SYNTHESIS REPORT

FOR PUBLICATION

DECISION-MAKING FOR REQUALIFICATION OF STRUCTURES RESTRUCT

CONTRACT No:	BRE2 - CT92 -0329
PROJECT N“:	BE-5935
PROJECT COORDINATOR:	MPA
PARTNERS:	AGIP AST COWI D' APPOLONIA DNVI MIT MPA SNAMPROGETTI GKM IVO LABORELEC

REFERENCE PERIOD FROM 01-01-93 to 31-12-95

STARTING DATE: 01-01-93 IXJRATION: 36 MONTHS

PROJECT FUNDED BY THE EUROPEAN COMMUNITY UNDER THE BRITE/EURAM PROGRAMME

DATE: FEBRUARY 1996

Table of contents:

1 Summary Page

1.1 Keywords

The following keywords can characterise the contents and main achievements of the project:

1. AHP
2. Bayesian
3. Bridges
4. Decision Support System
5. Fuzzy
6. Inspection and Maintenance Planning
7. Multi criteria decision making
8. W-shore
9. Power Plants
10. Requalification of structures
11. Structural assessment
12. Unified decision framework

The order of descriptors is alphabetical, not related to the priorities.

1.2 Abstract

This report summarises the work performed in the BRITE EURAM project BE5935 (Contract Nr.: BRE2 - CT92 - 0329) and gives a detailed description of the achieved results,

The overall achievement of the project is the improvement of the decision making related to the requalification of “older” structures in the offshore, bridges and power plants areas. Therefore, a methodology was developed, in which structural and/or mechanical integrity is the governing criterion, however other more qualitative criteria are also considered simultaneously. Furthermore, for the automation of the process, a set of engineering (software) tools handling several related problems has been developed.

The most innovative achievement of the project has been the development of multi-criteria decision analysis techniques which take into account various types of uncertainties involved in the evaluation of the decision criteria and constraints. Starting from the three separate well established decision techniques: Multi-Criteria Decision Methods (MCDM) namely

a) the deterministic criteria,

b} the fuzzy decision analysis with a single criterion involving “fuzzy” uncertainty, and

c) the bayesian decision analysis with a single criterion involving “stochastic” uncertainty,

have been developed through combining and merging them with either joint utility functions or the AHP method.

These developments have provided a comprehensive methodology for problems which may be encountered in practice. Guidelines have been provided to assist the users in the selection of a particular method for the problem being considered.

The project has been very successful in achieving its principal objective of providing a rational basis for decision-making for requalification of existing structures. A decision-theoretic framework has been proposed for requalification and innovative methods have been developed for decision analysis within this framework. The applicability and benefits of the developed methods have been demonstrated through a number of realistic examples. Finally, the developed methods have been implemented into an intelligent software system. The **exploitation potential** of the results is large (spin-off products commercialised already at the end of the project, exploitation agreement achieved) and the **European collaboration pattern** established in the project involving seven countries and several industrial areas stable.

The results of the BE5935 project and of the RESTRUCT software offer an excellent basis for development of these dedicated software systems in single DSS for each area of these area of application.

2 The consortium

AGIP Contact: Mr. Paolo Guaita AGIP P.O. Box 12069-20120 Milano MI I -20397 San Donato Milanese Italy Tel.: +39 252062836 Fax.: + 39 252061809	**COWIConsult, Consulting Engineers and Planners AS** Contact: Mr. Niels Peter Høj COWIconsult Parallelvej 15 DK -2800 Lyngby Dänemark Tel.: +45-45-97 2211 Fax.: +45 45 97'2212	**DNV - Det Norske Veritas Industry AS, Department for Subsea and Structures** Contact: Dr. Øisten Hagen Det Norske Veritas Veritasveien 1, P.O.Box 300 N -1322 Høvik Norway Tel.: +47-67-57 7250 Fax.: +47 67577474
MIT-Management Intelligenter Technologien GmbH Contact: Dipl.-Math, Karl Lieven MIT GmbH Korneliuscenter / Promenade 9 52076 Aachen Germany Tel.: +49 24 08/9 45%0 Fax.: +49 24 08/9 4.582	**MPA, Staatliche Materialprüfungsanstalt, Universität Stuttgart** Contact: Dr. A. Jovanovic MPA Stuttgart Pfaffenwaldring 32 D-70569 Germany Tel.: +49 7116853007 Fax.: +49 7116853947	
D'Appolonia Contact: Mr. Franco Zuccarelli D'Appolonia Via Siena 20 I -16146 Geneva Italy Tel.: +39 103628148 Fax.: +39 103621078	**Snamprogetti S.p.A.** Contact: Mr. Marcello Beranger Snamprogetti S.p.A. Via De Gasperi 16 20097 San Donato Milanese Italy Tel.: +39 252036175 Fax.: +39 252099407	**WS Atkins Science& Technology** Contact: Mr. Navil K. Shetty WS Atkins Science& Technology Woodcote Grove Ashley Road WV85BW Epsom Surrey United Kingdom Tel.: +44 1372726140 Fax.: +44 1372740055
Electrabel - Assistance Revisions. Contact: Mr. Marc De Witte Electrabel - Assistance Revisions Chemin de Mons à Gand 251 B -7864 Deux - Acren Belgium Tel.: +32-68 274130 Fax.: +32 68337214	**GKM - Grosskraftvverk Mannheim** Contact: Prof. Dr. Hans R. Kautz Großkraftwerk Mannheim AG Postfach2402 64 68172 Mannheim Germany Tel.: +49 621868 3702/3703 Fax.: +49 6218683710	**IVO - Imatran Voima Oy** Contact: Mr. Jan Rönnberg IVO - Imatran Voima Oy Rajatorpantie 8 01019 IVO Vantaa Finland Tel.: +358-0-8561 4738 Fax.: +358-O-5632225

Laborelec
Contact:
Mrs. Lieve Verelst
Laborelec
Rhodestraat 125
B -1630 Linkebeek
Belgium
Tel.: +32 23820496
Fax.: +32 23820241

VTT - Manufacturing Technology
Contact:
Mr. Pertti Auerkari
VTT Manufacturing Technology
P.O. Box 1704 (Kemistintie 3, Espoo)
SF -02044 VTT
Finland
TeL: +358 0 456 6850/4561
Fax.: +358 0456 7002/' 4567010

The consortium is organised as follows:

Organisation name	Role	Country	Area
AGIP	Partner	I	Offshore
SNAMPROGETTI	Ass. Partner	I	Offshore
D'APPOLONIA	Ass. Partner	I	Offshore
COWI	Partner	DK	Bridges
WS ATKINS	Ass. Partner	GB	Bridges
DNV	Partner	N	Methodology 1
MIT	Partner	D	Methodology 2
MPA Stuttgart	Co-ordinator	D	Power Plants
IVO	Sponsor	FIN	Power Plants
GKM	Sponsor	D	Power Plants
Laborelec	Sponsor	B	Power Plants

AGIP is a major oil and gas producer. Since the early eighties, this partner has been involved in the application of probabilistic techniques to structural analysis. The role of AGIP was to co-ordinate the tasks related to the offshore structures field of application (platforms and pipelines). It was involved in the compiling of the final report and guidelines.

COWI is a major international engineering company and it was contributing to the project with its wide experience within bridge design, construction and maintenance, supplemented with profound relevant experience within probabilistic assessment of structural reliability.

DNVS role in this project was :

- to develop the present Bayesian probabilistic methods and optimisation methods to incorporate the decision support ability considering several interacting criteria, regulatory constraints and failure probability evaluation.
- to develop software for "the decision support tool box" as an extension to previously developed software.

As an organisation that develops rules and regulations this will give knowledge about the acceptability of the developed methods.

DNV is in the forefront of present development of statistical tool for probabilistic assessment of failure probabilities and economical risk combined with the activity in optimisation tools of design and project economy with ability to incorporate additional information through a bayesian approach. The past and present activity of DNV is therefore closely connected to the fields in question and the project was given the opportunity to take the step into full decision analyses with some new angles of approach.

MIT's major role in this project was the customisation/development of the multicriteria decision methodologies applicable for structural engineering problems based on fuzzy set theory, possibility theory and evidence theory. Hence, they were also involved in their testing and implementation to practical problems, in the feasibility study of an expert system for structural engineering and decision making and in investigating the decision structures in the three application areas of concern in this project. One prime concern of MIT was also to assure that the available information is gathered properly and that the decision making tools which are developed are able to process the information supplied and to produce the decision support.

MPA is a research institute whose research is connected with material science. The main roles of this partner (project co-ordinator) with its sponsors (Electrabel, GKM, IVO, Laborelec, VTT)) was to provide input data, knowledge and other information related to power plant applications, as well as to organise testing and validation in the domain of power plants (together with the sponsoring utility companies), to assist MIT in development of the adapted methodology for engineering Multi-Criteria Decision Making in the domain of structural reliability (in particular for the power plant applications), to implement and deploy the methodology(ies) in the form of (software based) "decision support system tool box*'.

MPA has a quite unique experience in the domain of integration of various elements of knowledge based systems (data bases, numerics, expert systems, hypermedia, etc...), which was maximally exploited in the research work on this project.

SNAMPROGETTI's and D'APPOLONIA's role were mainly the identification and interpretation of decision making problems in the offshore industry, as well as the contribution to the development of a decision support system. The partners intention from the project is to promote the methodologies developed within this project in order to improve their engineering and consultancy services. Their contribution was mainly devoted to the following activities:

- identification and interpretation of decision-making problems in the offshore industry
- identification of pilot methodologies
- definition of the requalification methodologies for the requalification of structures.

WS Atkins (a big engineering house) has done basically same type of work as COWIconsult, taking the responsibility for the small span bridges.

3 Technical achievements

3.1 Methodology

In this project several approaches to support decision-making for requalification of structures have been suggested and investigated by the methodology partners. These approaches focus mainly on the handling of uncertain information by Bayesian and Fuzzy techniques and on decision making when multiple goals are present. The suggested techniques have advantages but also limitations for proper use.

in the following all the applied methods are briefly described.

3.1.1 *Fuzzy Rule-based modelling*

Fuzzy reasoning theory aims to provide a model for implementing a knowledge based system [Mamdani, Assilian 1975]. This knowledge will often be available in rules that link the input variables with the output variables by terms of linguistic variables. By far the most frequently used method of representing knowledge is by means of production rules. These **are** usually of the form:

IF a set of conditions is satisfied **THEN** a set of consequences can be produced **WITH** a certainty factor *f*.

Production rules are used to capture the expert-s rule of thumb or heuristic relations among the facts in the domain.

The Fuzzy rule based approach seems to be a powerful tool for modelling bridge condition states in that it reflects quite accurately the decision process that the bridge inspector has to go through when assigning condition states to the bridge components. However, the shape of the membership functions depends greatly on the operators chosen and hence appropriate operators need to be defined that reflect the compensatory effects of the different attributes satisfactorily.

Fuzzy rule based modelling also seems to be a good approach for the modelling of deterioration since analytical models are not available, however, the results of the predicted condition states are very sensitive to the choice of operators.

A further limitation is that it appears that a large number of fuzzy rules are often required to model a particular phenomenon adequately. The results obtained are clearly sensitive to the number of rules specified, although there are no sufficient conditions to help the user to define the optimum number of rules.

The methodology proposed for updating of fuzzy rules, although subjective, seems to be adequate for this practical purpose. However, the ‘Correction Function” **used to modify the certainty factors** need to be calibrated against **experience.** A **further limitation is that** the rule-base and the inspection results on deterioration **need to be defined over the same reference** time since updating can not be carried out over an intermediate period of time within the rule base, This can prove to be quite restrictive in practice.

3.?.2 *AHP*

The AHP (Analytical Hierarchy Process) [Saaty 1990] supports a decision maker in solving MADM-problems which can be depicted in general as shown in Figure 3.1.

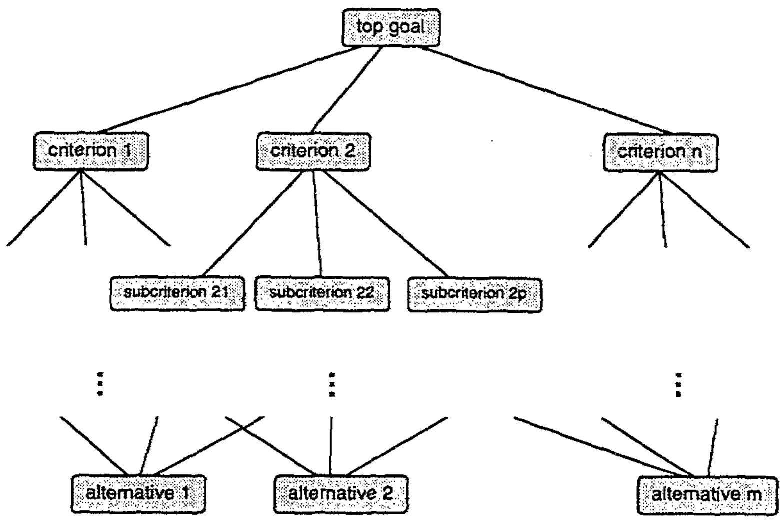


Figure 3.1 AHP scheme

The method of AHP was selected as an appropriate method of MCDM for the types of decision problems that the end users were expecting to model. As long as AHP is used within the limitations and guidelines specified in TEC-T3_1 -02 it is a powerful tool for ranking alternatives based on a number of criteria. [t has been acknowledged that rank reversal is a possibility if the guidelines are not followed and that pairwise comparisons are not always the best method of normalisation. Utility functions can also be used for the normalisation process which additionally avoids rank reversal problems.

3.1.3 *B-AHP*

A new development that has been carried out and documented in the project is the establishment of a Bayesian Analytical Hierarchy Process Model (B-AHP), in which all quantities in the AHP model, physical as well as subjective (linguistic) parameters, are allowed to be stochastic. An important aspect in the modelling is the decision makers weighting of attributes based on a knowledge of the probabilistic distribution of the parameters applied to derive the attribute values, and a utility description of each attribute, thus avoiding the rank reversal problem of the AHP model. The purpose of B-AHP is to include the effect of attribute randomness and comparison uncertainties in this ranking weight determination. Consequently, the resulting ranking weights will be random and represented through probabilistic distributions. B-AHP is meant to address the following two main extensions to ordinary AHP:

- Randomness of parameters describing the attributes values
- Uncertainty in pairwise comparisons

It **has been shown** that **ordinary** AHP can easily be modified to handle these two extensions. The main idea in B-AHP is the use of simulation for assessment of the effect of attribute randomness and pairwise comparison uncertainty. Each separate simulation run in B-AHP is equivalent to solving an ordinary AHP problem. Analytical expressions for the probabilistic ranking weight distributions will in general be difficult, if **not** impossible, to establish. However, the statistical moments for the weight distribution functions can be estimated through simulation. B-AHP uses Monte-Carlo simulation to calculate estimates for the first four statistical moments of any ranking weight, yielding e.g. estimates for the expectation, standard deviation, skewness, and kurtosis for the weights. Furthermore, the sensitivity of the decision measure (e.g. expected weight) for each of the considered decision alternative to the various model parameters are determined, thus providing measures of sensitivity of the final decision to the applied **model variables.** The safety of a structure as measured by its reliability and the sensitivity of the reliability to the various model variables are also determined, thus providing measures of where to most efficiently allocate resources in order to increase the reliability of the structure. A schematic overview of the B-AHP is shown in Figure 3.2.

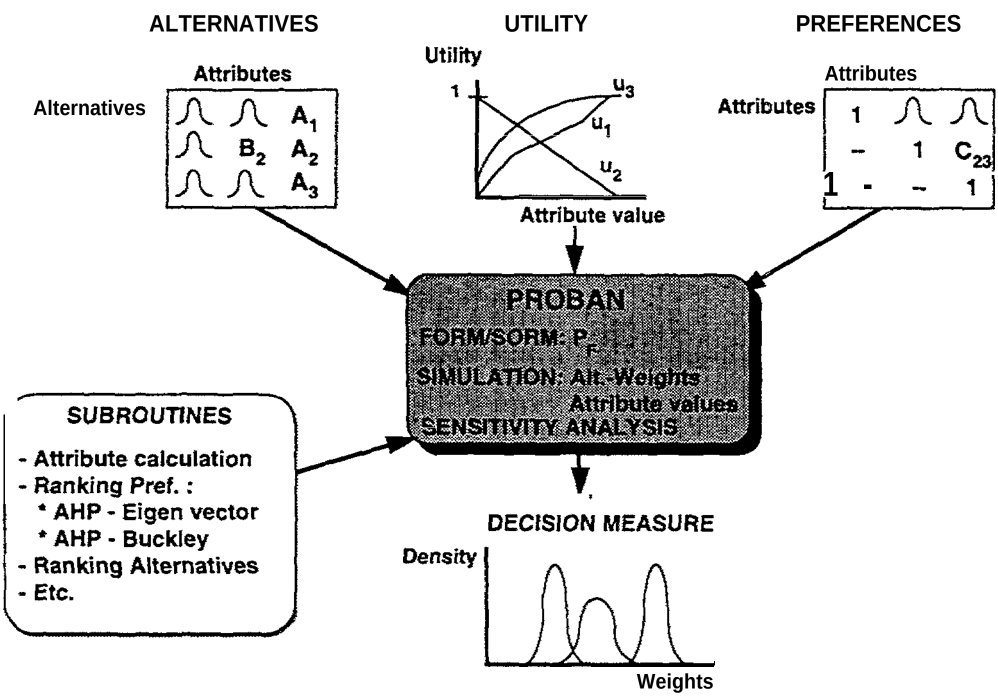


Figure 3.2 Schematic overview of the B-AHP

The probabilistic extension of AHP has been used by the offshore partners in this project. PROBAN computer program has been adopted to solve the pipeline requalification example, as well as the offshore platform requalification example.

Given the particularities of the example choosen for the real case application, no specific problems due to the methodology have been experienced. It seems that the methodology is capable of consider appropriately all the parameters to be considered in a requalification problem. It is, however, feeling of the Offshore group that only the extended use of the methodology will permit a correct definition of the applicability limits.

An important consideration can be derived in general for the application of a methodology that is purely Bayesian. It seems that for attributes that are not easily quantifiable, as REPUTATION, a Bayesian combined with Fuzzy AHP could be best appropriate approach.

3.1.4 *F-AHP*

The Fuzzy-AHP method is an extension of the classical AHP method [Buckley 1985]. The main difference can be found in the representation of the judgments given by the decision maker. In the F-AHP approach all judgments will be model led by trapezoidal fuzzy numbers.

This method has been used by the power plant and bridge partners in this project. Fuzzy modelling might be a useful approach in situations where the state variables are not defined precisely and analytical models are not available for the evaluation of output quantities.

There is, however, a limitation in the complexity of the membership functions which have to be trapezoidaL

3.7.5 *Combined Approach - FB-AHP*

The objective of approaches which combine different techniques for uncertainty modelling is to deal with decision problems in which crisp, fuzzy and probabilistic uncertainties are allowed simultaneously. Many methods where different uncertainty techniques have been combined are suggested. Especially the probability of a fuzzy event [Zadeh 1968] has found a lot of interest.

In this project the combined approach has been applied for using AHP as a multi criteria technique. The main idea of this method, called Bayesian-Fuzzy-AHP (BF-AHP), is to integrate both, stochastic and fuzzy uncertainties into AHP. Here the judgments in the comparison matrices may be modelled either by fuzzy numbers or by stochastic variables. Two implementations of this idea have been performed in this project. They differ only in the sequence of defuzzification and calculation of the expected values. More details can be found in TEC-3_4-01/REV 1. The following figure presents one of these suggestions.

The solution process of the BF-AHP approach can be represented by the flowchart in Figure 3.3:

BF-AHP is definitely the most innovative development of this project so far. It is quite common that different types of uncertainties are involved in the criteria used in decision-making. Some uncertainties are better modelled by stochastic variables and others by fuzzy numbers. This method, therefore, is very powerful to handle these two kinds of uncertainties.

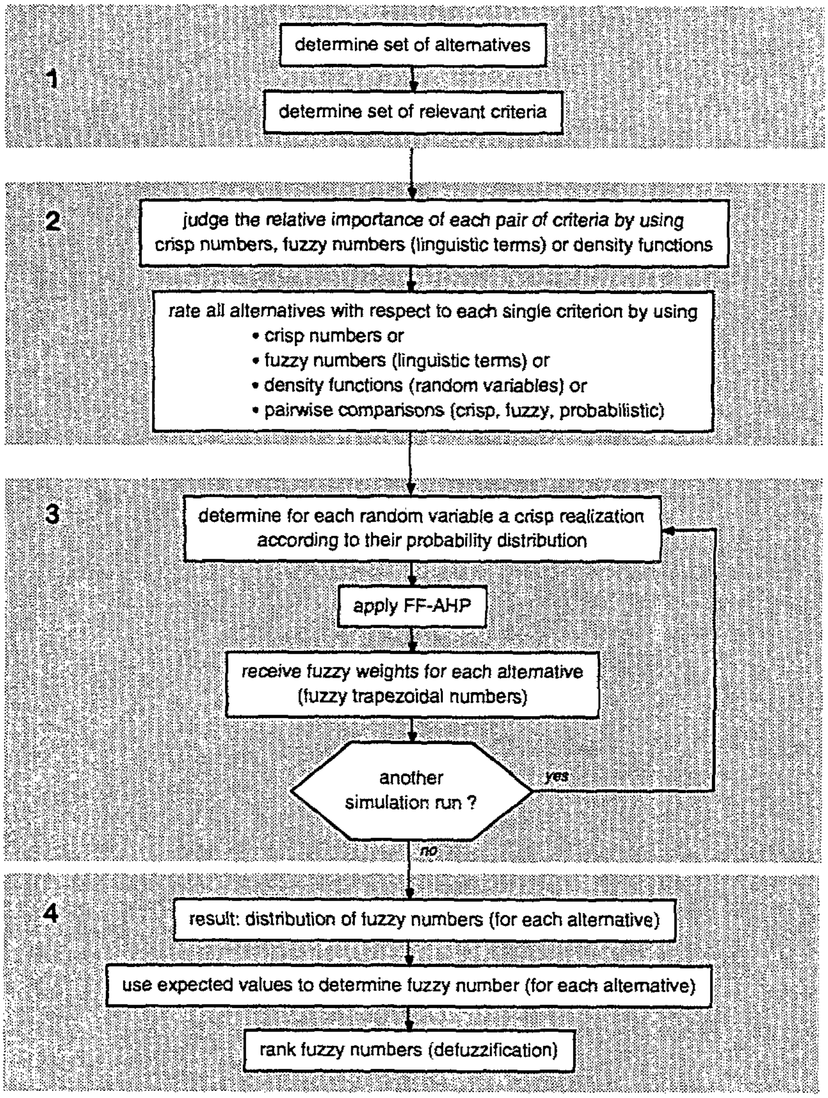


Figure 3.3 Solution process of BF-AHP

3.2 Decision Framework

3.2.1 *General*

The ultimate goal of the study for re-qualification is "to establish that the structure is fit for its intended purpose over the residual service life, and that the consequences in terms of risk to human life, to the environment and to the assets, in the event of structural failure, are acceptable both from a reliability and economical point of view".

The decision-making for re-qualification of structures involves in general choosing between a number of alternatives such as: use "as-is", repair, strengthen, reduce loads, reduce exposure of personnel, replace, abandon, or a combination of these measures. The identification of all relevant alternatives and selection of appropriate criteria to be used in the evaluation of the available alternatives are important tasks which require engineering skill.

The choice of any alternative is likely to have profound implications in terms of costs, risk to human life, to the environment and the future profitability of the structure/facility. Methods of multi-criteria decision analysis developed within the RESTRUCT project help to arrive at a rational decision in such situations.

The main activities involved in a re-qualification process have been grouped broadly into following tasks:

1. Specification of the Re-qualification Problem
2. Structural Assessment
3. Detailed Inspection and Maintenance Planning

The specification of the re-qualification problem involves the following three main steps

- Define the objective of the re-qualification
- Define the re-qualification set
- Define the decision maker

For more details of the above main steps, see TEC-T6-01.

A brief overview of tasks 2 and 3 is given in the following sections.

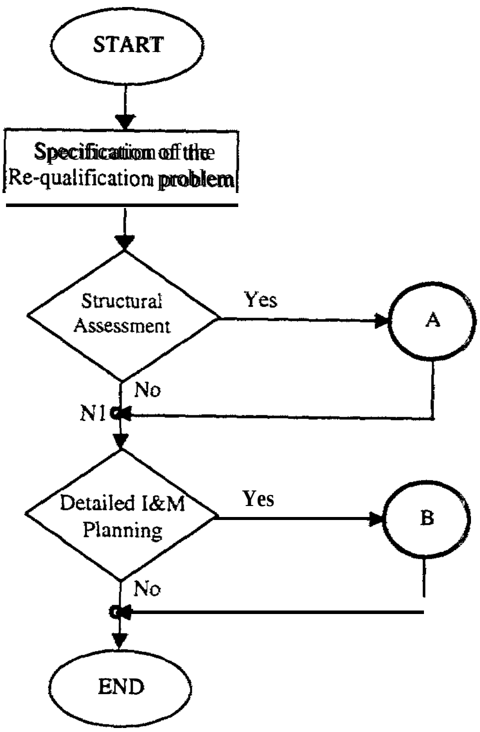


Figure 3.4 Flow chart for Decision Process for Re-qualification of Structures

3.2.2 *Structural* Assessment

The decision process for "structural assessment" is shown in Figure 3.5 and Figure 3.6. A detailed discussion of the basis of this approach can be found in the report TEC-T6-01, herein a brief summary is given.

The most common reason for re-qualification of an existing structure is when there is a doubt about the safety of the structure. The evaluation of the safety will in general first be assessed using simplified methods based on conservative assumption e.g. using conservative values for the properties of materials and loads and a conservatively set of safety acceptance criteria. If the structure fails this safety check, more advanced methods, such as non-linear methods or reliability analysis methods could be used. The methods and the safety acceptance criteria could be further refined by collecting material and loading data specific to the structure (thereby reducing the uncertainty in these values) and by considering the past performance of the structure. This reasoning forms the basis for the proposed complexity-level approach, which is used for assessing the safety of the structure.

If the structure in its present condition still fails the safety check, alternative remedial/ mitigation measures or reduction in the function will need to be assessed. In this case, ail the governing factors should be considered, as the alternatives will have different consequences in terms of risk to people, to the environment, the assets, costs, etc. This thinking forms the basis of the proposed staged approach.

The re-qualification procedure should be based on a formal decision-theoretic framework, in which the objective in each stage of the analysis is to identify the “optimal” solution according to the chosen criteria. When only one alternative is considered (for e.g. use "as-is”) it is implicitly assumed that it is the optimal option.

In order to make the re-qualification procedure simple, the stages of the analysis are arranged in such a way that the first two stages do not require the use of advanced decision analysis tools. The complexity levels for the evaluation of attributes within each stage are divided into: simplified methods, state-of-practice methods and state-of-the-art methods. Advanced methods are used only when the decision to re-qualify the structure cannot be made using simplified methods.

In summary, the stages may e.g. be as indicated in the following:

Stage O: A preparatory stage which does not result in a decision

Stage 1: Only the ‘as-is” alternative is considered with the constraints on minimum acceptable safety and durability for the structure.

Stage 2: If the structure cannot be re-qualified during Stage 1, a number of minor remedial/mitigation measures are considered in Stage 2 which are evaluated using cost criteria and constraints on safety, durability, and other factors.

Stage 3: If the re-qualification during Stage 2 fails, the Stage 3 is initiated in which a number of extensive remedial/mitigation/replace/abandon alternatives are considered. A number of criteria are used for evaluating the alternatives.

Within each stage, the attributes are evaluated using methods of increasing level of complexity, which are broadly grouped as:

Complexity-level 1: Simplified methods

Complexity-1evel 2: State-of-practice methods

Complexity-1evel 3: State-of-the-art methods

By going from one complexity-level to the next the constraints and the measures of the attributes will in general need to be revised. For example, the safety constraint may be defined in terms of partial safety factors for deterministic methods {Complexity-1evel 2), while for probabilistic methods (Complexity-level 3) it might be defined in terms of the probability of failure. This is formally a part of the problem formulation. The alternatives, attributes/criteria and the constraints also need to be re-formulated when going from one **Stage to the next in** the re-qualification process. The applied methods and the associated safety criteria for each Complexity-1evel of analysis should be established in such a way that if the structure passes a lower Complexity-level method it will also pass in all the higher Complexity-level methods. The higher Complexity-level methods are supposed *to* reduce conservatism and provide more confidence in the estimated safety of the structure.

Within each stage, a formal decision analysis is performed in order to define and evaluate the decision problem and if possible select a proper decision alternative (actions) or interrupt the process in the current stage and initiate the next stage.

The main steps involved in the decision analysis have been defined as;

- Formulation of the Decision Problem:

  A decision problem will in general involve choosing between alternative courses of act. Hereby, the selection of appropriate attributes for the alternatives to be used in the decision analysis is an important task since the final decision is totally dependent on these attributes. Further, it is important to identify all constraints and the uncertainty associated to them at the beginning of the re-qualification study since the optimal decision will usually depend heavily on these constraints.

- Evaluation of Attribute Values:

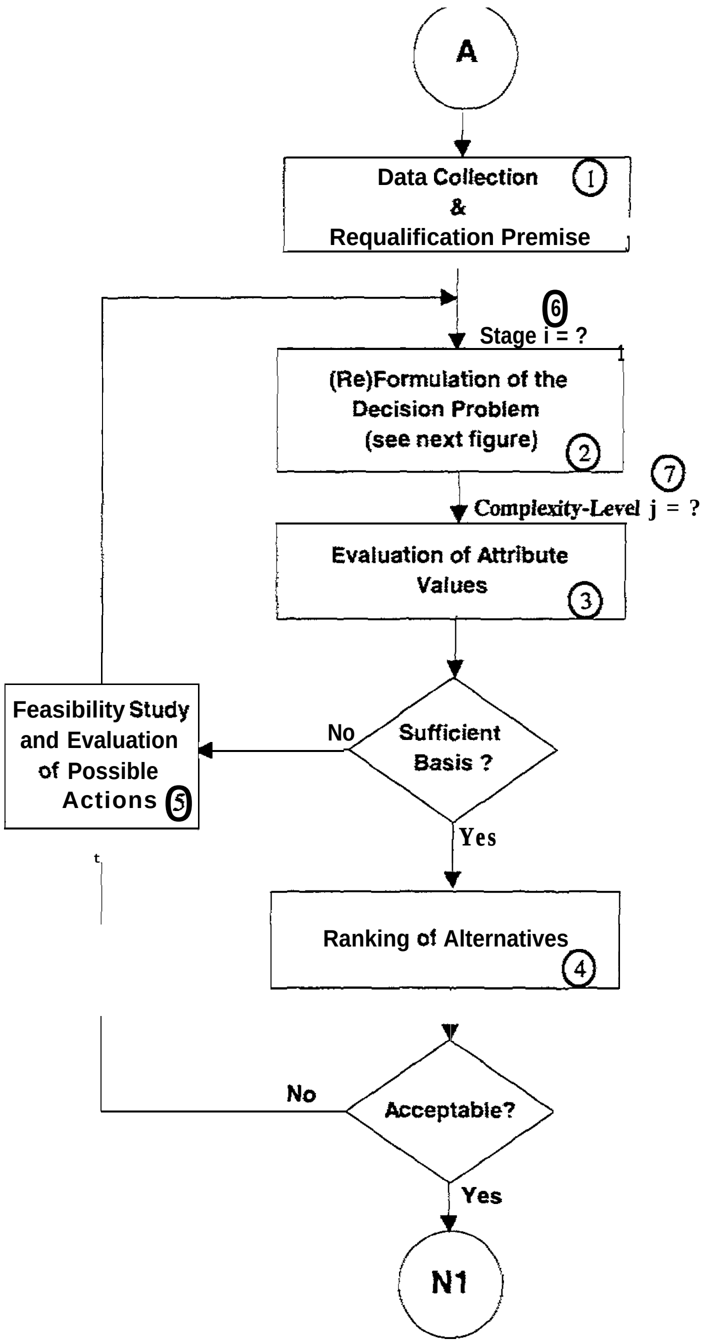
  For the success of the structural assessment process it is important to make sure that each attribute value in the attribute model represents the decision maker's preferences. The attribute values are in general modelled using two different categories of input data, the basic variables and the derived quantities. In the determination of the attribute **values the time** aspect must be considered.

- Ranking of Alternatives:

  The attribute models must be examined to see whether they provide a sufficient basis for and the necessary confidence to proceed with the decision analysis. If not, a number of actions are considered to improve the situation. After the necessary actions are taken, a decision has to be made about whether to re-compute the attributes using methods of higher complexity or to use a higher Level decision analysis for evaluating attributes.

  If sufficient basis for the decision analysis is found, the decision analysis may, depending on the level, involve a direct selection of the "as-is" alternative or a ranking of alternatives based on one attribute or the use of multi-criteria decision analysis techniques.

  Based on the ranking of alternatives and the sensitivities from the decision analysis, the best alternative is selected. This alternative is evaluated by the decision-maker to see if it is feasible and acceptable. If the proposed alternative is acceptable, an optimal I&M plan may be developed to ensure that the assumed structural condition is maintained during the remaining service life of the structure. If the proposed alternative is not acceptable, a feasibility study is carried out to see whether it is beneficial to use a more advanced method **for computing the attributes and to go to the next complexity level or whether the decision analysis** should instead be refined.



NOTES :

1. Data Collection
- **Existing** Documentation
- Review Service History
- Condition Survey
- Data/modes for prediction of present and further condition

2. Formulation of the decision problem:
- **Analyze** decision problem
- Specify the decision constraints
- Formulate decision altern ativ es
- Select and formulate the decision criteria/ attributes

3. Evaluation of attribute values:
- **Determine** attribute models
- Identify problem variables
- Collect data and identify/quantify uncertainties
- Evaluate attribute values and/or fuzziness and/or probability distributions for alternatives
- Eliminate non-compliant alternatives

4. Ranking of Alternatives:
- Specify single- or multi-attribute formulation
- Determine Preferences of DM
- Determine ranking method
- Choose solution method and software tool
- \+ Calculate ranking measures and rank/select between decision alternatives
- Evaluate the decision process and the selected choice

5. **Feasibility Study& Evaluation of Possible Actions:**
- More data ?
- More refined analysis ?
- New 1&M plan ?
- Operation restrictions?
- Reassessment of target safety ?
- Estimate effects/cost of actions
- Update/re-establish input parameters for analysis ?
- New Stage ?
- New Complexity-Level ?

6. **Possible Stages:**
- Stage-1: "As Is" Evacuation
- Stage-2: Minor Actions
- Stage-3: Major Actions

7. **Possible Complexity-Levels:**
Level-l: Simplified Methods
Level-2 : State-of-Practice Methods
Level-3 : State-of-the-Art Methods

Figure 3.5 Flow-Chart-A: Structural Assessment

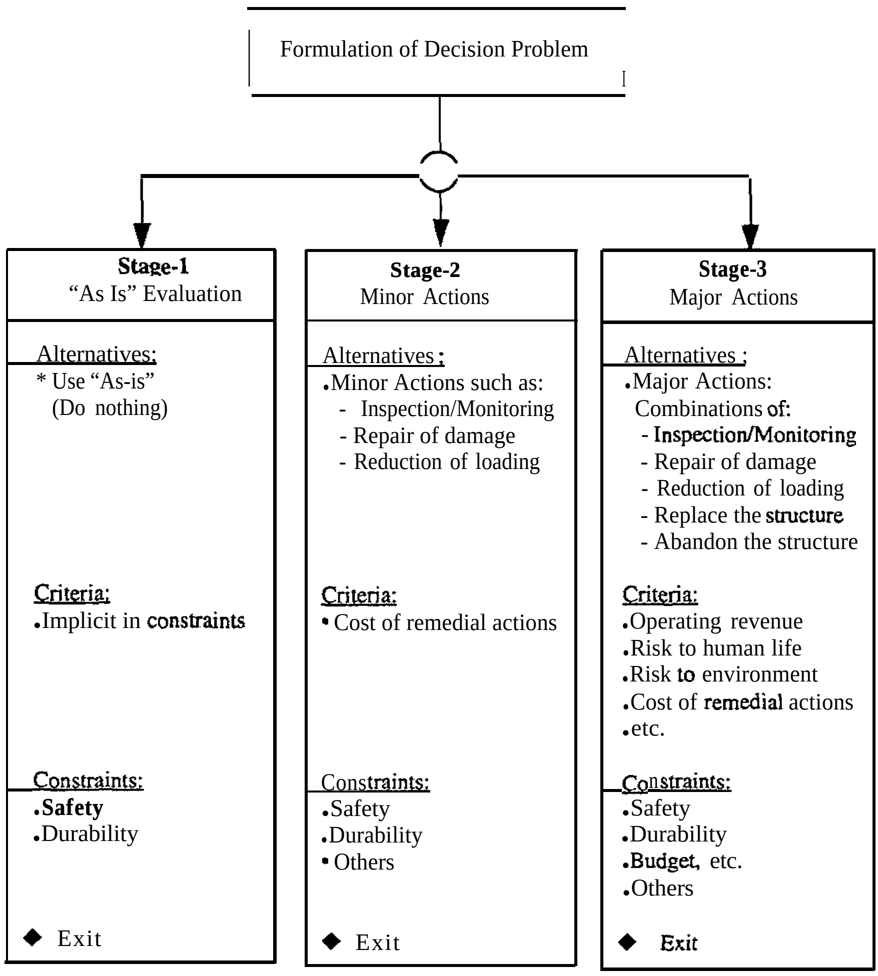


Figure 3.6 Typical Alternatives, Criteria and Constraints for the possible stages "as is", "minor actions" and "major actions".

3.2.3 ***Detailed Inspection & Management Planning***

The I&M should in general be seen as a part of the re-qualification process. However, for practical applications, it is in general sufficient to include a rough estimate of I&M costs for each alternative in order to reduce the computation time. An optimal I&M plan and the corresponding consequences for the selected re-qualification alternative is then developed in a more detailed study. The result of the detailed planning must be compared to the simplified approach to evaluate whether the difference might change the ranking of alternatives.

The optima! planning of I&M is an important consideration for existing structures as the costs involved can be quite high. The basic objective of I&M is to control the deterioration of the component/structure to ensure its long-term safety and functionality. The I&M is a continuous process of in the most general formulation determining numbers, times and qualities of inspections and inspection techniques and determining maintenance strategies. Thus, the planning for inspection and for maintenance are inter-linked. Maintenance works are planned based on the findings from inspections. The maintenance works carried out on a component influences its future deterioration and hence its inspection schedule. However, for reasons of simplicity, the planning can be done separately for inspection and maintenance if the interaction between the two is taken into account, Formulation of inspection/maintenance problems is to a large extent structure dependent and will be discussed in more details in separate reports for each of the three application areas of the RESTRUCT project.

Inspections in general are used for various purposes but the consideration here is limited to inspections which are used to monitor the deterioration of components. I&M planning is typically carried out for individual components of a structure. System considerations might be introduced, but are in general too computation time consuming if modelling is at all possible. The planning is usually made for a 'planning period' of 1, 2, 5, 10 years or the residual lifetime of the structure depending on the type of the structure. If the planning is performed for a period covering more than one normal inspection/maintenance cycle, the costs can in general be reduced and resources (finance and equipment) can easily be mobilised for the purpose. Often the I&M planning is governed by resource and other constraints, e.g. due to legislation, and these need to be modelled carefully for each application.

A general decision process for I&M is outlined in the form of flow-chart in Figure 3,7. The general activities involved are discussed in more details in the commentary.

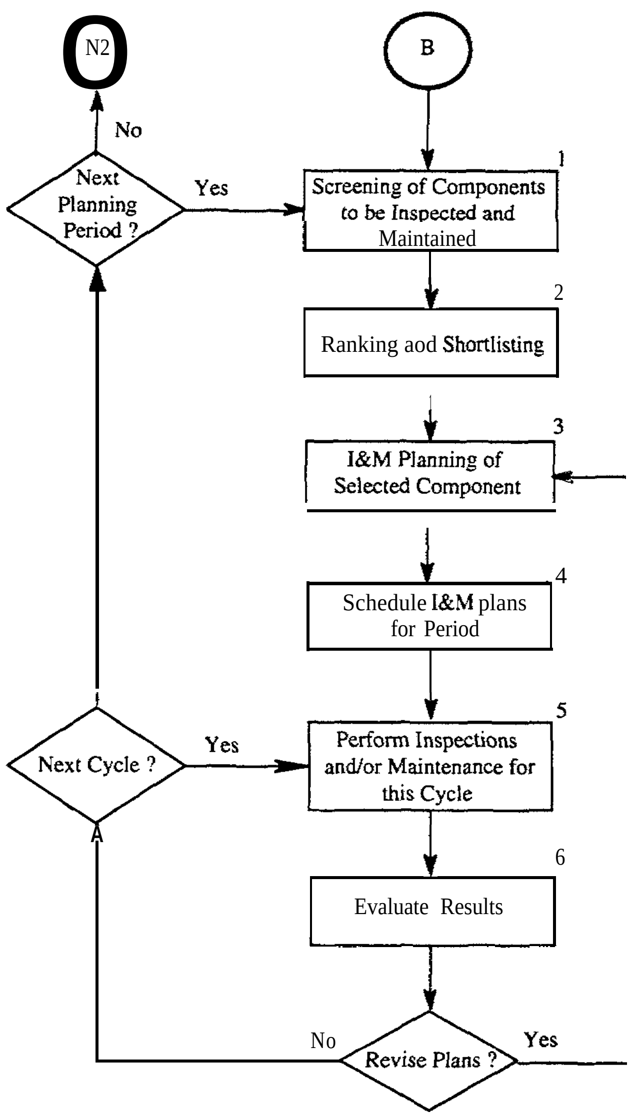


Figure 3.7: Flow chart 6: Decision Process for Detailed I&M planning

3.3 *Tools*

The prototype Decision Support System (DSS) developed under task 7 basically implements the unified decision-theoretic framework developed under task 6 into a software system. Links are being developed with the required data bases and engineering analysis tools in the respective areas to realise a fully operational and commercial DSS. This will preserve the knowledge gained within the project in an active other-than-paper form and ensure its future application. The basic architecture of the DSS is shown in Figure 3.8.

It consists of the following five sub-systems

1. Databases
2. Hypermedia based information system
3. Engineering Analysis Tools
4. Decision Analysis Tools
5. Intelligent front-end

To enable the user to save the results from MCDM analysis, Decision problem modelling and more into one session file one overall BE5935 session module has been established. All modules in the system can be started from the BE5935 module. Further, there is a possibility to store specific comments for one session by using the integrated notepad from the BE5935 module.

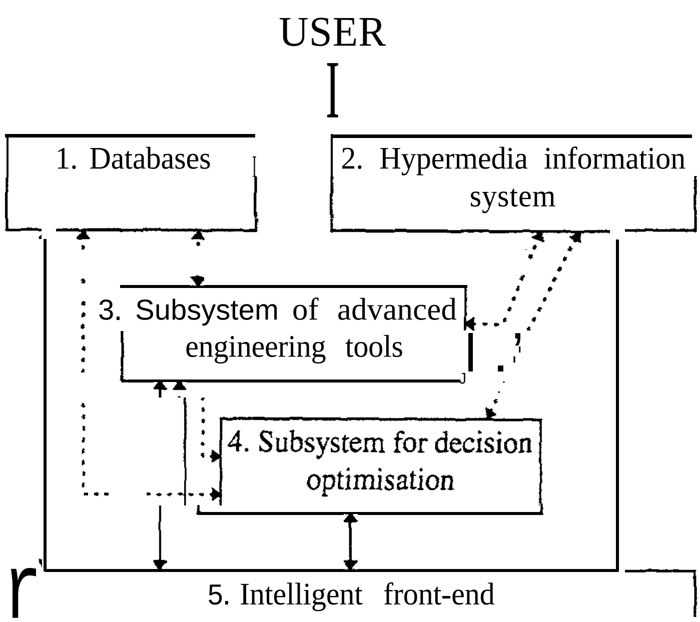


Figure 3.8 Structure of the decision planning optimisation system

The three main modules, in the following characterised as “Foreground Tools”, are the intelligent front end, the hypermedia based information system and the decision analysis tools, The tools made available to the project by the partners and the databases can be used as an additional support in the system and will in the following be characterised as “Background Tools”. To enable the user to save the results from MCDM analysis, Decision problem modelling and more into one session file one overall BE5935 session module has been established. All modules in the system can be started from the BE5935 module.

Further, there is a possibility to store specific comments for one session by using the integrated notepad from the BE5935 module.

3.3.1 *Foreground tools*

3.3.1.1 **Intelligent front-end:**

The tool allows communication between the DSS and the user enabling him to define and model the decision problem in an interactive way and to save the results from MCDM analysis, Decision problem modelling and more into one session file.

All modules including

- MCDM Module (Decision Analysis Tools)
- Documentation Base (Hypermedia based information system)
- Engineering Tools and
- Databases

are can be accessed from this so called BE5935 module (see Figure 3.9).

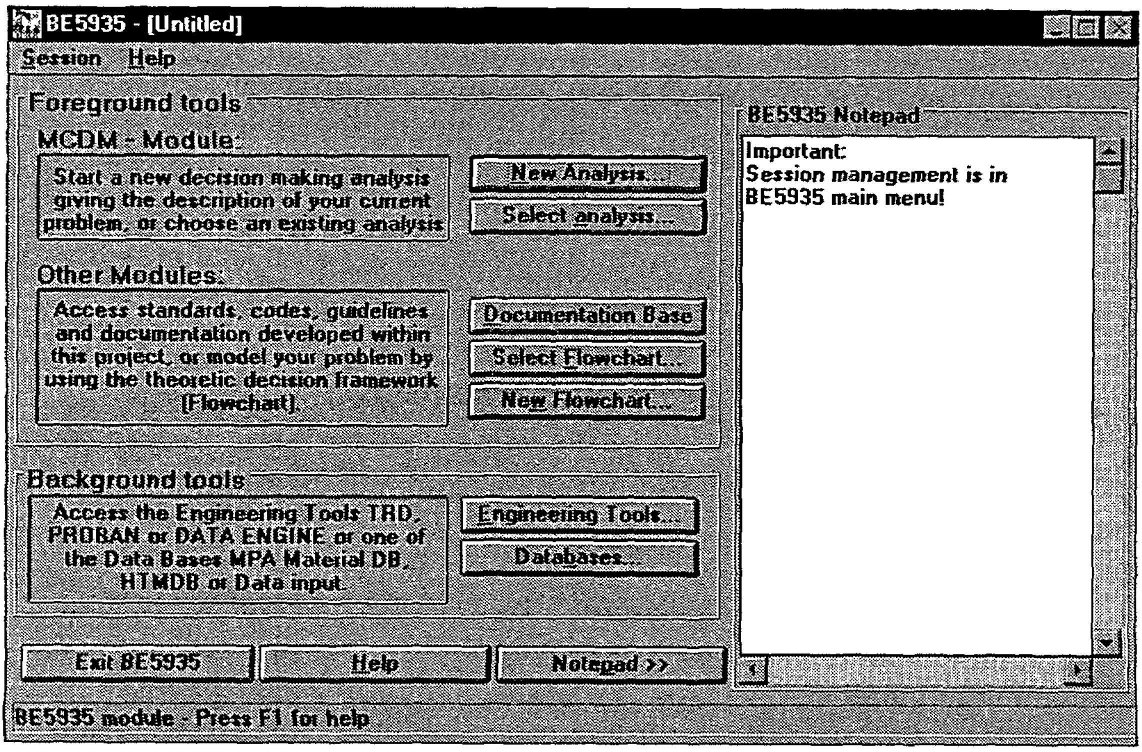


Figure 3.9 The BE5935 Module (Intelligent front-end)

Further, there is a possibility to store specific comments for one session by using the integrated notepad from the BE5935 module. The unified decision framework as well as the specific frameworks for the target areas of offshore, bridges and power plants developed within the project are all modelled by a software namely Expert Chart guiding the user through the decision problem.

3.3.1.2 Hypermedia based information system

The hypermedia based information system holds all the information relevant for the decision-making, for example standards, codes, guidelines and documents developed within this project in a form readily accessible to the decision-maker. This wilt be of considerable help during the modelling and solution of the decision problem and in providing justifications for the results. The module is developed by the means of a commercial hypermedia based information system prototype called "E-Publish".

3.3.1.3 Decision Analysis Tool

For the needs of the optimisation of the inspection planning in power plants a general MCDM software tool has been developed, implementing the general methodology of RESTRUCT. Thus, all ranking problems for all three application areas can be modelled with the same tool. In the following, some of the major features of the software tool will be described in detail.

The software tool is a Microsoft Windows based program, developed in the Visual Basic language, able to create and handle a database with all the relevant data needed to solve a MCDM problem (alternatives, criteria, criteria weights). Furthermore it can perform calculations according to the general RESTRUCT methodology and to present and save the results.

When opening a database previously created by the program, a form like the one in Figure 3.10 will appear:

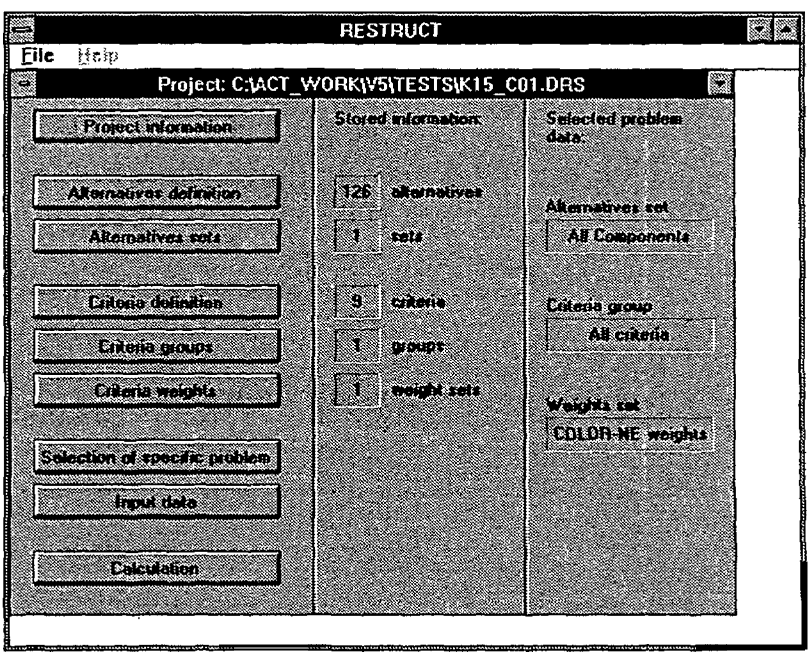


Figure 3.10 Main window of the general MCDM module

The left part of *Figure* 3.10 is representative of the structure of the *used* methodology. The buttons appearing in this left part represent the steps that should be performed in order to solve any MCDM problem:

1. Project information
2. Modelling of the problem (Definition of alternatives and sets of alternatives, definition of criteria, sets of criteria and corresponding weights)
3. Selection of specific problem
4. Input data
5. Calculation

Comparing with the methodology structure only small differences are to be found:

- The determination of the criteria weights is placed in the modelling of the problem instead of being in the input data step. This is done because, for the ranking problems analysed within this project, the criteria weights were pre-defined. However, the user may change everything he likes.
- Some extra steps are used. The "Project information" is the equivalent to the title of a report. The "Alternatives sets" and "Criteria groups" are closely related to the extra step "Selection of specific problem". These extra steps are needed to model situations like the situation in a power plant, where we have a big number of components (alternatives) that should be grouped according to the system and subsystem they belong (Block j - Piping k, Block j - boiler m, etc.). Furthermore, they increase the usability of the software. By the "Selection of specific problem" the user has then to select one set of alternatives, one group of criteria and one of the corresponding sets of weights so as to proceed with the data input and the calculation.

In general, one can structure the defined alternatives and criteria according to Figure 3.11:

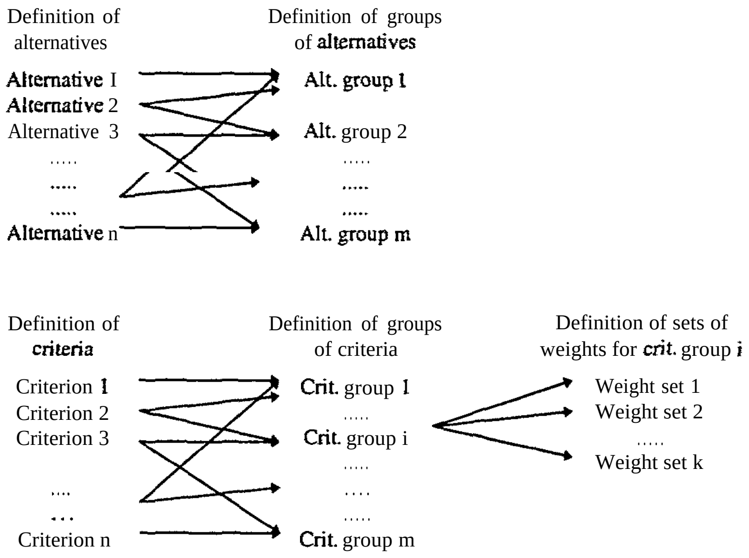


Figure 3.11: Possible structure of alternatives and criteria

After selecting a specific problem, in other words a certain set of alternatives, a group of criteria and a corresponding set of weights, and after completing the input phase, one can

continue with the calculation. Thereafter, the output is presented in the form of tables and bar-charts. Typical outputs for an IVO-steamline are shown in Table 3.1 and Figure 3.12.

Table 3.1 Ranked alternatives for the IVO-steamline 2RA12

Alternative	COA	A	B	C	D
2RA12Z205	64.094	60.715	62.968	65.220	67.472
2RA12Z204K1	45.822	44.686	45.443	46.200	46.9.57
2RA12Z204K2	45.822	44.686	45.443	46.200	46.957
2RA12Z292	42.937	39.448	41.774	44.100	46.426
2RA12Z294	37.003	34.132	36.046	37.960	39.874
2RA12Z203	33.948	32.231	33.375	34.520	35.665
2RA12Z813	33.657	31.248	32.854	34.460	36.066
2RA12Z807	28.603	26.692	27.966	29.240	30.514
2RA1277	26.874	25.295	26.348	27.400	28,452

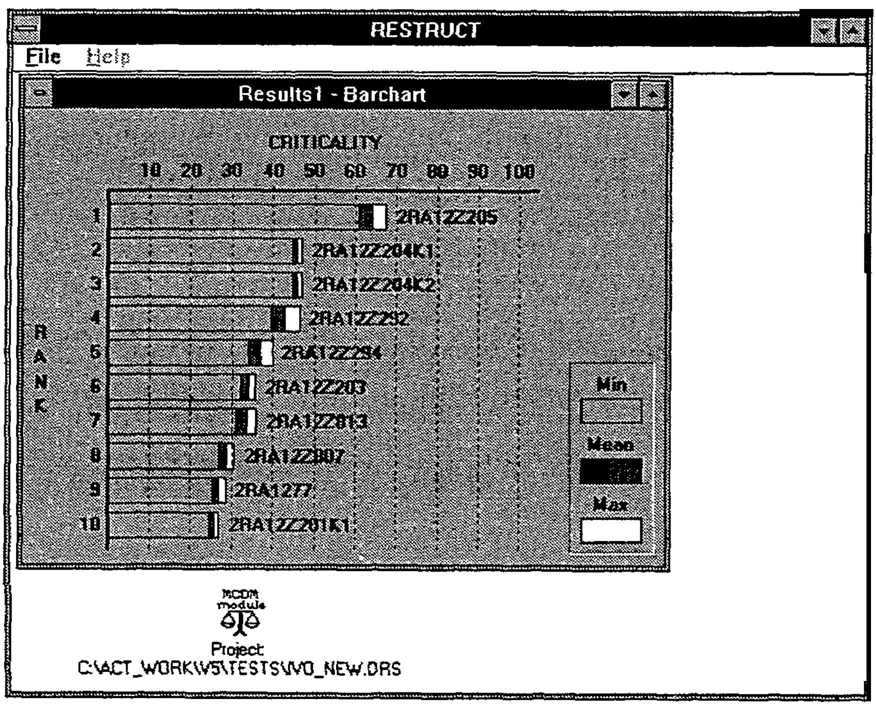


Figure 3.12: Ranked alternatives for the IVO-steamline2RA12 (Barchart)

3.3.2 *Background tools*

3.3.2.1 Databases

To make the access to standard material property data for the analysis of the decision problem possible, the structural data bases

- **MPA Material DB and**
- **HTMDB has been included in the DSS Data Bases Module.**

The DSS provides appropriate links for connecting existing data bases developed in this project such as

- COLOR and
- ISTRA databases.

The required data and data bases has been made available by the partners during the execution of the project.

3.3.2.2 Engineering Analysis Tools

A number of analysis tools, for example for the evaluation of loading, capacity of structural components, deterioration and for the evaluation of safety and reliability of structural components and systems will be used within a decision process. These tools are made available to the project by the individual partners such as

- TRD (Technische Regel für Dampfkessel)
- PROBAN and
- Data Engine

Appropriate links are defined in the DSS for connecting these engineering tools.

4 Exploitation plans and follow-up actions

The results will be used for the target areas of offshore, bridges and power plants. Each field of application will have its own customised commercial version of the results as the decision is dependent on the background information which is very application-specific.

Initial exploitation scheme (Figure 4.1) established in the Work Program me has been examined more in detail in the reporting period: possible steps for implementation of the "after - BRITE" phase have been examined among the partners and also with the monitoring off icer.

Atkins, AGIP, Snamprogetti, D'Appolonia, COWI and DNV are going to use the results of BE 5935 for in-house purposes and consultantcies.

MPA will use the results for development of a tool for power plants. MPAs sponsors use them only in-house. MPA will follow up the results of RESTRUCT with the already proposed BRITE EURAM project COPIN - BE95-1 566 (Cost-Effective Integrated Optimiser for Planning of Power Plant Inspections), This project will be re-submitted in the second call after being B-Rated in the first call.

MIT's aim is the development of a general tool, applicable also for areas outside this project {a “shell”).

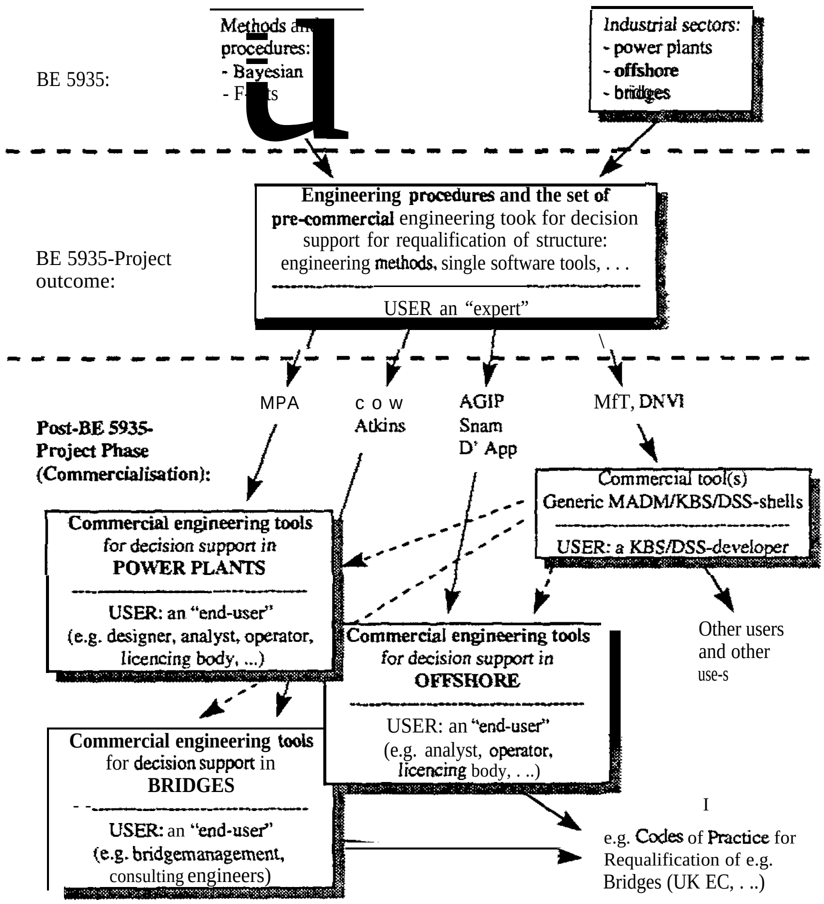


Figure 4.1: **From BE 5935 development to pre-competitive BE 5935 outcome and further, to commercialisation**

5 Collaboration sought

Generally, the collaboration sought by partners should help to

- maintain and
- further develop

the methodology and, especially, tools developed in BE 5935. This means that collaboration with Potential further end-users, both in original BE 5935 areas (off, br, pp) and in other areas (e.g. process plants) is sought in order to support this kind of activity and, through involvement of their particular experience, assume broader applicability and tools.

Another type of collaboration is sought for

- external exploitation and
- commercialisation

of the system. For this purpose, collaboration with service and country organisations, as well as with software houses could be beneficial.

Many of these issues are tackled by the exploitation plans and/or agreements of the BE 5935 partners already.

6 References

Publications resulting from the project:

Høj, N P: QRA of Failure for Structural Decision Making, "Structural Engineering in consideration of Economy, Environment, Energy" 15th Congress of IABSE, Copenhagen, Denmark, June 16-20, 1996

Jovanovic, A., Auerkari, P., Kautz, H. R., Schwarzkopf, Ch., Psomas, S. M., (1994a) 'Computer-aided inspection planning of high temperature piping in fossil-fired power plants", American Society of Mechanical Engineers (ASME), New York, ASME paper 94-JPGC-PWR-36.

Jovanovic, A., Psomas, S., Bath, U.,(1 993) "BRITE-EURAM BE5935: Decision making for requalification of structures -power plants-", SMiRT 12, Post Conference Seminar Nr. 13 on Knowledge-based (Expert) System Applications in Power Plant and Structural Engineering, Constance Germany, Aug 23-25, 1993.

Jovanovic, A., Psomas, S., de Witte, M., Bath, U., (1993a), "Development of an integrated system for decision optimization in power plants maintenance", in: Proceedings of the First European Congress on Fuzzy and Intelligent Technologies, Aachen, September 1993, p.83-86.

Jovanovic, A., Psomas, S. M., Auerkari, P., (1995) "Decision support system for planning of inspections in power plants. Part I - Methodology", BALTICA III International conference on plant condition & life management, Proc. Vol II, pp. 563-579.

Jovanovic, A., Psomas, S. M., Ellingsen, H. P., Kautz, H. R., McNiven, U., Rönnberg, J., Auerkari, P., (1995) "Decision support system for planning of inspections in power plants. Part II - Applications", BALTICA III International conference on plant condition & life management, Proc. Vol II, pp. 581-596.

Jovanovic, A., Psomas, S. M., Schwarzkopf, Ch., Auerkari, P., Kautz, H. R., Rönnberg, J., (1994c) "KBS-supported planning of periodic inspections in power plants", Proceedings of the 20th MPA Seminar, Oct. 6-7, 1994, vol. 3, SPRINT/KBS Dissemination Workshops, Ed. A. Jovanovic, MPA Stuttgart, Stuttgart, Germany, paper 5.4.

Jovanovic, A., Auerkari, P., Kautz, H. R., Ellingsen, H. P., Psomas, S. M., (1995) "Intelligent software systems for inspection planning- The BE5935 project", 13th International Conference SMiRT, Applications of Intelligent Software Systems in Power Plant, Process Plant and Structural Engineering, Session IV.

Shetty, N K, Roberts, C M, Knowles, N C: Risk Considerations in Decision-Making for Re-assessment of Bridges and Planning of remedial works, "Structural Engineering in consideration of Economy, Environment, Energy" 15th Congress of IABSE, Copenhagen, Denmark, June 16-20, 1996