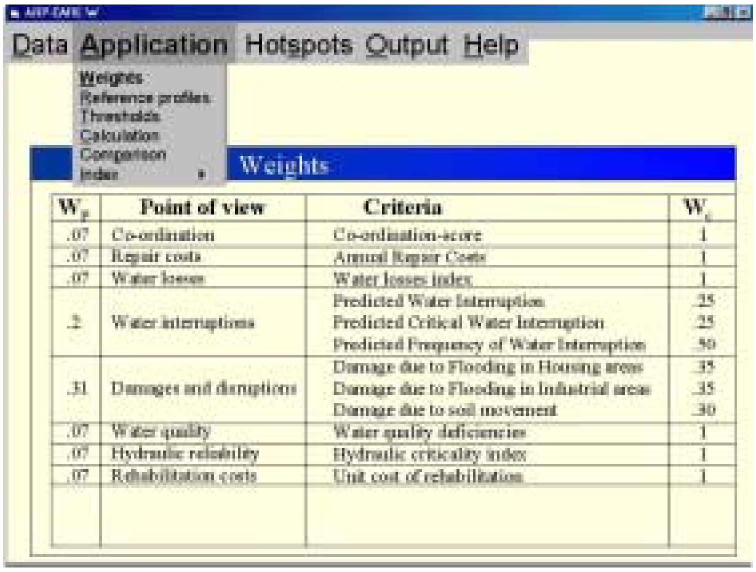
Appendix 1

Screenshots of the ELECTRE TRI prototype - 3 examples

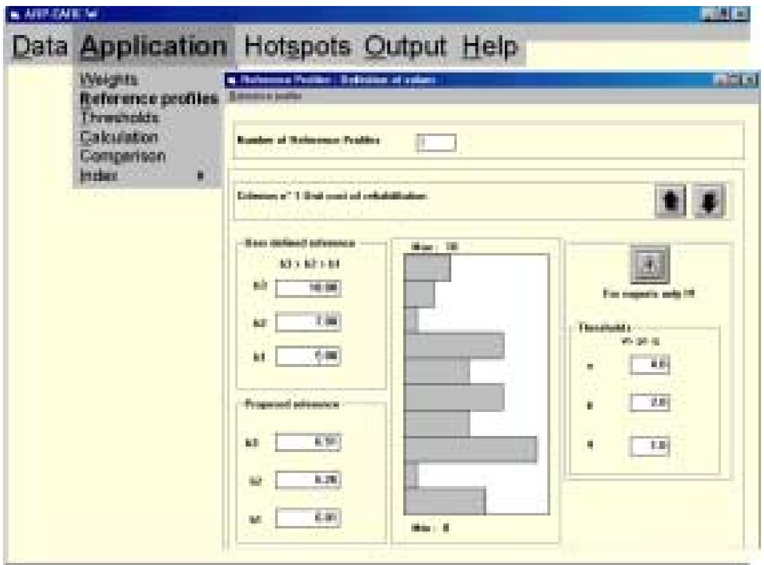


The software is structured in menus. In the DATA menu, general operations such as data import, project loading and saving, and printing are available. Additionally, specific functionalities are provided for the control of “Knowledge Bases” and the calculation of criteria from the information matrix.



The APPLICATION menu contains the functionalities for running the ELECTRE TRI procedure, and provides the opportunity to compare results from various runs with different parameter sets, or to compare the results with those obtained from an aggregation model.

The HOTSPOTS menu provides an effect control of the result. In the OUTPUT menu, standard output options (tables, graphs) are provided.



The sub menus, where the user must customize parameters (for example the REFERENCE PROFILES), are supported by graphical tools, such as histograms for the distribution of criteria values.

Appendix 2

Data availability for the calculation of criteria for the ARP procedure - the case of Reggio Emiglia

	Information	CASE AGAC REGGIO E. TOWN DATASET FOR PRIORITISATION / RANKING		
		STATUS	**WAY**	**NOTE**
Pipe ID		IN PROGRESS	Pipe ID is the road name. Each road is composed by many links. They will be extracted. The way to do it automatically is under study as well as the link coordinates of each component.	For test it could be considered a typical length: 300 m inside the center.
Length in m				
Material				
Diameter in mm				
Pressure in Mpa	Max pressure at night flow	IN PROGRESS	Pressure is under calculation with the upgrading of a math model. The used model is EPANET. The model has two sets of data: one set considers the trunk mains and the distribution to the districts, the second one considers the distribution within the district.	
Number of people supplied by the link	If not available, maybe a population density of the zone can be given	COMPLETED	It has been calculated with the use of the customer consumption in one year, sorted by road. A mean consumption for a user in Reggio is 140 m3/year. Hence it can be derived the number of users per road. The procedure is repeatable.	
Sensitive customer	yes/no, please specify	COMPLETED	It has been a selection of users with civil and social scope. It has been added those who have high consumption for commercial and industrial use.	
customer complaints	yes/no or No.	TO DO	It is feasable. It should be done jointly with contribution to water quality deficiency. Medium term.	
Predicted burst rate PBR	from WP2 model, or local information (observation)			
Predicted failure rate PFR	from WP2 model, or local information (observation)			

	Information	**CASE AGAC REGGIO E. TOWN DATASET FOR PRIORITISATION / RANKING**		
Hydraulic criticality index	from WP2 model, or local information (observation)	COMPLETED	The roads which have been chosen have the pipes which feed the districts. The district can have either one or two inlets.	
Co-ordination score	code of category according to KB1, **This can be a list of codes!**	TO DO	It is feasable. It will be studied how. Medium long term.	
Unit Cost of Repair UCRp	code of category according to KB2	TO DO		The unit cost to repair is in the range of either the half or whole cost to replace one service pipe. To see the unit cost of rehabilitation.
Unit Cost of Rehabilitation UCRh	code of category according to KB3	DONE	It has been considered the 2002 accountability and town cases of new pipe rehabilitation.	The unit cost is for high density and low density service pipes within the road.
Contribution to Water quality deficiency	code of category according to KB6	TO DO		
Contribution to leakage	code of category according to KB5	IN PROGRESS	The leakage values are those from the active control scheme 2000. The town has been recently completed with the last districts. The leakage is allocated to each component (road) of the district. Each district has a code. The length of the district has been calculated with the cartographic system.	
Rehab Cost factor CF	code of category according to KB4			
Co-ordination cost saving factor in %		NOT DONE	If the coordination is with roadway rehabilitation, then this can be deduced form the table enclosed of rehab costs.	

	Information	CASE AGAC REGGIO E. TOWN DATASET FOR PRIORITISATION / RANKING	
Expected duration of repair	code of category according to KB7	NOT DONE	
Sensitivity of housing areas due to flooding SFH	code of category according to KB8	NOT DONE	
Sensitivity of industrial areas due to flooding SFI	code of category according to KB9	NOT DONE	
Risk of landslide LS	code of category according to KB10	NOT DONE	
Street category factor SR	code of category according to KB11	DONE	The main roads are those which have a civil purpose like hospital inlet and outlet from the town, fire brigades, red cross presidies. It has been observed the traffic intensive roads to commute in out from the town.
Parallel infrastructure factor SI	code of category according to KB12	NOT DONE	To explore. Medium long term.
Intensity factor IFH, IFI	code of category according to KB13	NOT DONE	
Vulnerable values in housing areas factor VFH	code of category according to KB14	TO DO	It is feasable. It will be study the cartographic database to cross with different data sources to pinpoint collective buildings with numerous flats, attached housse of small height, rural, housing then open air storage, education buildings, sport halls, industrial plants. Medium long term.

	Information	**CASE AGAC REGGIO E. TOWN DATASET FOR PRIORITISATION / RANKING**	
Vulnerable values in industrial areas factor VFH	code of category according to KB15	TO DO	
Number of previous failure NOPF	additional information if available, please specify	DONE	New. It is reported in the document dedicated to the break analysis. The procedure is to work out from calls the accidental breaks amount per year and cumulate it with the past years. To add 2001.
Special users	additional information if available, please specify	DONE	New. For each road it has been shown special water users which can have an annoyance or commercial loss due to water interruption as studied by CEMAGREF. The procedure elaborates data from yellow pages.
Info3	additional information if available, please specify		
Info4	additional information if available, please specify		

Appendix 3

Knowledge Bases (KB) with example data

KB1	Co-ordination score	
code of category	score	description
1	1	Service connections have to be rehabilitated
2	1	Work of other utilities in the same location
3	1	Roadway rehabilitation: rebuilding
4	0.5	Roadway rehabilitation: resurfacing
5	-0.5	Work of other utilities in the same location in the last n years
6	-1	Service connections have been rehabilitated in the last **3 (n)** years
7	-1	Roadway has been rehabilitated in the last **5 (n)** years
8	-0.5	Roadway is planned to be rehabilitated later
…	…	

KB2	Unit Cost of Repair UCRp	
code of category	€	description
1	3000	unknown
2	1900	diam < 300mm & easy context
3	3100	diam < 300mm & normal context **or** diam >= 300mm & easy context
4	4700	diam >= 300mm & easy context **or** diam < 300mm & difficult context
5	6200	diam >= 300mm & difficult context
…	…	

KB3	Unit Cost of Rehabilitation UCRh	
code of category	€/m	description
1	100	unknown
2	90	< 80 mm
3	105	81-105 mm
4	120	106-155 mm
5	140	156-205 mm
6	170	>206 mm
…	…	

KB4	Rehabilitation Cost Factor	
code of category	multiplier	description
1	1	unknown
2	0.8	low service connection density & easy soil condition
3	0.9	high service connection density & easy soil condition
4	1	low service connection density & difficult soil condition
5	1.3	medium service connection density & difficult soil condition
6	1.7	high service connection density & difficult soil condition
…	…	

KB5	Contribution to leakage	
code of category		description
1	0	unknown
2	0	none
3	0.1	low
4	0.5	medium
5	0.9	high
…	…	

KB6	Contribution to Water quality deficiencies	
code of category		description
1	0	unknown
2	0	none
3	0.1	low
4	0.5	medium
5	0.9	high
…	…	

KB7	Expected duration of repair	
code of category	hours	description
1	3	unknown
2	2	low
3	5	medium
4	10	high
…	…	

KB8	Sensitivity of housing areas to flooding **or KB13 & KB14**	
code of category		description
1	0	low
2	0.4	medium
3	1	high
…	…	

KB9	Sensitivity of industrial areas to flooding **or KB13 & KB15**	
code of category		description
1	0	low
2	0.4	medium
3	1	high
…	…	

KB10	Risk of Landslides	
code of category		description
1	0	low
2	0.4	medium
3	1	high
…	…	

KB11	Street category factor	
code of category		description
1	0	no traffic
2	0.4	low traffic density
3	0.7	medium traffic density
4	1	high traffic density
…	…	

KB12	Parallel infrastructure factor	
code of category		description
1	0	low
2	0.4	medium
3	1	high
…	…	

KB13	Intensity factor Flooding in housing/industrial/commercial areas	
code of category		description
1	0	low: no basement, first floor below ground, no significant slope
2	0.4	medium: basement, first floor above ground, (no) significant slope
3	1	high: basement, first floor above ground, significant slope
…	…	

KB14	Vulnerable values in housing areas	
code of category		description
1	0.69	individual housing with retail shop
2	0.65	individual housing with retail shop, allotments
3	0.65	rural housing
4	0.56	collective buildings with numerous flats
5	1	attached houses of small height
6	1	attached collective buildings of small height
…	…	

KB15	Vulnerable values in industrial/commercial areas	
code of category		description
1	0.03	open air storage
2	0.15	education buildings
3	0.15	industries allotment
4	0.2	sports halls
5	0.22	wide industrial site
6	0.23	big stores
7	0.4	industrial plant
8	1	offices
…	…	

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