BRIDGELIFE version 1.1.

Part I: User Manual
Part II: Calculation principles

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PART I: USER MANUAL

1 Program Bridgelife in short

A new life cycle design tool was developed in cooperation with the Finnish Road Administration, with the purpose of providing the Finnish project level Bridge Management System with life cycle design services. Extensive work was done between the years 1998-2005 for developing and implementing the system. As a result the life cycle design tool “Bridgelife” was programmed on Microsoft Excel as a Visual Basic application. A considerable part of the development work was done during the years 2001-2003 under the auspices of the project “Life Cycle Management of Concrete Infrastructures for Improved Sustainability” (LIFECON), EC-GP-V-RTD, TRA 1.9 Infrastructures. The principles of the LIFECON life cycle management system were the following: predictive, integrated, probabilistic and life-cycle based. The program Bridgelife was implemented according to these principles /1, 2/.

The life cycle design tool ”Bridgelife” was developed for bridge owners, maintainers and designers. With help of the design tool it is possible to predict the condition of bridge components, plan the MR&R actions and calculate the maintenance costs, user costs and environmental impacts during the design period. The condition analysis of structures is stochastic and it covers the whole design period. The maintenance and repair actions can be automatically triggered based on given condition limits. The life cycle costs and the environmental impacts are automatically determined.

The main idea of the life cycle design tool is to combine the life cycle performance analysis with life cycle cost and life cycle ecology analyses with Markov Chain based condition analysis. The Markov chain method allows a continuous and probabilistic presentation of condition over the whole design period. An automatic condition guarding system is built on the condition analysis so that and the maintenance and repair actions can be automatically triggered based on preset condition limits. When the timings of maintenance and repair actions are known the life cycle costs and the environmental impacts can also be automatically calculated by the side of the condition analysis.

The program Bridgelife performes the life cycle planning either separately for each selected bridge or as a batch process. The batch process produces the life cycle plan for every bridge in the initial data file. It also produces a special output file of the analysis results. This output file is used by the main program of the project level management system “Hanke-Siha” so that the results of the LC plans can be seen on the displays of “Hanke-Siha”. In both cases the program Bridgelife uses an initial data file which is worked out by a special database routine connected to “Hanke-Siha” and using the Bridge Register as data source. The initial data contains both bridge and component specific data related to materials, structural measures and environmental conditions. In both cases the so called decision trees are used for automatic specification of MR&R actions. The decision trees take into account the specific features of the components in order to select optimal MR&R actions in each case.

In the independent use of the program the user can manually change the automatically prepared plan. The designer can freely change the definitions and timings of MR&R actions, as well as add and remove actions. The automatically prepared plan is then replaced by the manual plan when also the MR&R costs and environmental impacts are recalculated. The results of the design are obtained as tables and graphs on the screen. They can also be output on paper or stored in a separate file.

The program Bridgelife includes also a separate module for service life design of new bridges. With the help of this module bridge components can be designed so as to meet the service life requirements imposed to the bridges. The basic idea of the service life design is to make sure that the predicted service, which is calculated by the program, is longer than the design service life at the required safety level. To affect the predicted service life the designer can specify material properties, structural measures and protective measures such as coatings.

A new degradation type, crack corrosion was added to the Bridgelife version 1.1. Accordingly the degradation of structures can be evaluated based on two degradation types: surface degradation and crack corrosion. A new repair action, “Filling of cracks”, was also added to version 1.1 respectively.

Apart from the subprograms included in Microsoft Excel or macro programs included in program Bridgelife no other subprograms are used in the design process. To run the program in PC environment only Microsoft Windows XP (SP-1) and Microsoft Excel (version 2002 or newer) is required.

In the following chapters the instructions for the use of program Bridgelife are presented.

2 Guidelines for the User

2.1 GENERAL

The front page of the program Bridgelife is presented in Figure 1.

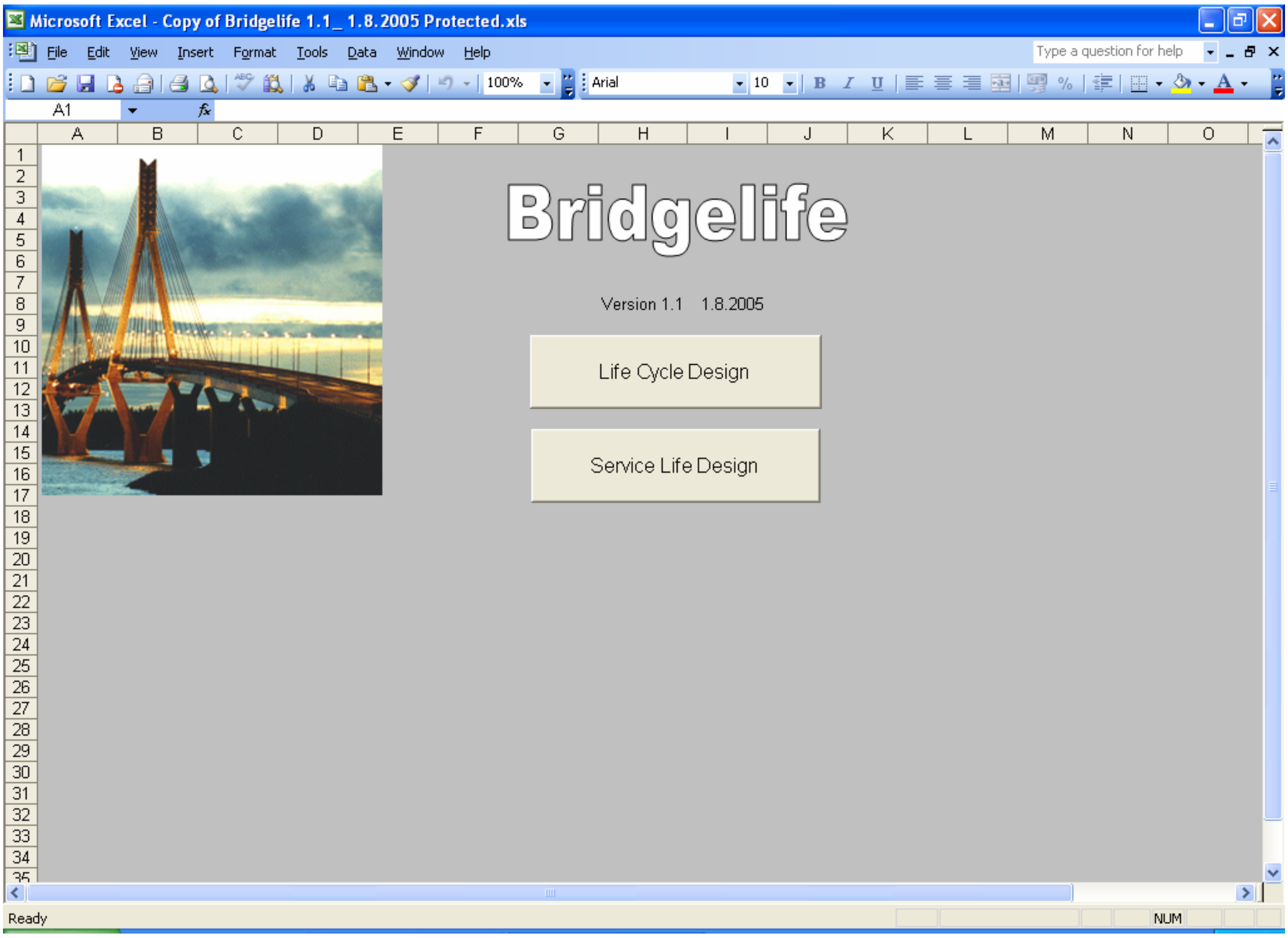


Fig. 1. Front page of program Bridgelife.

Two buttons can be seen on the front page:

- Life Cycle Design and

- Service Life Design

The user selects the program by buttons. The Life Cycle Design is for making life cycle plans for existing bridge structures. The Life Cycle Design program uses an initial data file as the initial data source for bridges and components. The life cycle design contains prediction of condition, specification and timing of MR&R (maintenance, repair & rehabilitation) actions, calculation of life cycle costs and determination of the environmental impacts from the design period.

By the Service Life Design program new bridge components can be designed so as to meet the service life requirements imposed to them with the required safety level. The program evaluates the Predicted Service Life which has to be longer than the Design Service Life with the required safety level. To influence the predicted service life the user can do choices on material qualities, structural features and protections.

2.2 PREPARATION OF LIFE CYCLE PLAN

2.2.1 Starting of Life Cycle Design

By pressing the button "Life Cycle Design" on the front page of Bridgelife, the program checks first the initial data. If it observes any faults in the initial data, the user is asked to answer the following question:

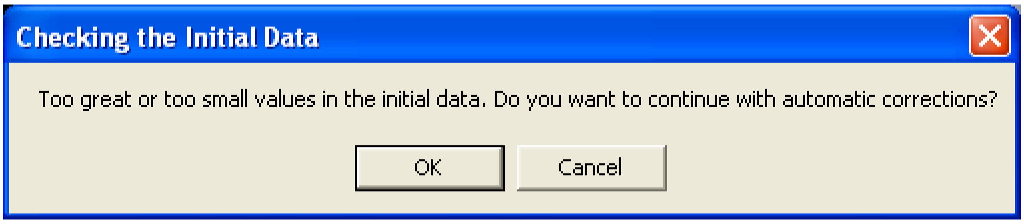


Fig 2. Announcement on faults in the initial data.

Usually it is possible to start the planning in spite of the faults in the initial data file as the program automatically performs some corrections for the faults. For instance too great values or too small values of some parameters are automatically corrected to the respective minimum and maximum values specified for those parameters. However, it is recommended to correct those data in the initial data file and then restart the program. The correction of initial data is explained in chapter 3.1.2.

Finally the Initial Data form is opened (Figure 3).

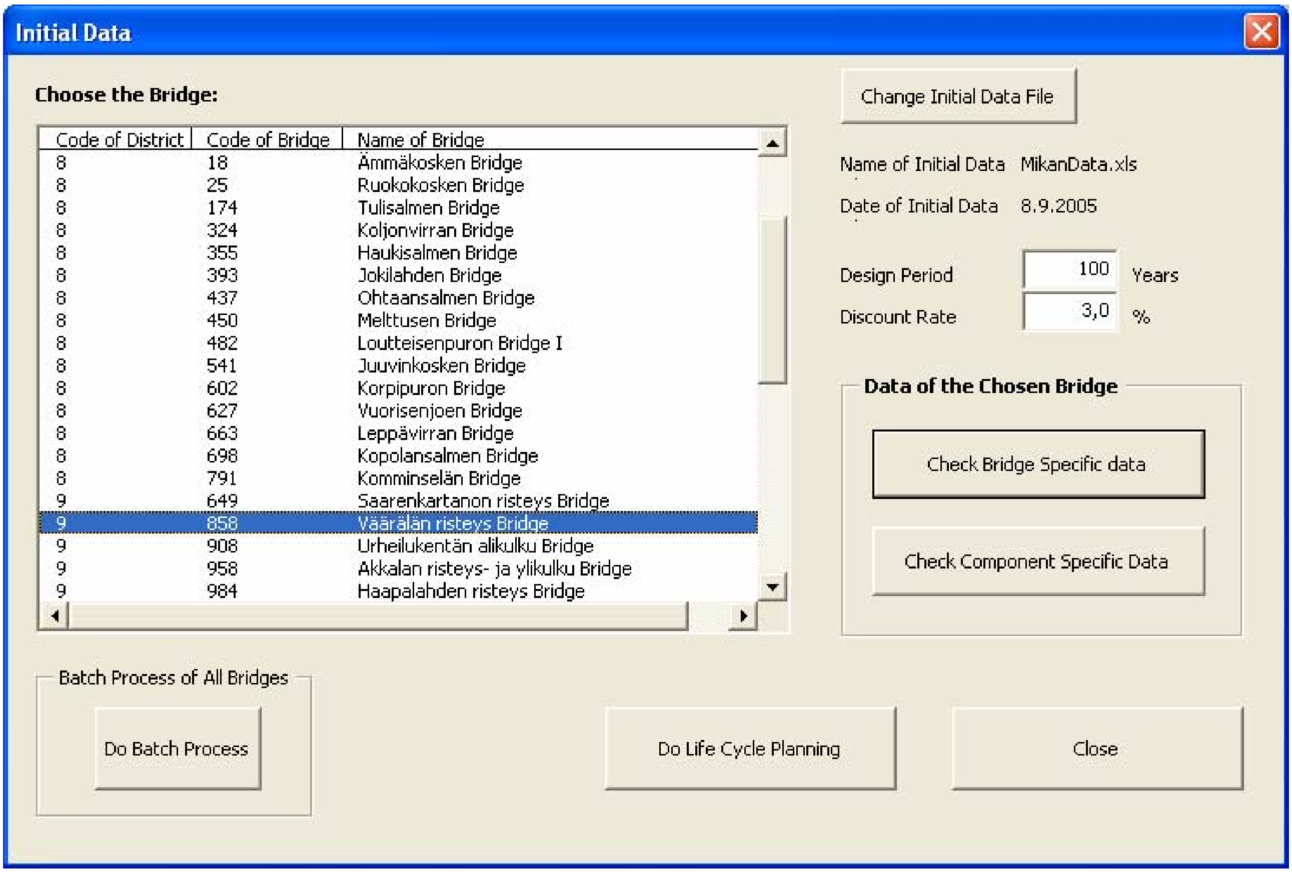


Fig 3. Initial Data Display.

On the Initial Data Display it is possible to select:

- Initial data file
- Length of the design Period
- Discount rate
- Bridge

When pressing the button ”Change Initial Data File” a directory tree is opened. From the directory tree the initial data file is chosen by the user. When changing the initial data file the data of the new initial data file is checked. The name and the date of the initial data file are displayed.

The length of the design period must be between 50-200 years. The program checks that the given design period is between this range. The discount rate must be between 0 – 15 %.

2.2.2 Checking of the bridge and component specific data

All bridges contained in the initial data file are seen in the list window. The program uses the data of the initial data file which contains all the relevant bridge and component specific data from the bridge register.

When the user selects one bridge from the list the initial data of the selected bridge can be checked, changed or supplemented before calculation by pressing the buttons in the frame ”Data of the Chosen Bridge”:

- Check Bridge Specific Data
- Check Component Specific Data

If the user of the program has some data which is not included in Bridge Register, he/she may do the changes/additions in the opening forms before calculation.

For all the initial data default values have been specified. So the program is not interrupted if any of the initial data is lacking as it automatically applies the default data instead of any lacking initial data in the initial data file.

Bridge specific data

By pressing "Check Bridge Specific Data" the following display is opened:

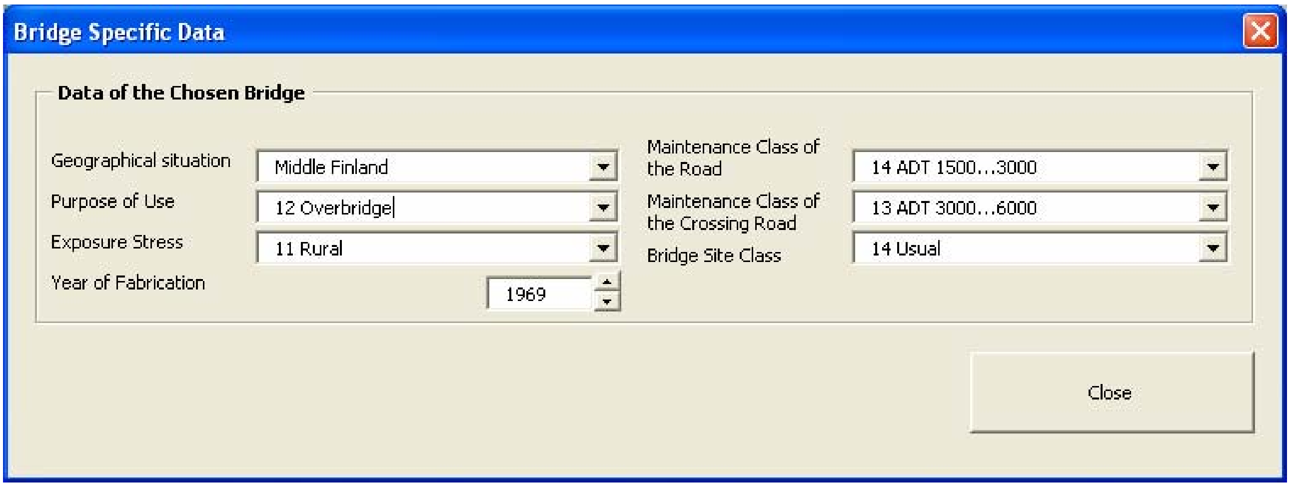


Fig. 4. Display of Bridge Specific data.

The relevant bridge specific data of the chosen bridge are presented on the display:

- Geographical situation
- Purpose of use
- Exposure stress
- Maintenance class of the road
- Maintenance class of the crossing road
- Bridge site class
- Year of fabrication

The purpose of use, exposure stress, maintenance class of the road, maintenance class of the crossing road and the year of fabrication are defined as they are defined in the Bridge Register. The geographical situation is defined as follows: (1) Coastal Finland (2) Middle Finland and (3) Northern Finland. Usually bridge specific data are not liable to changes but if necessary they can be changed on this display. The changes are not stored in the initial data file, however. They are maintained only during the calculation.

Component specific data

By pressing the button " Check Component Specific Data" the following display is opened:

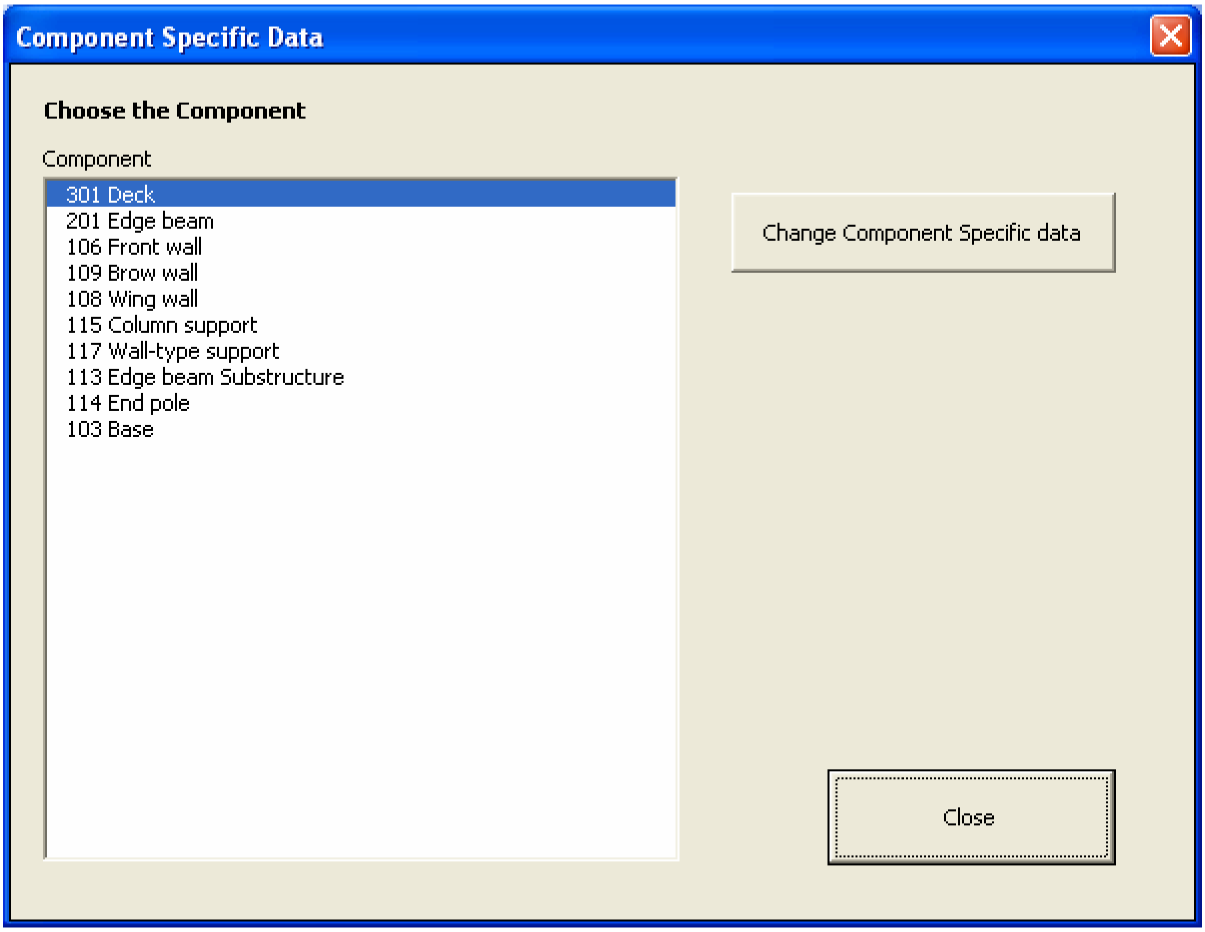


Fig 5. Display of Component Specific Data.

The list on the display shows the components of the selected bridge. As there may be several components of the same component name same identification data of these components are also presented from the initial data file. The identification data is the number of identical components (e.g. id2), the longitudinal situation and the transversal situation. The definitions of the situation are given according to the definitions of the Bridge Register. The user selects from the list a component the data of which he/she wants to check. When pressing the button ”Change Component Specific Data” the following display is opened:

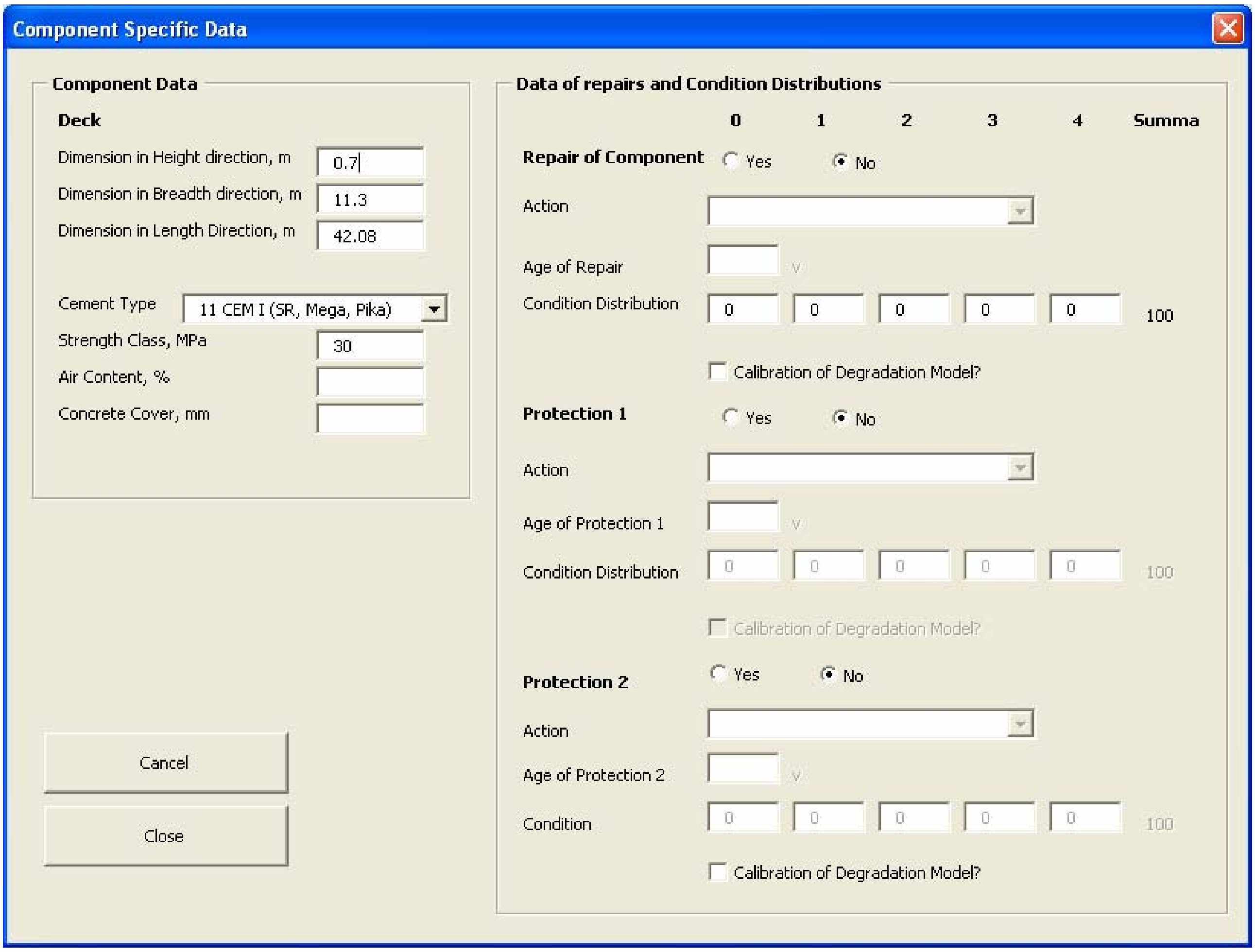


Fig 6. Display of the Component Specific Data.

The component specific data fields are presented in the frame "Component data". They are:

- Dimension in height direction, m
- Dimension in breadth direction, m
- Dimension in length direction, m
- Quality of cement
- Strength class of concrete
- Air content of concrete, %
- Concrete cover, mm

The data fields are prefilled by the component specific data of the Initial data file.

All these data are defined according to the respective data table in the Bridge Register. The dimensions of the component are defined in height, breadth and length directions of the **bridge** notwithstanding on the type or situation of the component.

The definition of cement types is presented in the following table.

Table 1. Classification of cement.

Code	Type of Cement
11	CEM I
12	CEM II/A-S
13	CEM II/B-S
14	CEM II/A-D
15	CEM II/A-LL
16	CEM II/A-M
17	CEM III/A
18	CEM III/B

The classification is according to the European Cement standard /3/.

Compressive strength of concrete, air content and the concrete cover are data items which in principle can be measured in situ from the structure. If these in situ measurements are performed it is recommended to store these data in the Bridge Register from which that they automatically will be transferred to the Initial data file of program Bridgelife. However, they can be input also from the "Component specific data" display but then they are used only for the time of calculation. They are not stored in the Initial data file.

When doing field measurements on components it is to be noted that the strength class is not the same as the average compressive strength. The strength class is closely related to the nominal compressive strength of concrete expressed as cube strength.

As the data pertaining to protections can not be input into the Bridge Register this display is the only way to transfer them into calculations. As the repair and condition data pertaining to structural components may be defective or unreliable it is recommendable to use this display to check those data. The component specific data is used for determination of the present condition and for evaluation of the degradation rate. The following data are given:

- Repaired or not (Yes/No)
- Action
- Age of the repair
- Distribution of condition
- Calibration of degradation models (check mark)

If it is known that the component has been repaired, the Yes option is chosen (Default is No). Then the list of possible actions is appeared in the data field of "Action". The action which has been used in the repair is chosen. In the next data fields the age of the repair and the condition distribution respective to the age are asked. The given condition distribution is assumed to be the same as the present day condition distribution.

The condition distribution is presented with the scale 0-4 according to the Inspection manual /4/. The fraction of structures, which belongs to each condition state is given. The fractions are presented as percentages from the whole component. The sum of all fractions must be 100.

If the designer wants that the degradation models are calibrated using the inspection data a check mark is placed in the check box "Calibration of degradation models". If no mark is placed the program uses the original degradation models to evaluate the rate of degradation.

If the option button of ”Repair of the component” is in ”No” position the program still approves of the condition distribution and the claim for calibration. In this case the program assumes that the component is never repaired during it is service life and that the given condition distribution is valid for the present day distribution. Then the age of the structure is calculated based on the ”Year of fabrication”.

As for Protection 1 the following data can be provided:

- Protection 1 (yes/no)
- Action
- Age of the protection 1
- Condition distribution of Protection 1
- Calibration of the degradation model (check mark)

If the component was protected by coatings or other protection methods under the title ”Protection 1” the “Yes” button is pressed for Protection 1 (ref. Table 3). Then all the actions belonging to Protection 1 group are appeared. The used protection method is selected. Then the age of the protection is given and the condition distribution respectively to the age. If it is desired that the program evaluates the rate of degradation of protection 1 based on the given data a check mark is placed to the check box ”Calibration of the degradation model.

The data pertaining to the group Protection 2 is given in the same way.

The informed data is put into force by pressing the button ”Close”. At this context the program performs some checks about the data given. The age of both the repairs and protections must be within the range of 1-100 years. In addition the age of repair cannot be longer than the age of the bridge. The age of Protection 2 cannot be longer than the age of the repair and the age of the Protection 1 cannot be longer than the age of the Protection 2. The program prompts a message if these rules are transgressed. Also the sum of the condition distribution percentages must be 100. Otherwise the designer is asked to correct the data.

The program stores the given data so that when returning to the “Component specific data” display and again to “Component specific data” display the newly specified data are still visible. The manually input data is lost only when the designer returns to the front page of the program.

By pressing the button “Cancel” the information given on the “Componet specific data” display is ignored.

2.2.3 Making a life cycle plan

To do a life cycle plan for the selected bridge the designer presses the button “Do Life Cycle Planning”. Then the program goes through all the components of the bridge in a row and specifies the MR&R actions using the decision trees and gives timings to the actions using the automatic condition guarding system. The program also automatically combines actions that are close to each other to the same year thus planning preliminarily the “projects”. So the program may slightly change the component level optimal timings of actions to synchronise with project level optimal timings.

The reason for reorganising the MR&R actions into projects is that the optimal timings for various actions (for various components) will scatter too much. Project planning based only on the component level optimal timing of actions would result in too many small projects to be executed for the same object. So the optimisation in the preliminary project planning is performed from a wider perspective than at the component level winning economic savings by synergy profit.

By the button “Close” the program returns to the front page.

The process of making the life cycle plan is better described in Part II: Calculation principles.

2.2.4 Results

As a result of the calculation process the Results form is opened. On the Results form the designer can:

- see the component specific results of planning
- see the bridge specific results of planning
- do manual changes to the life cycle plan and
- print the results of the life cycle planning on paper or to store them in another file.

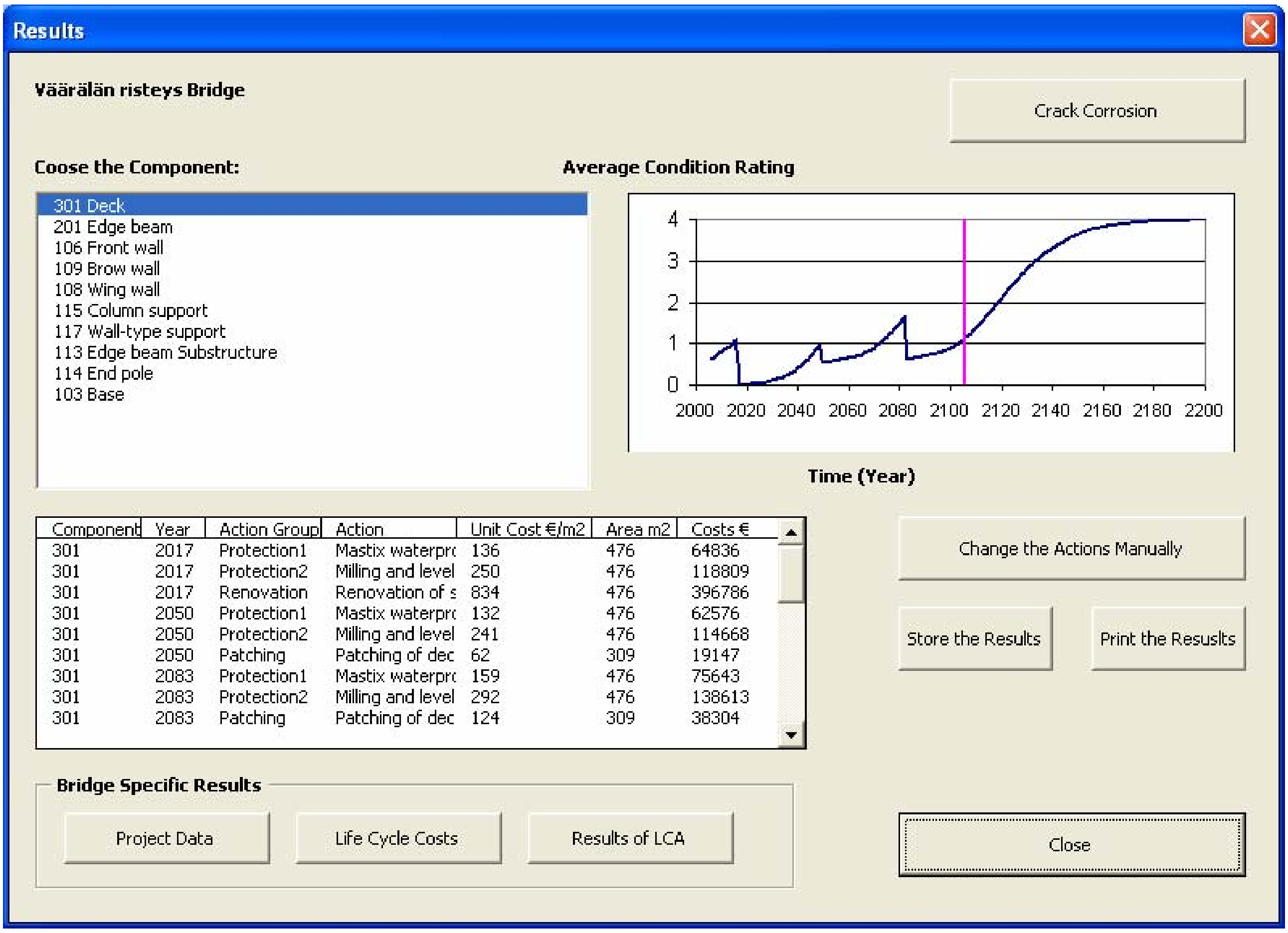


Fig. 7. Results display.

Component specific results

At the upper left corner of the Results form the list of components of the selected bridge can be seen. When the designer selects one of the components by the mouse the list of MR&R actions pertaining the selected component is updated in the middle of the frame. The following data is presented in the list of actions:

- Component (code)

- Year
- Action Group
- Action
- Unit costs
- Surface area and
- Costs

At the upper right corner of the form a graph of the average condition rating (condition state) over the design period is presented. The graph shows how the degradation and different MR&R actions affect the condition with time. The condition in this figure is evaluated with respect to the “surface damage” which is a combination of frost attack and general corrosion of reinforcement. Surface damage is evaluated based on the amount of scaling and spalling of concrete (as a result of frost attack and corrosion of reinforcement) and the resulting reduction in structural performance. However, the condition of the component is evaluated with respect to another damage type too. The damage type ”Crack corrosion” is evaluated based on the corrosion of reinforcement at cracks as the relative loss of the cross sectional area of steel bars of the main reinforcement. The loss of the cross sectional area in main reinforcement affects directly on the bending capacity of the component.

The red line in the figures shows the end of the design period.

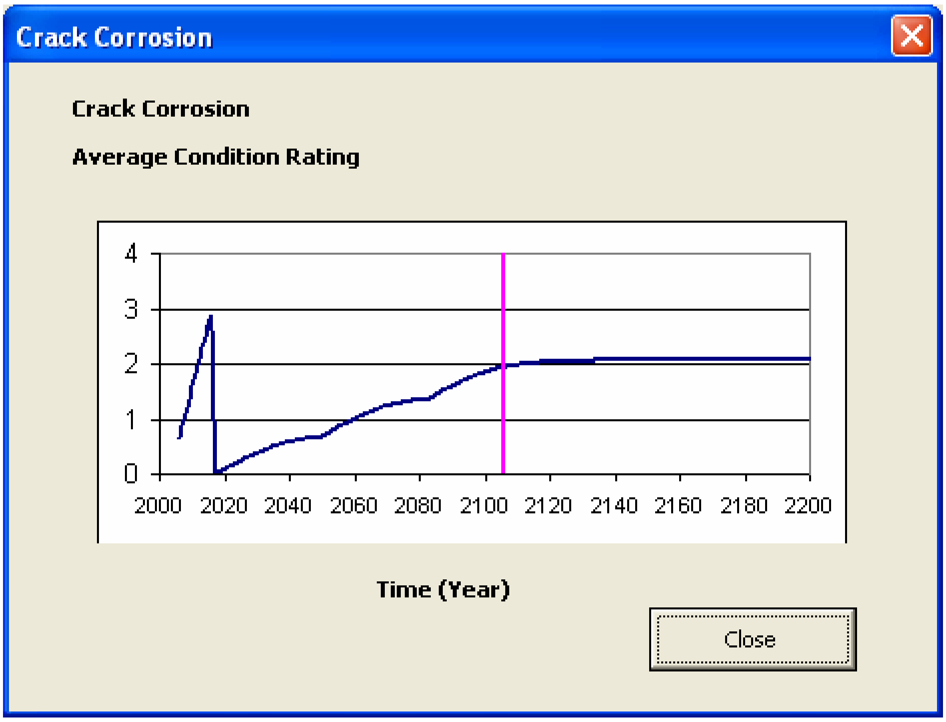


Fig 8. Display of “Crack Corrosion”.

By using the automatic condition guarding system the condition of the structure never exceeds preset condition limit because the system automatically triggers the repair action at the condition limit.

Bridge specific results

At the lower edge of the Results form there is a frame with the title ”Bridge specific results”. Within the frame there are three buttons:

- Project data
- Life Cycle Costs and
- Results of LCA

By pressing the button "Project data" the “Projects” display is opened (Figure 9):

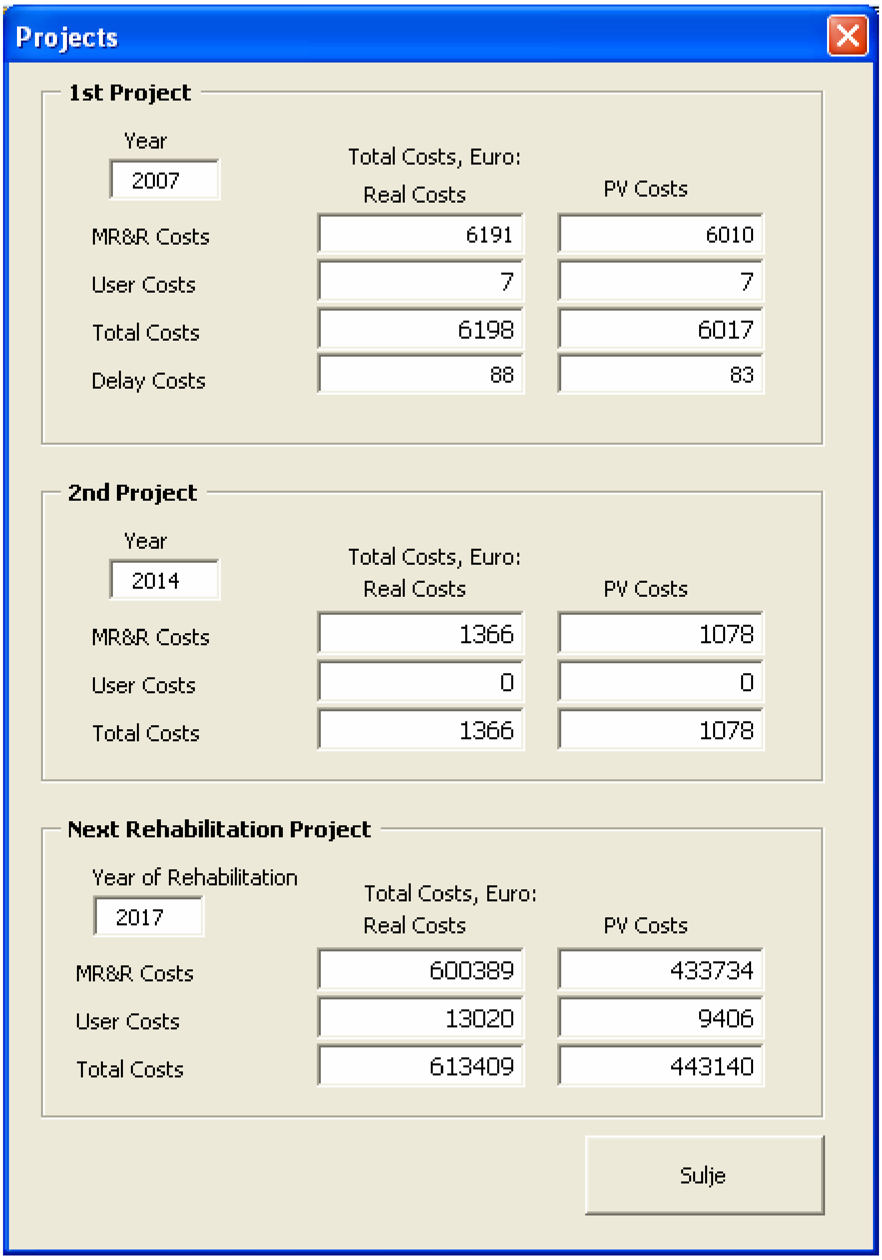


Fig 9. Projects display.

The data of pertaining to the following projects are presented:

- 1st project
- 2nd project
- next rehabilitation project

The MR&R costs, user costs and the total costs are presented from each project. The total costs mean the sum of the MR&R costs and the user costs. From the first project also the delay costs are calculated. The delay costs refer to the extra cost that the agency has to pay if the project is postponed by one year. All costs are calculated as real costs and present value costs. The present value costs are discounted costs using the given discount rate.

By pressing the button "Life Cycle Costs" The Life Cycle Costs display is opened (Figure 10). On that form the cumulative life cycle costs of the selected bridge from the selected design period are presented. Also the average annual costs are presented. The MR&R costs and user costs are shown as real costs and present value costs.

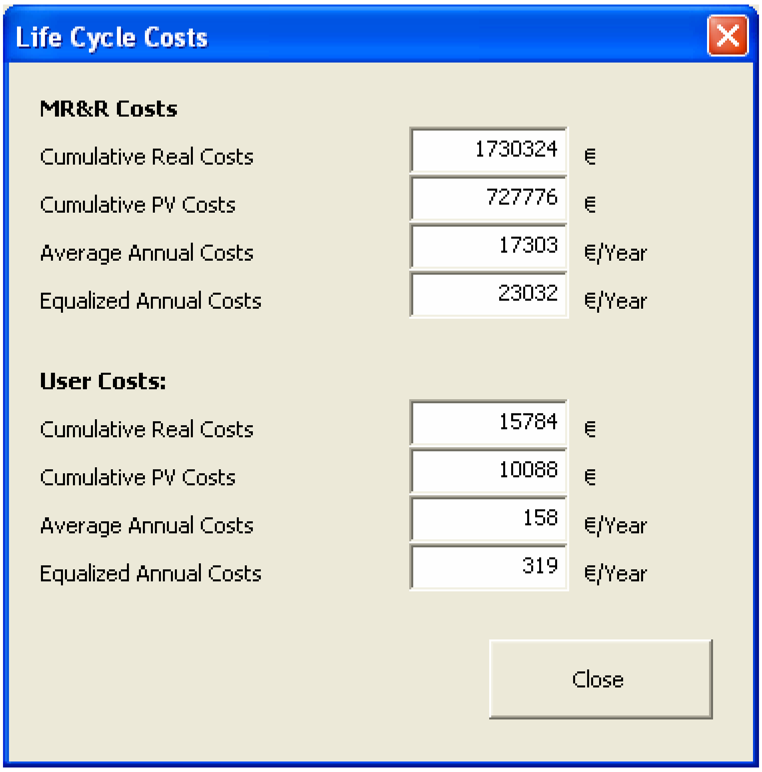


Fig 10. Life Cycle Costs display

By pressing the button "LCA Results" a frame with the same title will open. On that the total environmental burden from the whole bridge and from the whole design period is presented. The burden is separated as follows:

- Renewable Energy, GJ
- Non-renewable energy, GJ
- CO_2, kg
- SO_2, kg
- NO_x, kg
- Particles, kg
- CH_4, kg
- Mineral raw materials, kg and
- ELU, Euro

ELU is an environmental index, which is determined based on the releases, see Pat II: Calculation principles.

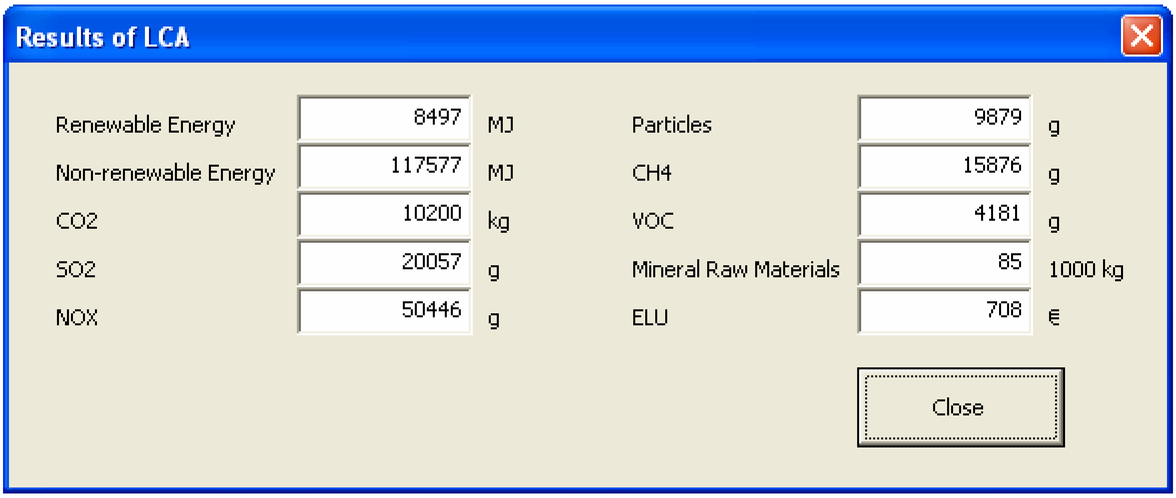


Fig 11. Results of LCA display.

On all bridge specific displays the ”Close” button returns the view on the ”Results” form.

Paper output and storing the results

By pressing the button ”Print the results” the life cycle plan is printed on paper. An example of the output is presented in Chapter 3.2.1 "Example of results".

The prepared plan can also be stored in another file. This is possible by applying the button “Store the results”. When printing the button a directory tree is opened by which the address and the name of the file can be determined. The results data are stored in the specified file (see Chapter 3.2.2).

By pressing the ”Close” button on the ”Results” form the ”Initial Data” form will return on the screen.

2.2.5 Doing Manual Changes in the Life Cycle Plan

The automatically prepared life cycle plan can be changed manually. Manual changes can be done based on the basis of the existing plan. However, this does not prevent the designer in any way to make a plan of his/her own mind. The designer starts the manual planning by first selecting the component and then pressing the button “Change the actions manually” on the “Results” form. Then the ”Definition of actions” display is opened (Figure 12):

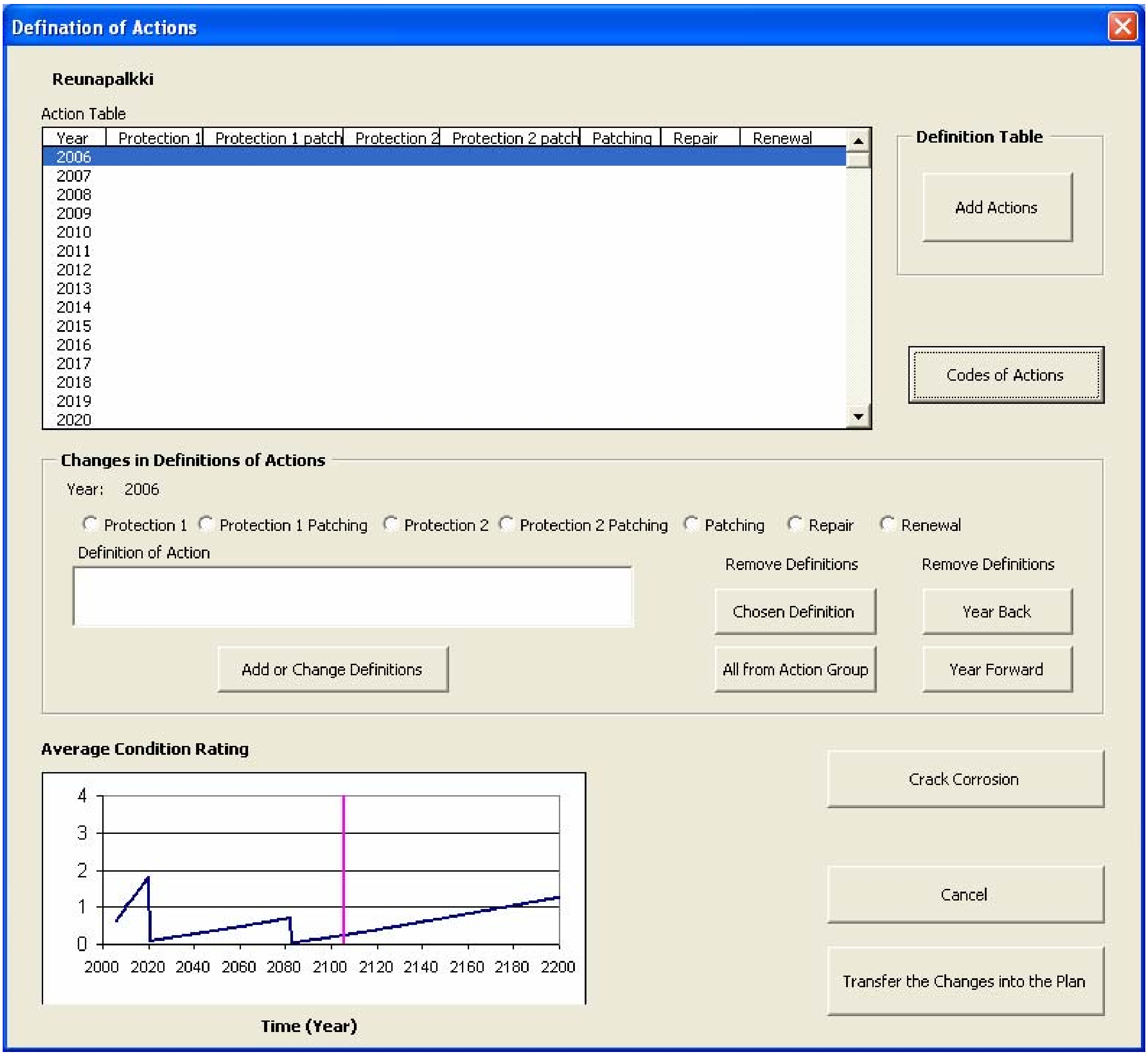


Fig 12. Definition of Actions display.

The "Action table" on top of the display shows the defined actions with their timings according to the existing life cycle plan. The designer can read from the table the action group (column), timing (row) and the code (number) of the action.

The condition guarding system which automatically triggers actions is not in force in the manual design. Instead there is the graph presenting the average condition rating of the component with time with respect to the “Surface damage”. A respective figure with respect to “Crack corrosion” can be made visible by pressing the button “Crack damage”. From these figures the designer can check the consequences of his/her design on the condition of the component and make sure that the required condition limits are not exceeded.

The designer can add, remove or change the actions using two methods:

- The definition table method or
- The action table method.

Definition table method

The definition table method is specially recommendable when a completely remarkable changes are desired to be done to the original design. All the definitions of the existing plan can be removed by placing a mark in the check box in the upper left corner of the form. If no check mark is placed the actions defined by the definition table are only added to the existing plan.

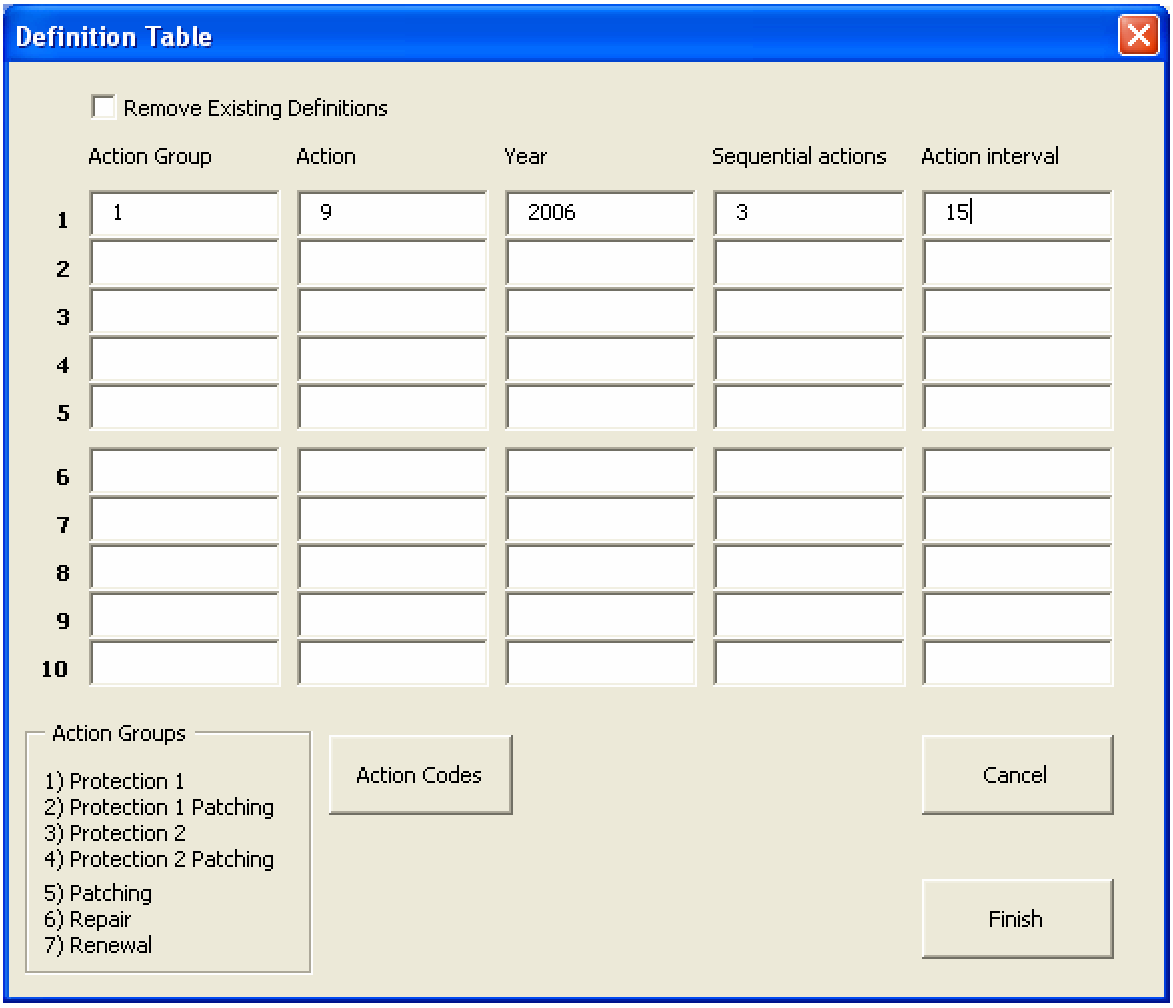


Fig 13. Definition table.

The following data are given for each action definition:

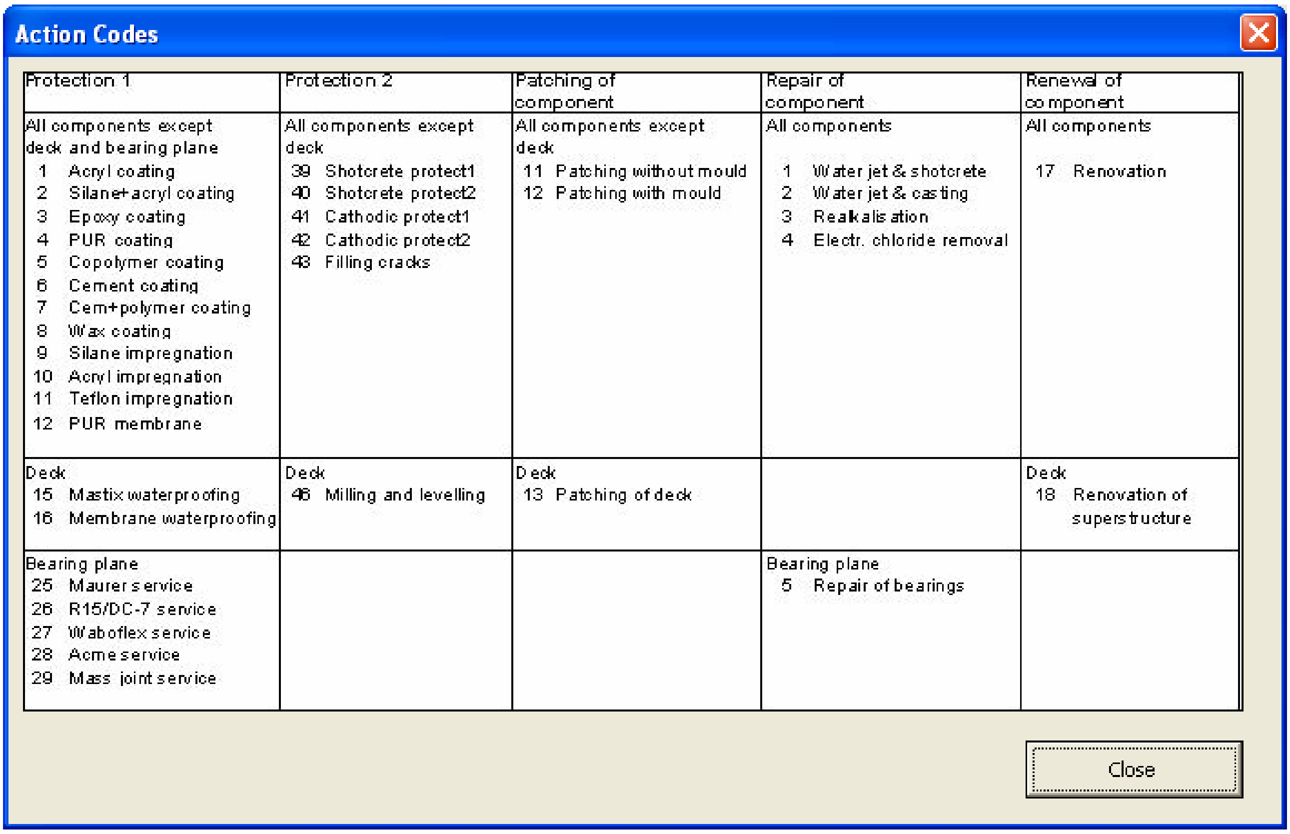
- Action group (code)
- Action (code)
- Year, when the action is performed for the first time
- Number of repetitions of actions
- Action interval

The action group codes are the following (seen also on the form):

Table 2. Action group codes.

Code	Action group
1	Protection 1
2	Protection 1 patching
3	Protection 2
4	Protection 2 patching
5	Patrching (of the structure)
6	Repair (of the structure)
7	Renewal (of the structure)

The code numbers of the actions can be made visible by pressing the button ”Action Codes” on the Definition Table form. The rules related to the actions as presented in Chapter below have to be considered by the designer.



Action Codes

Protection 1	Protection 2	Patching of component	Repair of component	Renewal of component
All components except deck and bearing plane 1 Acryl coating 2 Silane+acryl coating 3 Epoxy coating 4 PUR coating 5 Copolymer coating 6 Cement coating 7 Cem+polymer coating 8 Wax coating 9 Silane impregnation 10 Acryl impregnation 11 Teflon impregnation 12 PUR membrane	All components except deck 39 Shotcrete protect1 40 Shotcrete protect2 41 Cathodic protect1 42 Cathodic protect2 43 Filling cracks	All components except deck 11 Patching without mould 12 Patching with mould	All components 1 Water jet & shotcrete 2 Water jet & casting 3 Realkalisation 4 Electr. chloride removal	All components 17 Renovation
Deck 15 Mastix waterproofing 16 Membrane waterproofing	Deck 46 Milling and levelling	Deck 13 Patching of deck		Deck 18 Renovation of superstructure
Bearing plane 25 Maurer service 26 R15/DC-7 service 27 Waboflex service 28 Acme service 29 Mass joint service			Bearing plane 5 Repair of bearings	

Close

Fig. 14. Action Codes display.

Year is the calender year during which the action is planned to be implemented (for the first time). The action can be planned to be repeated by defining the number of repetitions and the action interval in years.

In the example of Figure 13 a silane impregnation has been specified for the component. The first application is in 2006 and the next three application are repeated at intervals of 15 years.

Action table method

By the action table method the designer makes the changes in the life cycle plan directly to the action table on the Definition of Actions form. The use of this method is recommendable especially when anly small changes in the existing plan are needed to do. The designer can add, remove or change the existing definitions.

Any changes in actions are defined by selecting (1) year (=row) and (2) action group (=column) on the Definition of Actions table. The year is selected by clicking at the left edge of the table where the calender years are presented. The action group is selected by the option buttons in the frame ”Changes in definitions of actions”. In the window within this frame the optional actions will appear when selecting the action group. If an action has already been defined in the specified year for the selected action group the action is written in the same window.

The changes and additions can be defined by selecting from the list of ”Definition of actions” the desired action and pressing the button ”Add or Change Definition”. Then the previous definition is replaced by the new one or when there is no previous action the selected action is defined as a new action.

If it is desired to remove an action the designer first specifies the Year-Action_group combination and then presses the button ”Remove the chosen definition”. If it is desired to remove all the definitions from the selected Action group (=column) the designer presses “Remove all from action group”.

By the buttons "Change the timings" the timing of actions can be removed forwards or backwards. By pressing these buttons the timing of the selected action is changed by a year forward or backward. Note that the action does not change only the timing of the selected action but all actions in the same Action group after the selected action. If it is desired that the timings of actions after the selected action do not change the timings after the selected action must be returned to their former position by selecting the year after the selected action and by choosing then the opposite change in the timing.

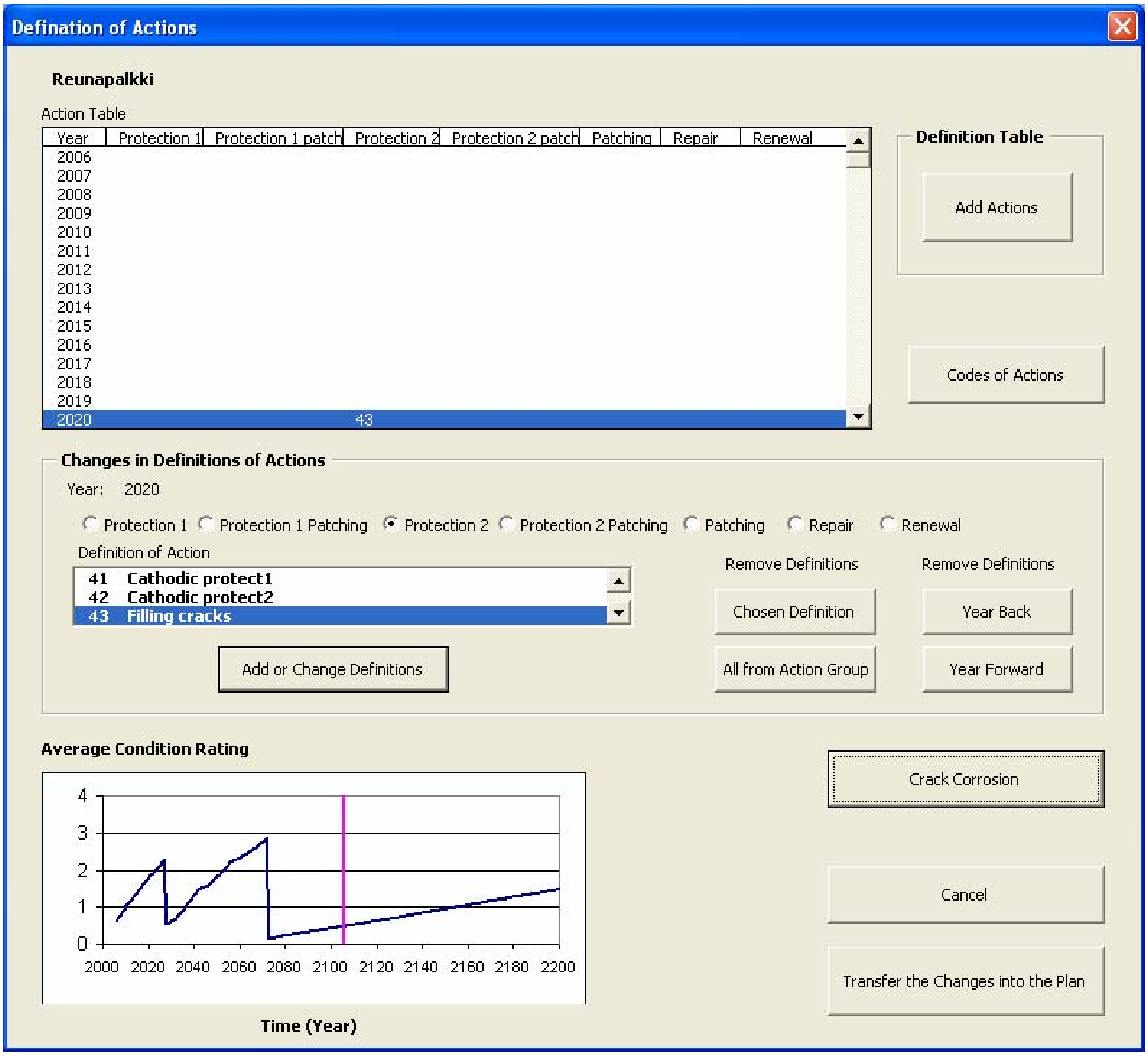


Fig 15. "Definitions of Actions" display after manual changes of actions.

For example in the Figure 15 some manual changes have been made by the Action table method. Patching of the structure has been specified to the year 2028. The first silane impregnation has been also defined for the same year and then repeated silane applications in years 2043 and 2058. The repair of the edge beam was postponed to the year 2073. In addition filling of the cracks was timed to 2020 to prevent the progress of crack corrosion. The changes in the condition curve with respect to Surface damage is seen in Figure 15 and with respect to Crack corrosion in figure 16 respectively.

The changes in the life cycle plan are confirmed by pressing the button "Transfer the changes into the plan". Then the Results form is appeared on the screen with all data updated according to the manually made plan. By pressing "Cancel" the manual changes are omitted.

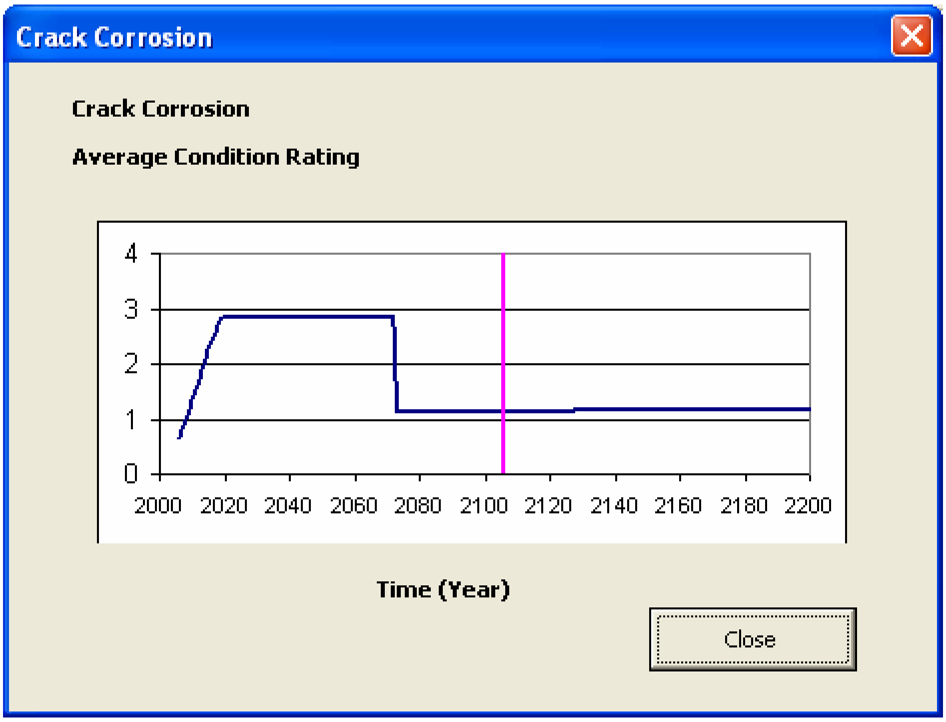


Fig 16. "Crack corrosion" display after manual changes of actions.

Rules for the actions

The designer specifies the MR&R actions as divided into action groups. For the same component and for the same year it is possible to specify any action contained in the action lists for different action groups. However it is not possible to specify patching of a component with repair or repair with renewal in the same year .Neither is it possible to specify patching of protection with the actual protection in the same year.

Coatings, surface treatments and water membranes are included to Protection 1. The available protection actions are, however, dependent on the component of the bridge. In the case of bridge deck Protection 1 allows using water membranes for the protection of the deck (repair of water membrane includes repair of the whole surface structure). In the case of bearing plane Protection 1 refers to the rubber seal in the expansion joint mechanism above the bearing plane (the rubber seal is understood to protect the bearing plane as a coating). For other components there is available a number of protective coatings and other surface treatments.

Table 3. Protection 1. Actions and action codes.

Concrete bridge structures save deck and bearing plane	
1	Acryl coating
2	Silane + acryl coating
3	Epoxy coating
4	Polyurethane coating
5	Copolymer coating
6	Cement based coating
7	Cement + polymer coating
8	Wax coating
9	Silane impregnation
10	Acryl impregnation
11	Teflon impregnation
12	PUR water proofing
Deck	
15	Mass waterproofing
16	Membrane waterproofing
Laakeritaso	
25	Maurer, service (replacement of rubber seal)
26	R15/DC-7, service (rubber seal)
27	Waboflex, service (rubber seal)
28	Acme, service (rubber seal)
29	Mass joint, service

Protection 2 consists of concrete and mortar protections and special protection methods such as cathodic protection and filling cracks. In the case of bridge decks the milling and concrete levelling is understood as to be a protection method including to Protection 2. For other concrete components the shotcrete methods and cathodic protection methods as well as filling of cracks are available. The difference between shotcrete protection 1 and shotcrete protection 2 is in the thickness of the layer (20 mm and 30 mm respectively). In cathodic protection 1 and cathodic protection 2 there is no difference at the moment. Filling of cracks means epoxy injection.

Table 4. Protection 2. Actions and action codes.

Concrete components without deck	
39	Shotcrete protection 1
40	Shotcrete protection 2
41	Cathodic protection 1
42	Cathodic protection 2
43	Filling of cracks
Bridge deck	
46	Milling and concrete levelling

Pertaining to Protection 1 and protection 2 it is possible also to specify patching of protection (or service of protection depending on the case). This is addressed to the part of the component in which the preset condition limit is exceeded (the surface area of patching is determined based on the condition of the protection). The patching of protection must be consistent with the prevailing actual protection. If for instance the prevailing actual protection is acryl coating the patching of the protection must also be performed with acryl coating.

Patching of the component itself (not patching of protection) is a limited repair action which is addressed to the part of the component in which the preset condition limits are exceeded. So the extent of the repair depends on the condition of the structure. The depth of patching is equivalent with the depth of actual repair i.e. the patching is performed around the main reinforcement. The patching methods are presented in the following table:

Table 5. Patching of Component. Actions and action codes..

Concrete components without deck	
11	Patching without mould
12	Patching with mould
Deck	
13	Patching of deck

The actual repair methods of concrete componets are presented in Table 6. They return the condition of the structure to almost the best possible condition (or initial condition) thus starting a new life cycle.

Table 6. Repair of components. Actions and action codes.

Concrete components without bearing plane	
1	Waterjetting and shotcreting
2	Waterjetting and casting of concrete
3	Realkalisation
4	Electrochemical chloride removal
Bearing plane	
5	Repair of bearing plane

Renewal of a component is a special repair method in which the whole structure is replaced by a new one. The methods of renewal are presented in Table 7:

Table 7. Renewal of components. Action codes.

All components except deck	
17	Renewal of the component
Deck	
18	Renewal of the deck (super structure)

2.3 BATCH PROCESS

Batch process means a procedure in which the calculations of the life cycle planning are performed for all bridges in the initial data file in a row. The Batch process produces also a special output file which is used by the main program of project level bridge management in the Finnish Bridge management System, “Hanke-Siha”. Thee name of the output file produced by “Bridgelife” is

EK_HS.xls. This file includes all the data of the life cycle planning which is designed to be visible on the displays of Hanke-Siha”.

To start the run the designer first specifies the length of the design period and the discount rate. It is also possible to do additions or changes in the bridge and component specific data before the run if necessary. These changes are performed in the same way as in the design of single bridges (see. Chapter 2.2.2 "Checking of the bridge and component specific data ").

Then the actual run is started by pressing the button "Do Batch Process". As the batch process takes a long time and to make sure that pressing of the button was intended the program prompts the following message box:.

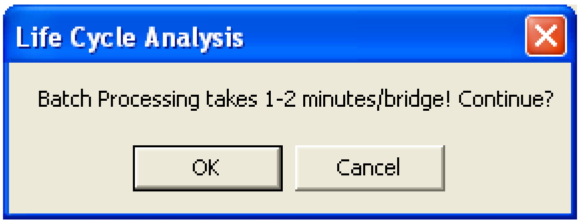


Fig 17. Message box of the Batch process.

By answering ”OK” the batch process is started. The calculation time depends on the amount of bridges, amount of components in bridges, length of the design period and calculation rate of the computer. In case of emergency the program can be interrupted by pressing Ctrl Break.

2.4 SERVICE LIFE DESIGN

2.4.1 General

The service life design module is a tool by which the bridge designers can prove the bridge components to meet the service life requirement. The service life design is addressed to new components of concrete bridges. However, the tool can be applied to existing bridges too.

2.4.2 Starting Service Life Design

By pressing the button ”Service Life Design” on the front page of program Bridgelife the following form will appear on the screen:

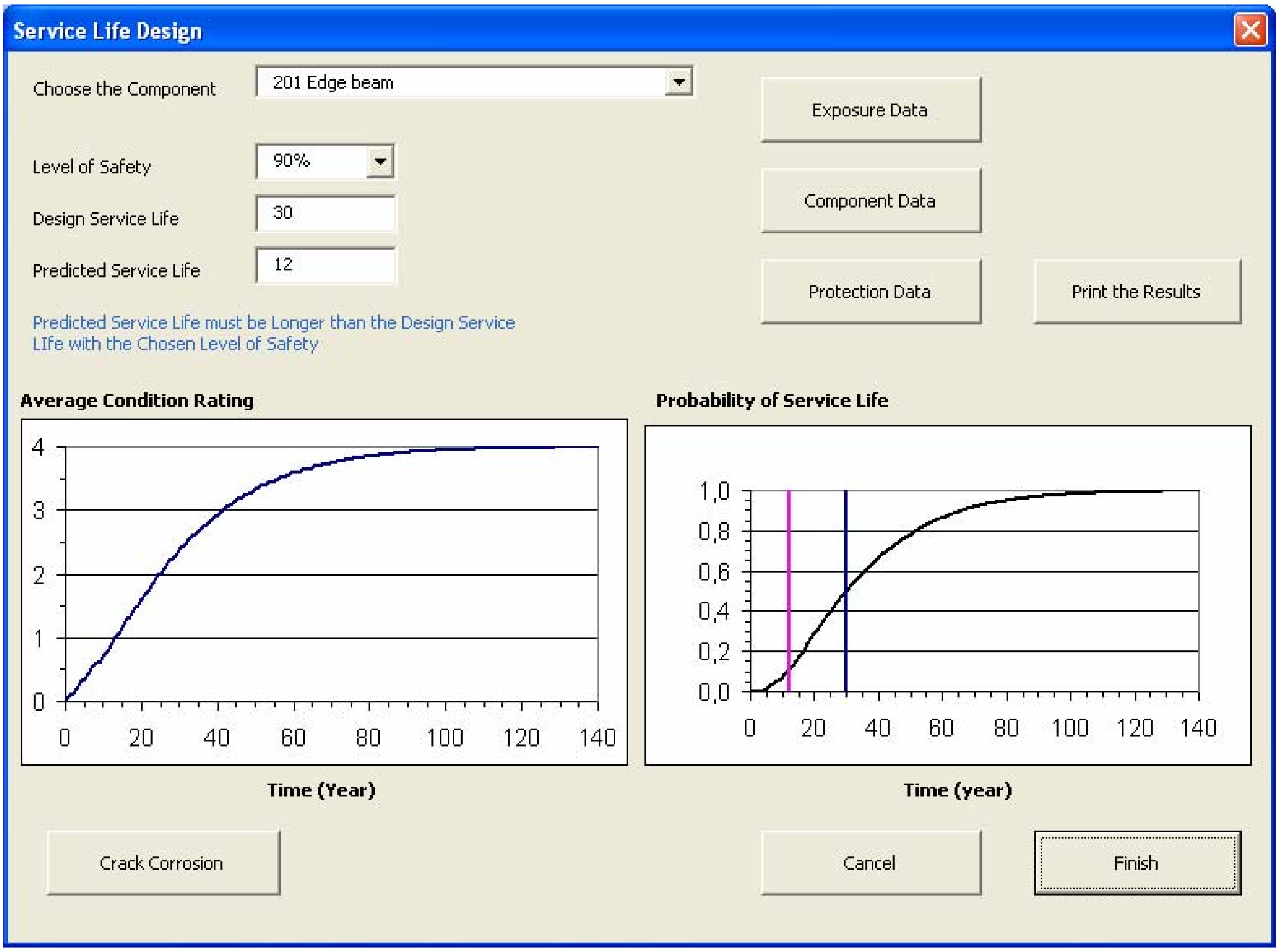


Fig 18. Service Life Design display.

At first the designer chooses the component at the upper edge of the form. Then he/she defines the level of safety and the design service life. Prefilled values are provided in the sites of these data items, but the designer can freely change them. Usually the safety level should be 95 - 90 % if there is not any special reason to deviate from this practice. The Predicted service life is calculated by the program. The main idea of the service life design is to ensure that the Predicted service life is longer than the Design service life with the chosen level of safety.

There are two pictures in the middle of the display. The picture on the left presents average condition rating as a function of time (age) with respect to “Surface damage”. Surface damage takes into account the frost attack and the spalling of concrete as a result of general corrosion of reinforcement. The graph on the right presents the probability of not attaining to the design service life (or the probability of exceeding the limit condition state) as a function of time (age). Two vertical lines are depicted on this figure. The blue one shows the design service life. The red one shows the predicted service life respectively. The line of the predicted service life crosses the probability curve at the point where the probability of service life is 1 minus safety level. For instance if the safety level is 90% the crossing point with the probability curve is at the probability of 1 – 0,90 = 0,1. The designer has to make sure that the red line (predicted service life) is on the right side of the blue line (design service life)

By pressing the button ”Crack corrosion” another pair of pictures is appeared. These figures show the condition of the component with respect to “Crack corrosion”, which is the other degradation type in program Bridgelife. Crack corrosion is defined by the amount of corrosion in the main reinforcement at cracks.

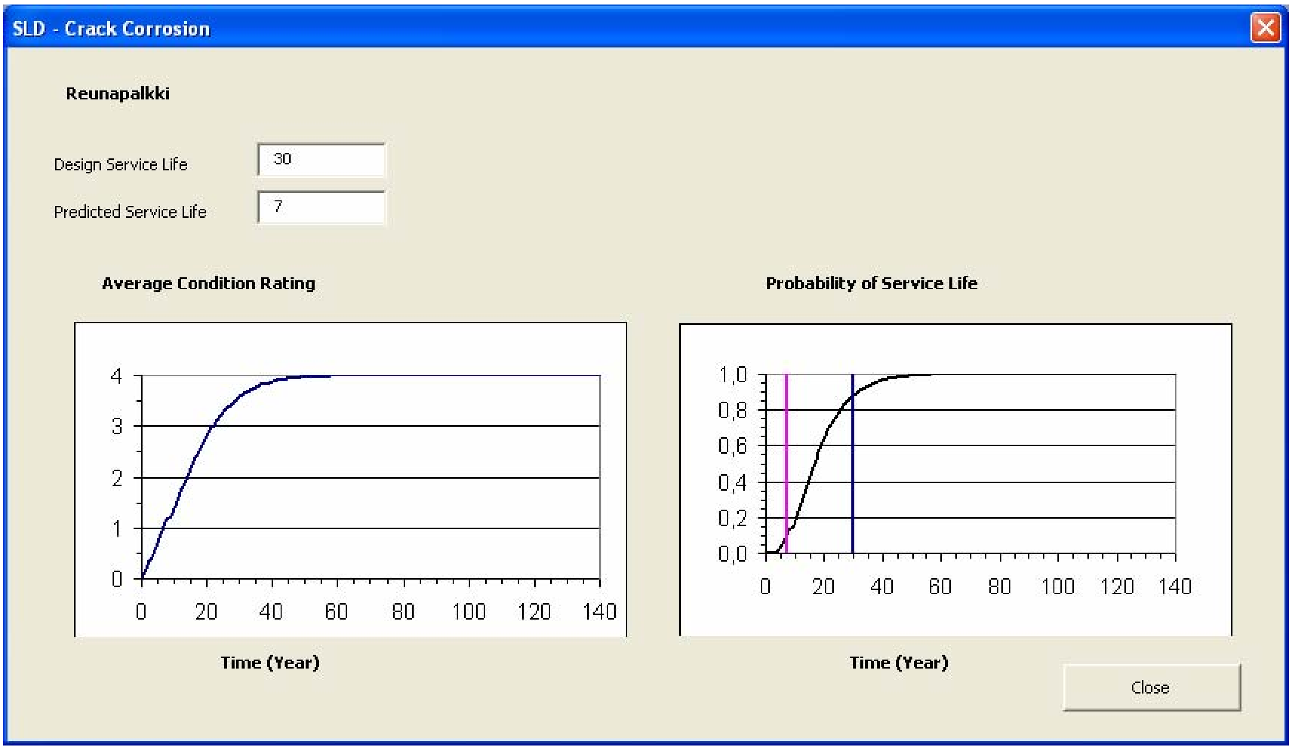


Fig 19. The display of Crack Corrosion in service life design

2.4.3 The procedure of Service Life Design

First the designer checks that the defined environmental stresses are consistent with the actual environmental stresses attacking the object of design. Then the designer specifies the quality of the concrete and the thickness of concrete cover in the component so that the predicted service life is longer than the design service life. However, if the environmental stresses are such that these measures are insufficient to meet the service life requirement the designer can use protection methods i.e. coatings, protective concrete layers and other protections to fulfil the service life requirement.

The parameters of design are available under three buttons which are:

- Exposure data
- Component data and
- Protection data

Exposure data

By pressing the button "Exposure data" a form titled with the same name will appear:

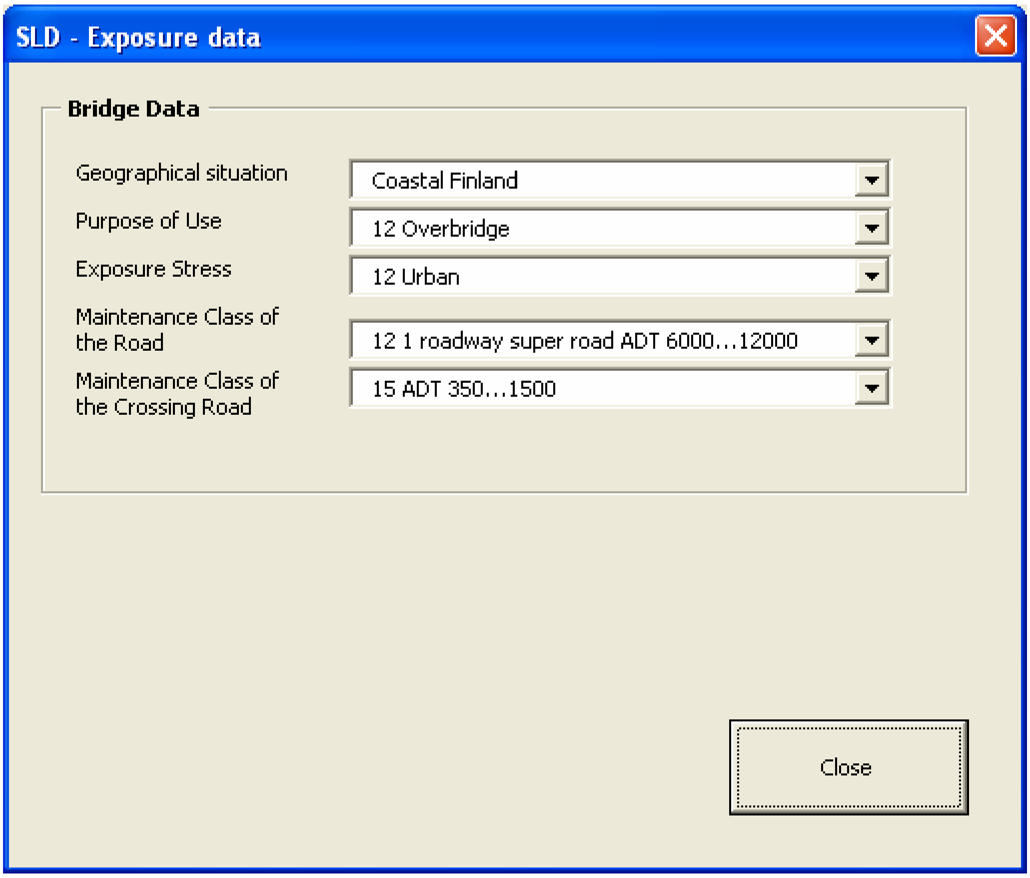


Fig 20. Exposure data display.

The following parameters describing the exposure of the bridge are available for the designer:

- Geographical situation
- Purpose of use
- Exposure stress
- Maintenance class of the road
- Maintenance class of the crossing road

The purpose of use, exposure stress, maintenance class of the road and the maintenance class of the crossing road are defined in the same way as they are defined in the Bridge register. The maintenance class is directly dependent on the road type and the average daily traffic. The Geographic situation of the bridge is defined as follows: (1) Coastal Finland (2) Middle Finland and (3) Northern Finland.

Component data

By pressing the button ”Component data" the ”Component data” display will open. In the data fields of the display the default values of the component specific data are presented. To extend the predicted service life the designer is supposed to the values of these parameters which are:

- Cement type
- Strength class of concrete
- Air content, %
- Thickness of concrete cover, mm

All these data are defined as in the corresponding table of Bridge Register. The classification of cements is presented in Table 1.

An example of changed initial data is presented in Figure 21.

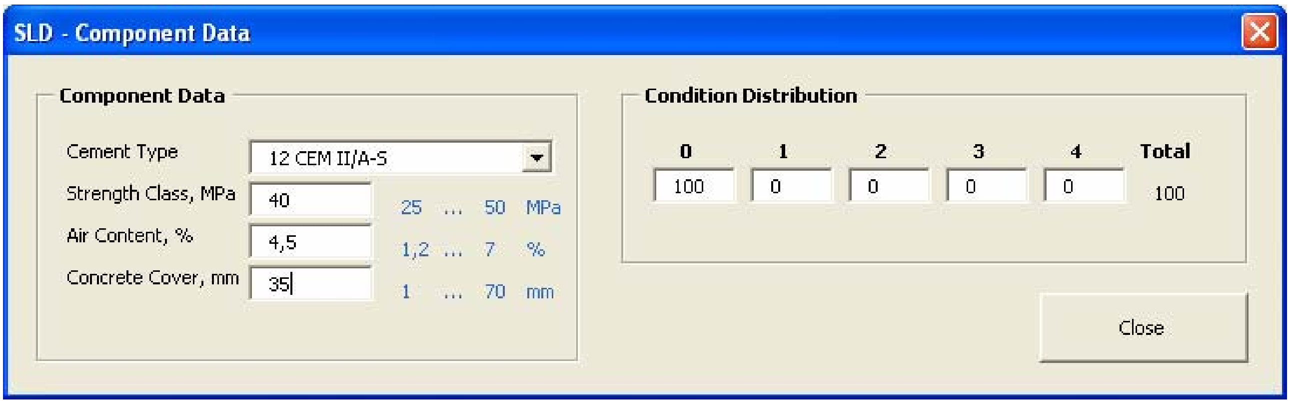


Fig. 21. Example of changed values of initial data.

The condition distribution of the component at the start of the service life can also be input on the Component Data form. Normally when planning new bridge structures the condition distribution of the component is the best possible i.e. the probability of the component to be at the condition state 0 is 100% (ref. Figure 21). However, if it is desired to use the Service Life Design program for evaluating the remaining service life of the component, this field is used for presenting the present day condition distribution of the component. Then the user of the program is supposed to make sure that also the other parameter data is in conformity with the real state of the component and the environmental conditions.

Protection data

By pressing the button "Protection data" the Protection data form of the Service Life Design will open.

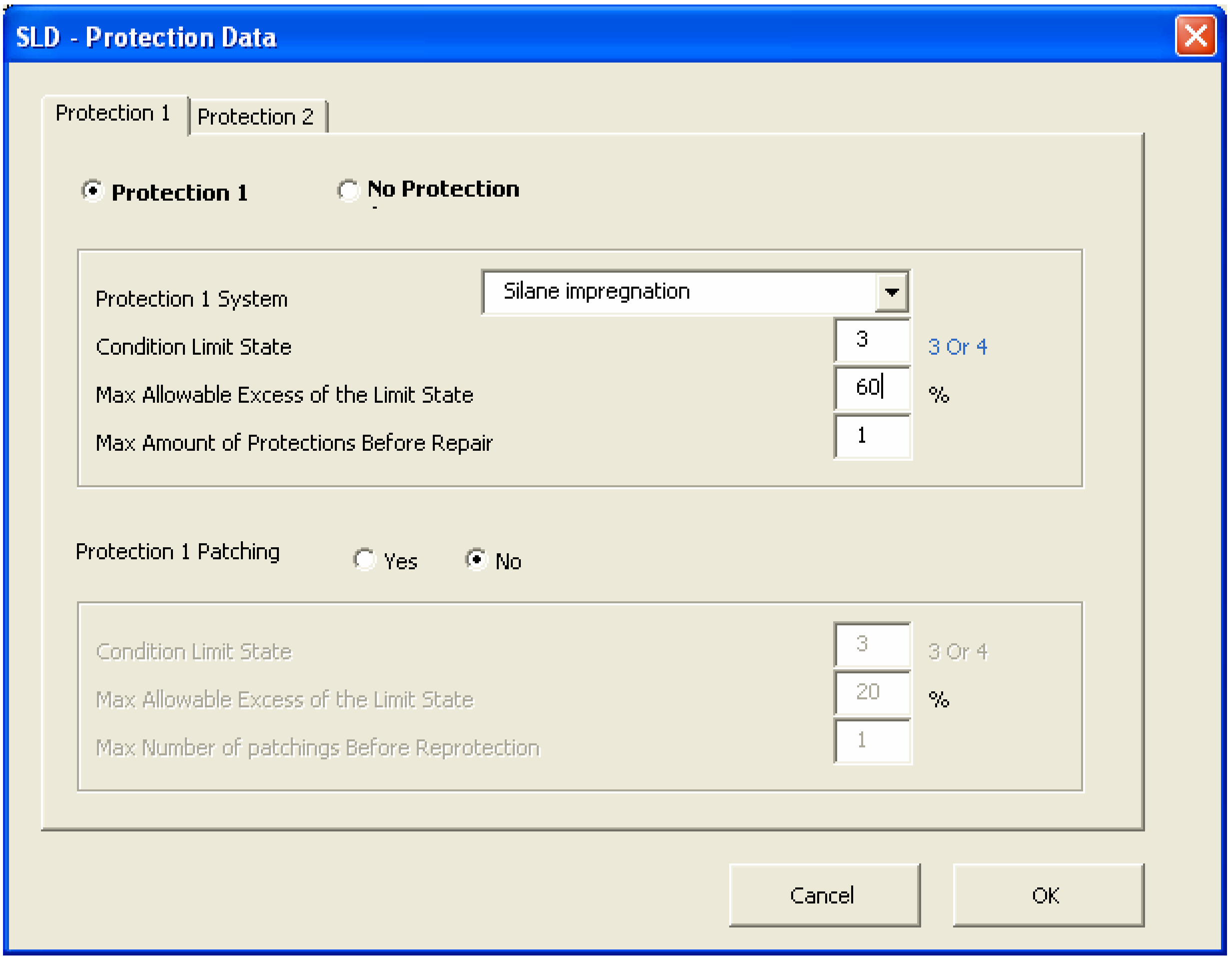


Fig. 22. Protection Data display of Service Life Design.

On the form of Protection Data the designer can specify coatings or other protections for the structure. There are two groups of protections (respectively to the life cycle design) which are presented on separate interleaves. Generally coatings and other surface treatments are included in Protection 1 while other protection methods are included in Protection 2. The lists of protection actions and their codes are presented in Tables 8 and 9.

There is an option button “Protection / No Protection” to sign whether the protection group is active or not. If the protection group is selected active it is necessary to do the also the following definitions.

Table 8. The definitions of the Protection Actions.

- Protection system	Code of the protection system (in Protection groups 1 or 2).
- Limit state of condition	Preset condition state representing the end state of service life
- Maximum allowable probability for exceeding the limit state of condition	Exceeding of the maximum allowable probability triggers the protection action.
- Number of sequential protection times	The protection action is repeated max. the defined number of times.

Figure 23 shows an example of the definitions of Protection 2.

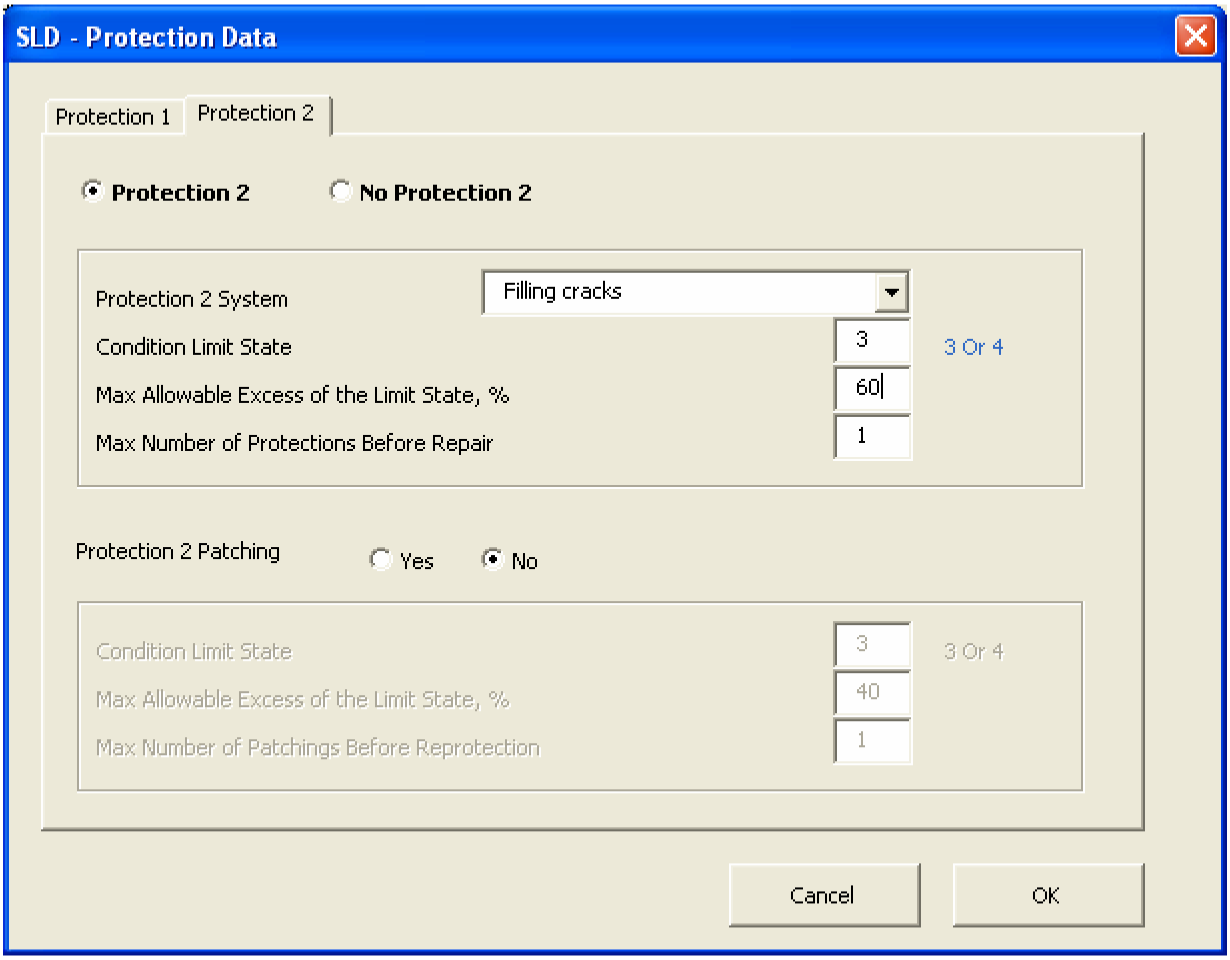


Fig. 23. Example of the definitions of protection.

For Protection 1 and Protection 2 it is also possible to define the patching of protection. Patching may refer to real patching (e.g. coating) or other service of the protection addressed to the part of the component in which the condition limit state has been exceeded. These definitions are given in the same way as the definitions of the actual protection method (Table 8).

When the designer presses the "OK" button the initial Service Life Design form is returned in the screen. The predicted service life is recalculated using the newly defined values of parameters. By pressing "Cancel" no definitions of protections are considered.

In Figure 24 an example of an approvable plan is seen. The predicted service life (39 years) is longer than the design service life (30 years)

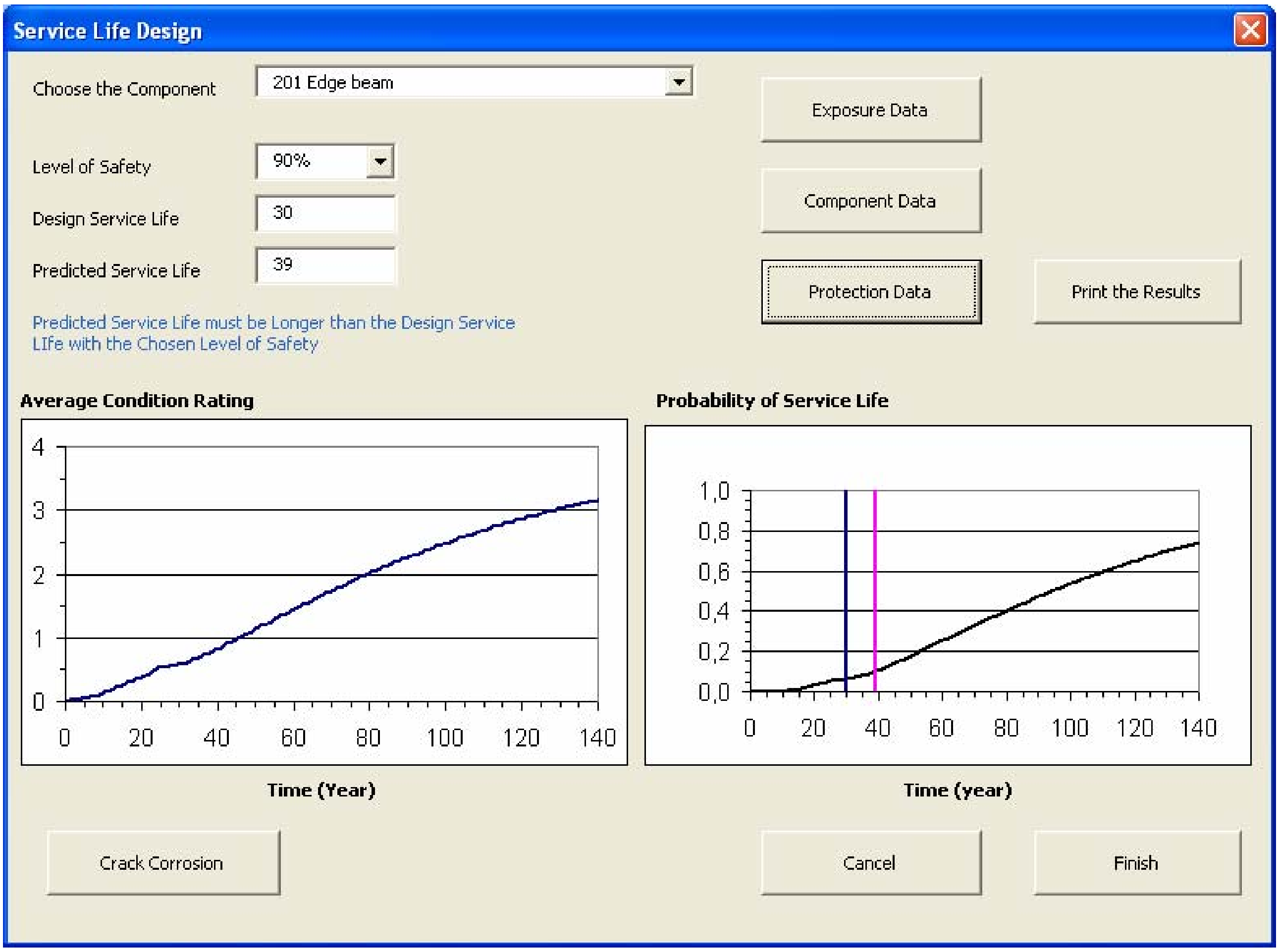


Fig 24. The result of the Service Life Design (Example).

By using filling of the cracks as a protection method the service life with respect to crack corrosion is very long (ref.. Figure 19).

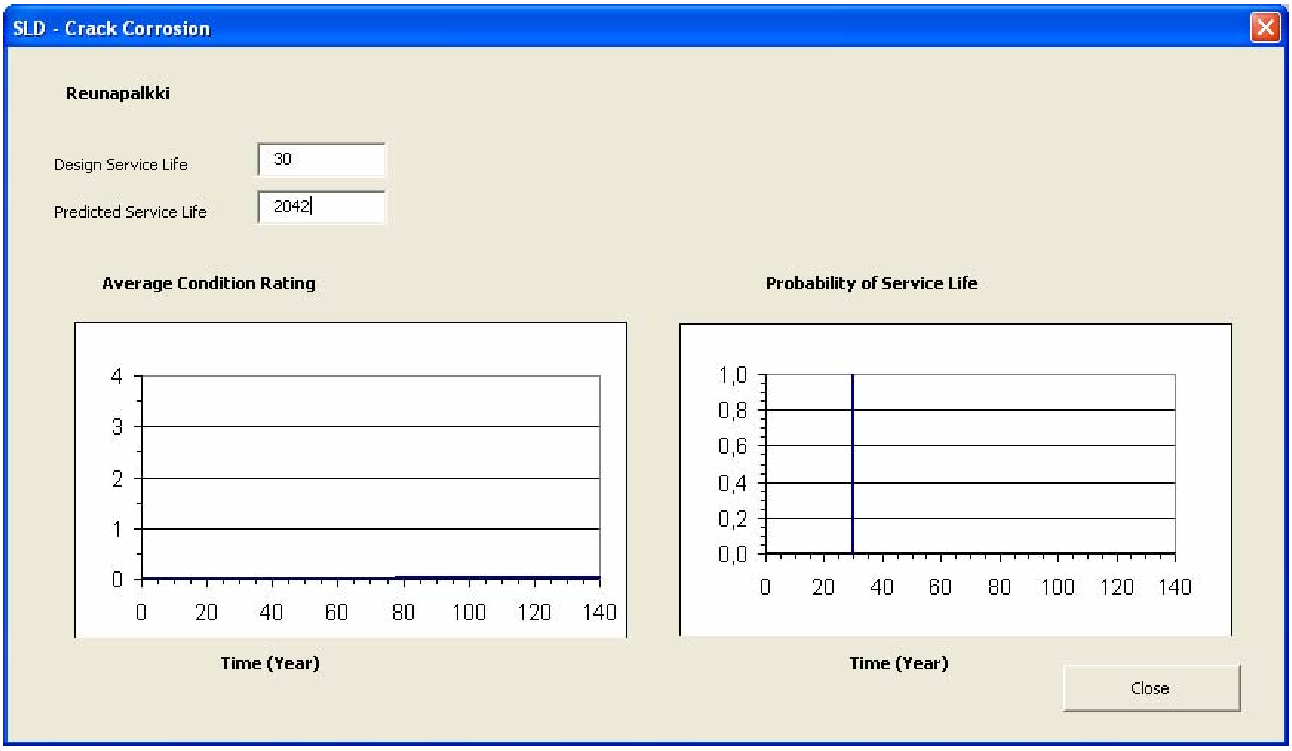


Fig 25. Results of Service life Design on the Crack Corrosion form.

2.4.4 Printing of the results of the design

By pressing the button “Print the Results” on the upper right edge of the Service life Design display the results of the Service Life Design are printed on paper. An example of the output is presented in Chapter 3.5 "Paper output of the Service Life Design".

3 Supplementary instructions

3.1 INITIAL DATA FILE

3.1.1 Contents of the initial data file

The initial data file is produced by a special data base routine using the Bridge Register as data source. The initial data file contains all the bridge specific and component specific data which are needed in the program Bridgelife. If some data are missing in the initial data file the program Bridgelife uses default data instead of specific data. The default data is usually the statistical mean of that data.

The name of the initial data file is SR_EK.xls. It is divided into two data tables (=two sheets), one containing the bridge specific data and the other component specific data. The data is presented in the horizontal direction so that on the first row there are titles of the data items starting from the cell A1 and then the data of each bridge below the title row. In Table 9 the data titles and the examples of data are presented in the vertical direction because of limited space on the page.

The dimensions of bridges are given in meters. The two last data items”First_row_component” and ”last_row_component” refer to the rows in the Data Table of Components, where the component data of the bridge are situated.

Table 9. Bridge specific data.

Data	Title of the data	Example of data
Identification number of the bridge	**Bridge_id**	6
Road district code	**Road_district**	1
Number of bridge	**Bridge_number**	3
Name of the bridge	**Name**	Bemböle bridge
Geographical situation	**Geograph_situation**	1
Purpose of use	**Purpose**	11
Exposure stress	**Exposure_stress**	12
Maintenance class of the road	**Maintenance_overway**	11
Maintenance class of the crossing road	**Maintenance_underway**	
Site class	**Bridge_site**	14
Total length of the bridge (m)	**Length**	16,35
Total breadth of the bridge (m)	**Breadth**	10,80
Average clearance height (m)	**Heigth**	0,68
ADT of the road	**ADT_overway**	7165
ADT of the crossing road	**ADT_underway**	
Percentage of the truck traffic of road (%)	**Truck%_overway**	11,7
Percentage of the truck traffic of crossing road	**Truck%_underway**	
Limitation of speed of traffic (km/h)	**Speed_overway**	60
Limitation of speed of traffic on crossing road	**Speed_underway**	
Length of the detour route (km)	**Detour_overway**	10
Length of the detour route of crossing road (km)	**Detour_underway**	
Year of fabrication of bridge	**Year_fabrication**	1938
First data row in the Table of Components	**First_row_component**	2
Last Data row in the Table of Components	**Last_row_component**	4

The other data table of the initial data file consists of the component specific data. The data in this table is also presented in the horizontal direction the first row containing the titles of the data and the rows below the title row the data of components. One row is preserved for each component. The first column contains the identification number of the bridge. This number is a code by which the components can be linked with the right bridge. In the next column the code of the component is presented. The components pertaining to a bridge are supposed to be presented in the following order since the order of the components affect the timing of actions:

- deck (301)
- edge beam (201)
- bearing plane (110)
- front wall (106)
- brow wall (109)
- other walls
- other components.

By using an additional qualifier of a component the stresses addressed to the component can be further specified. Table contains the components to which additional qualifiers can be specified and the codes of the qualifiers.

Table 10. Additional qualifiers of the component.

Component	Qualifier (code)
Front wall Brow wall bearing plane	1 = expansion joint (above) 2 = no expansion joint (above)
Column support Pole support Wall support Oblique support	1 = near the road 2 = far from the road
Upper surface of deck	1 = waterproofing 2 = no waterproofing

Table 11 presents the component specific data of the initial data file in the vertical direction because of the limited space in the horizontal direction. The dimensions are presented in meters except for the diameter of reinforcing bar and the concrete cover which are expressed in millimetres. The strength quantities are expressed in MPa.

Table 11. Component specific data.

Data	Title of data	Example of data
Identification number of bridge	**Bridge_id**	6
Component code (Bridge Register))	**Component_code**	106
Additional qualifier	**Qualifier_code**	1
Number of identical components	**Number_id_component**	2
Longitudinal situation (e.g. number of support)	**Longitud_situ**	
Transversal situation (e.g. v = on the left, o=on the right)	**Transvers_situ**	
Dimension in longitudinal direction, min (m)	**Dim_long_min**	
Dimension in longitudinal direction, max (m)	**Dim_long_max**	
Visible dimension in longitudinal direction (m)	**Dim_long_visible**	
Dimension in transversal direction, min (m)	**Dim_trans_min**	14,7
Dimension in transversal direction, max (m)	**Dim_trans_max**	
Visible dimension in transversal direction (m)	**Dim_trans_visible**	14,7
Total height, min (m)	**Heigth_min**	2,35
Total height,max (m)	**Heigth_max**	
Visible heigth (m)	**Heigth_visible**	1,2
V = horizontal P = vertical	**Surface_dir**	P
Distance from road (road bridge) or water (water bridge)	**Distance_road**	0
Quality of cement	**Cement**	
Compressive strength from design (MPa)	**Nom_strength_plan**	
Compressive strength from special inspection, min (MPa)	**Nom_strength_SpInsp_min**	
Compressive strength from special inspection, max (MPa)	**Nom_strength_SpInsp_max**	
Strength class of concrete (MPa)	**Concrete_grade**	30
Tensile strength of concrete, min (MPa)	**Tensile_strength_min**	
Tensile strength of concrete, max (MPa)	**Tensile_strength_max**	
Diameter of the rebar nearest to the surface (mm)	**Steel_diam_surface**	12
Diameter of the main rebar (mm)	**Steel_diam_main**	18
Protection method in use if any (code)	**Concrete_protection**	
Year of starting protection	**Protection_year**	
Condition state of protection (evaluated by inspection)	**Protect_CondSt**	
Date of inspection	**Protect_insp_date**	
Frost resitance number P	**Frost_resistance_P**	

Air content of concrete (%)	**Air_content**	4
Protection pore ratio from design	**ProtPorRatio_plan**	
Protection pore ratio from special inspection	**ProtPorRatio_SpInsp**	
Concrete cover from design, min (mm)	**Concr_cover_plan_min**	30
Concrete cover from special inspection, min (mm)	**Concr_cover_SpInsp_min**	
Concrete cover from special inspection , max (mm)	**Concr_cover_SpInsp_max**	
Depth of carbonation, min (mm)	**Carbonat_min**	5
Depth of carbonation, max (mm)	**Carbonat_max**	15
Chloride content, min (%)	**ChloridCont_min**	
Chloride content, max (%)	**ChloridCont_max**	
Moisture content, min (%)	**Moisture_min**	
Moisture content, max (%)	**Moisture_max**	
Corrosion potential of steel, min (mV)	**ElPotential_min**	
Corrosion potential of steel, max (mV)	**ElPotential_max**	
Width of crack (mm)	**Crack_width**	0,3
Is component repaired (0 = No, 1 = Yes)	**Is_repaired?**	
Repair action (code)	**Repair_action**	
Age of component at inspection, years	**Component_age**	34
Condition state distribution (% at state 0)	**CondSt_distr_0**	20
Condition state distribution (% at state 1)	**CondSt_distr_1**	30
Condition state distribution (% at state 2)	**CondSt_distr_2**	40
Condition state distribution (% at state 3)	**CondSt_distr_3**	10
Condition state distribution (% at state 4)	**CondSt_distr_4**	0

3.1.2 Checking the validity of data in the initial data file

When the life cycle design is started by pressing the button at the front page of Bridgelife the program first checks the initial data. During this check the validity of all the bridge specific and the component specific initial data are checked. The validity with respect to the following matters is examined:

- There are no non-numeric values in the initial data, if they are supposed to be numeric.
- The numeric initial data is between given minimum and maximum values.
- The sum of the condition distribution is 100 .
- The code of the component is consistent with the defined list of components.

The observed erroneous initial data prompt a message box. For some erroneous values the program itself makes the correction allowed by the designer. For instance if an initial data value is smaller than the preset minimum, the program uses the minimum value or respectively if an initial data value is greater than the preset maximum the program uses the maximum value instead. In addition the program can automatically correct the condition state distribution if the sum of it is not 100 provided that the sum is not 0 or negative. The correction is done by changing the relative portions of the condition states so that the sum of the revised distribution is 100.

The preset minimum and maximum values of initial data are presented in the page ”Sallitutarvot”. This page is not normally visible but it can be made visible as follows. First the page tabs are made visible by using the commands Tools_Options_View, and by placing a mark at the check box for “Sheet tabs” and then pressing “OK”. Then by pressing the tab “Sallitutarvot” the page of the same name is opened. On this page the user can change the preset minimum and maximum values of data items.

The possible errors observed during the check of the initial data file are also presented on the ”Sallitutarvot” (allowed values) page . The program informs on which column the error was found and what was the erroneous value. If the component code is not consistent with the preset component code list the error message is given in Cell D15 of the same page.

Based on these hints the errors in the initial data file can be localised and corrected. The initial data are found on the pages ”SR_Silta” (bridge specific data) and ”SR_Rakosa” (component specific data). These pages are also normally invisible but they can be made visible in the same way as the “Sallitutarvot” page. It is essential to correct the erroneous data so that the program no more prompts an error message.

3.2 PRINTING AND STORING THE RESULTS

3.2.1 Printing on paper

Printing on paper is started by pressing the button ”Print the Results” on the ”Results” form. An example of the results print is presented below.

On the first page of the results print the project costs are presented. The costs of the first nearest project and the second nearest project as well as the next rehabilitation project are presented as real costs and as present value costs. The costs are separated out as follows: (1) MR&R Costs, (2) user costs, (3) Total of MR&R costs and user costs and (4) delay costs. The MR&R costs are presented also as a bar diagram with time.

On the second page the MR&R costs and the user costs of the whole bridge from the whole design period are presented. These costs are separated out as follows: (1) real costs (total), (2) present value costs (total), (3) average annual costs and (4) equalised annual costs. The accumulation of costs with time is presented also graphically.

On the third page the total of environmental impacts resulting form the MR&R actions for the whole bridge and for the whole design period are presented. The environmental releases are presented also as a bar diagram.

From the forth page forward all the MR&R actions addressed to the bridge during the design period are presented. The actions are presented in the order of calendar year so that the actions pertaining to each project can be distinguished by the calendar year. The following data is presented in the table: (1) component (to which the action is addressed), (2) year, (3) action code, (4) action group, (5) action clearly written, (6) unit costs, (7) surface area and (8) action costs.

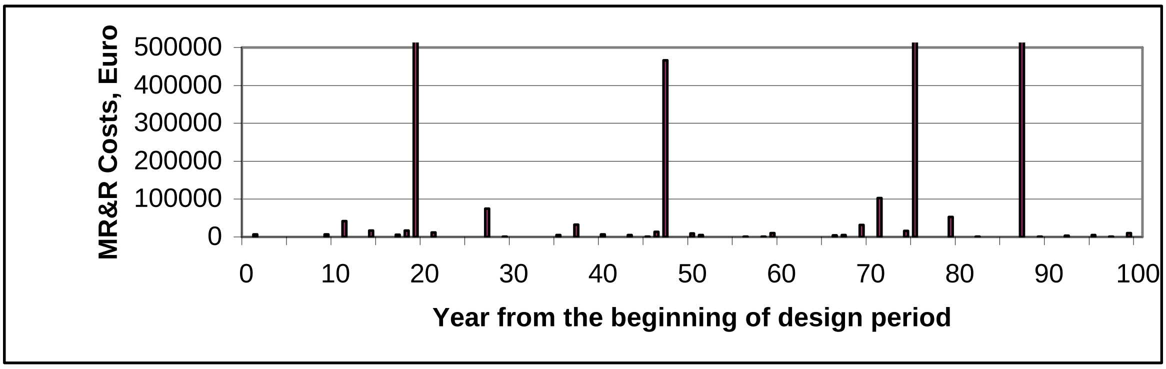
Bridgelife

PROJECT COSTS			
Date of analysis	9.8.2006		
Bridge	Ämmäkosken Bridge	Road District	8
Bridge_id	8061	Bridge	18

Year of first project	2007	
	Total Costs, Euro	
	Real Costs	Present Value Costs
MR&R Costs	6743	6546
User Costs	13	12
Costs Total	6755	6559
Delöay Costs	194	183

Year of second project	2015	
	Total Costs, Euro	
	Real Costs	Present Value Costs
MR&R Costs	6394	4900
User Costs	13	10
Costs Total	6406	4910

Year of first rehabilitation project	2025	
	Total Costs, Euro	
	Real Costs	Present Value Costs
MR&R Costs	975513	556322
User Costs	2618	1493
Costs Total	978131	557814

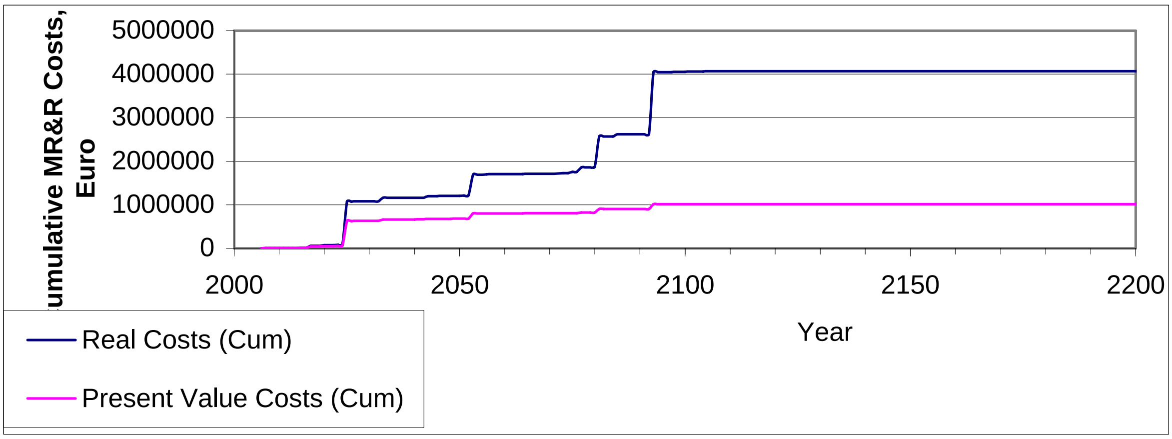


Bridgelife

Life Cycle Costs			
Date of analysis	9.8.2006		
Bridge	Ämmäkosken Bridge	Road District	8
Bridge_id	8061	Number	18
Design period, vuotta	100		
Discount rate, %	3		

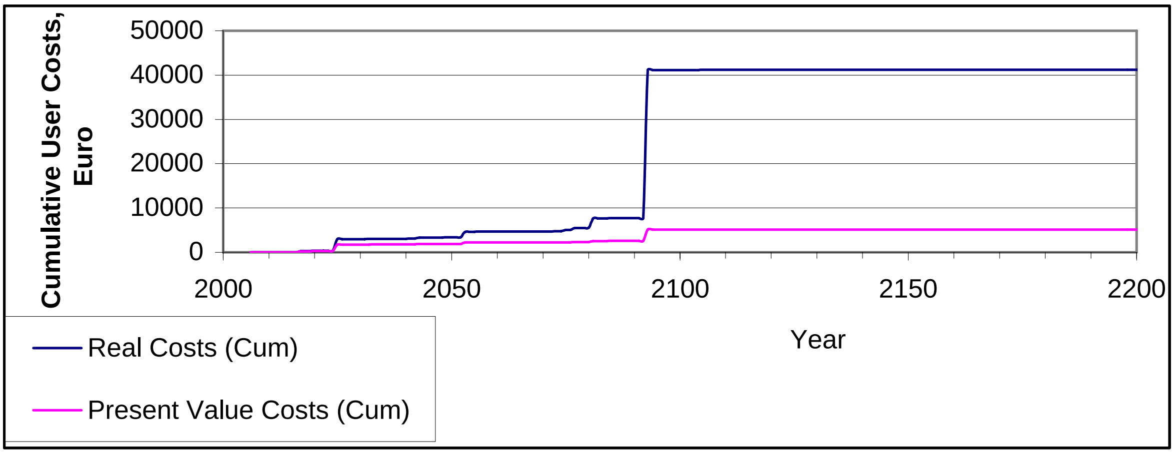
MR&R Costs

Cumulative Real Costs	4068121	Euro
Cumulative Present Value Costs	1015315	Euro
Average Annual Costs	40681	Euro/year
Equalised Annual Costs	32131	Euro/year



User Costs

Cumulative Real Costs	41235	Euro
Cumulative Present Value Costs	5119	Euro
Average Annual Costs	412	Euro/year
Equalised Annual Costs	162	Euro/year

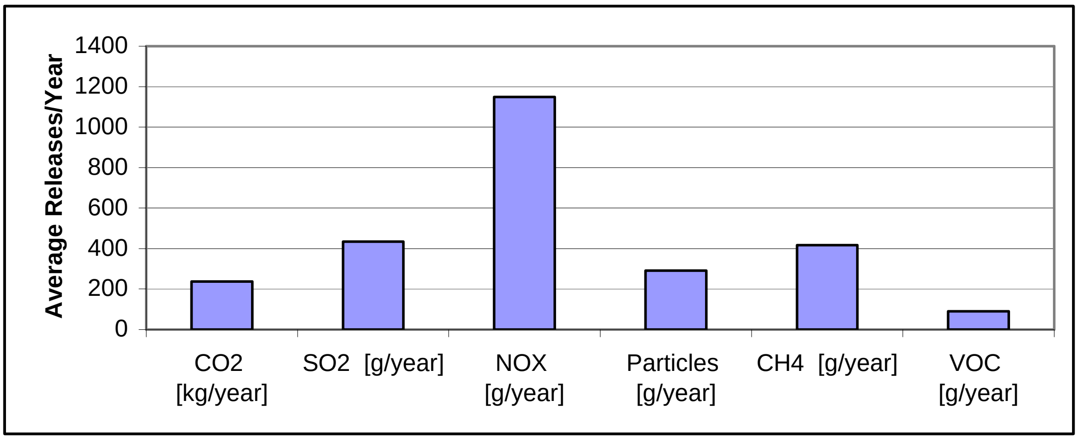


Bridgelife

ENVIRONMENTAL EFFECTS

Date of analysis	9.8.2006		
Bridge	Ämmäkosken Bridge	District	8
Bridge_id	8061	Bridge	18
Design period, years	100		
Discount rate, %	3		

Energy, Non-Renewable	263053	MJ
Energy, Renewable	18526,7	MJ
CO_2	23736	kg
SO_2	43391	g
NO_X	114874	g
Particles	29149	g
CH_4	41739	g
VOC	9060,1	g
Mineralogical Raw Materials	198,58	1000 kg
ELU	1651	Euro



MR&R ACTIONS ACCORDING TO CALENDER YEAR

Bridgelife

Date 9.8.2006
Bridge Ämmäkosken Bridge
Bridge_id 8061
Road District 8
Bridge 18

Component Code	Year	Action Code	Action Group	Action	Unit Costs Euro/m^2	Surface Area m^2	Costs Euro
201	2007	116	Protection1	Silane impregnation	19	283	5255
108	2007	116	Protection1	Silane impregnation	19	25	462
108	2007	116	Protection1	Silane impregnation	19	23	417
113	2007	116	Protection1	Silane impregnation	19	13	243
113	2007	116	Protection1	Silane impregnation	19	12	219
114	2007	116	Protection1	Silane impregnation	19	8	147
201	2015	116	Protection1	Silane impregnation	20	283	5661
113	2015	116	Protection1	Silane impregnation	22	13	288
113	2015	116	Protection1	Silane impregnation	22	12	260
114	2015	116	Protection1	Silane impregnation	23	8	184
108	2017	116	Protection1	Silane impregnation	21	25	514
108	2017	116	Protection1	Silane impregnation	21	23	464
202	2017	701	Protection1	0	0	104	0
202	2017	102	Repair	Water jet & casting	359	104	37326
114	2017	116	Protection1	Silane impregnation	24	8	191
114	2017	102	Repair	Water jet & casting	441	8	3496
110	2020	603	Protection1	Maurer service	33	24	772
106	2020	603	Protection1	Maurer service	0	69	0
109	2020	603	Protection1	Maurer service	0	44	0
113	2020	116	Protection1	Silane impregnation	24	13	314
113	2020	102	Repair	Water jet & casting	467	13	6105
113	2020	116	Protection1	Silane impregnation	24	12	284
113	2020	102	Repair	Water jet & casting	467	12	5516
201	2023	116	Protection1	Silane impregnation	21	283	5973
301	2024	701	Protection1	Mastix waterproofin	138	1225	169040
301	2024		Protection2	Milling and levelling	253	1225	309760
301	2024	904	Renovation	Renovation of super	834	1225	1022506
114	2024	116	Protection1	Silane impregnation	17	8	138
106	2025	701	Protection1	Membrane waterpro	0	69	0
109	2025	701	Protection1	Membrane waterpro	0	44	0
117	2025	102	Repair	Water jet & casting	661	89	58650
117	2025	102	Repair	Water jet & casting	661	93	61468
117	2025	102	Repair	Water jet & casting	661	98	65026
117	2025	102	Repair	Water jet & casting	661	102	67407
117	2025	102	Repair	Water jet & casting	661	91	60248
108	2027	116	Protection1	Silane impregnation	23	25	571
108	2027	116	Protection1	Silane impregnation	23	23	516
108	2027	102	Repair	Water jet & casting	458	23	10307
113	2027	116	Protection1	Silane impregnation	17	13	227
113	2027	116	Protection1	Silane impregnation	17	12	205
201	2029	116	Protection1	Silane impregnation	22	283	6179
201	2029	102	Repair	Water jet & casting	399	283	113073
108	2029	116	Protection1	Silane impregnation	23	25	577
108	2029	102	Repair	Water jet & casting	463	25	11521
114	2032	116	Protection1	Silane impregnation	18	8	139
106	2034	102	Repair	Water jet & casting	458	69	31666
109	2034	102	Repair	Water jet & casting	458	44	20212
113	2034	116	Protection1	Silane impregnation	17	13	228

113	2034	116	Protection1	Silane impregnation	17	12	206
110	2035		Repair	Electr. chloride remo	270	24	6344
201	2037	116	Protection1	Silane impregnation	17	283	4893
108	2037	116	Protection1	Silane impregnation	17	23	389
108	2039	116	Protection1	Silane impregnation	17	25	431
114	2039	116	Protection1	Silane impregnation	18	8	140
113	2042	116	Protection1	Silane impregnation	18	13	230
202	2042	701	Protection1	0	0	104	0
202	2042	102	Repair	Water jet & casting	305	104	31782
113	2042	116	Protection1	Silane impregnation	18	12	208
201	2045	116	Protection1	Silane impregnation	17	283	4926
110	2045	603	Protection1	Maurer service	27	24	624
106	2045	603	Protection1	Maurer service	0	69	0
109	2045	603	Protection1	Maurer service	0	44	0
114	2045	116	Protection1	Silane impregnation	18	8	142
114	2045	102	Repair	Water jet & casting	328	8	2595
108	2047	116	Protection1	Silane impregnation	17	23	391
108	2049	116	Protection1	Silane impregnation	17	25	433
113	2049	116	Protection1	Silane impregnation	18	13	233
113	2049	116	Protection1	Silane impregnation	18	12	210
301	2052	701	Protection1	Mastix waterproofing	113	1225	138184
301	2052		Protection2	Milling and levelling	207	1225	253218
301	2052	105	Patching	Patching of deck	9	796	7072
201	2052	116	Protection1	Silane impregnation	18	283	4969
114	2052	116	Protection1	Silane impregnation	17	8	135
108	2057	116	Protection1	Silane impregnation	17	23	393
113	2057	116	Protection1	Silane impregnation	18	13	237
113	2057	102	Repair	Water jet & casting	351	13	4593
113	2057	116	Protection1	Silane impregnation	18	12	214
113	2057	102	Repair	Water jet & casting	351	12	4150
108	2059	116	Protection1	Silane impregnation	17	25	436
114	2059	116	Protection1	Silane impregnation	17	8	136
201	2060	116	Protection1	Silane impregnation	18	283	5041
110	2060		Repair	Electr. chloride remo	179	24	4204
113	2065	116	Protection1	Silane impregnation	17	13	223
113	2065	116	Protection1	Silane impregnation	17	12	202
108	2067	116	Protection1	Silane impregnation	18	23	397
114	2067	116	Protection1	Silane impregnation	17	8	137
201	2068	116	Protection1	Silane impregnation	18	283	5134
110	2068	603	Protection1	Maurer service	26	24	601
106	2068	603	Protection1	Maurer service	0	69	0
109	2068	603	Protection1	Maurer service	0	44	0
108	2068	116	Protection1	Silane impregnation	18	25	439
113	2073	116	Protection1	Silane impregnation	17	13	224
202	2073	701	Protection1	0	0	104	0
113	2073	116	Protection1	Silane impregnation	17	12	203
114	2075	116	Protection1	Silane impregnation	18	8	140
201	2076	116	Protection1	Silane impregnation	19	283	5245
108	2076	116	Protection1	Silane impregnation	18	23	400
202	2076	701	Protection1	0	0	104	0
202	2076	102	Repair	Water jet & casting	304	104	31659
108	2078	116	Protection1	Silane impregnation	18	25	443
201	2079	116	Protection1	Silane impregnation	19	283	5278
201	2079	102	Repair	Water jet & casting	341	283	96585
106	2079	102	Repair	Water jet & casting	348	69	24029
109	2079	102	Repair	Water jet & casting	348	44	15338
301	2080	701	Protection1	Mastix waterproofing	119	1225	145649

3.2.2 Storing the Results

The designer can store the results of the life cycle planning by pressing the button ”Store the results” on the ”Results” display. Then the ”Save_As” display of Excel is opened and the saving is performed normally to the desired file in the desired address.

The storing command saves the ”Paperitul” (Paper results) page as a whole. The “Papertul” page contains all the data and graphs of the paper print previously described. The”Paperitul” page can be made visible by first making the sheet tabs visible (as described in Chapter 3.1.2) and then by pressing the tab with the same name.

3.3 USE OF PROGRAM BRIDGELIFE WITH ”HANKE-SIHA”

3.3.1 Connection to “Hanke-Siha”

The connection between programs ”Bridgelife” and the main program of the project level Bridge Management System ”Hanke-Siha” can be seen schematically in Figure 26. The initial data is first imported from Bridge Register to Bridgelife through the interface file ”Sr_Ek.xls” which is produced by a module contained in Hanke-Siha. The initial data is processed in the batch process of program Bridgelife. The results of the life cycle planning are then stored in a special interface file Ek_Hs.xls. The results data contained in this file is imported to program Hanke-Siha and stored in its database tables. The data can then be seen on the displays of Hanke-Siha.

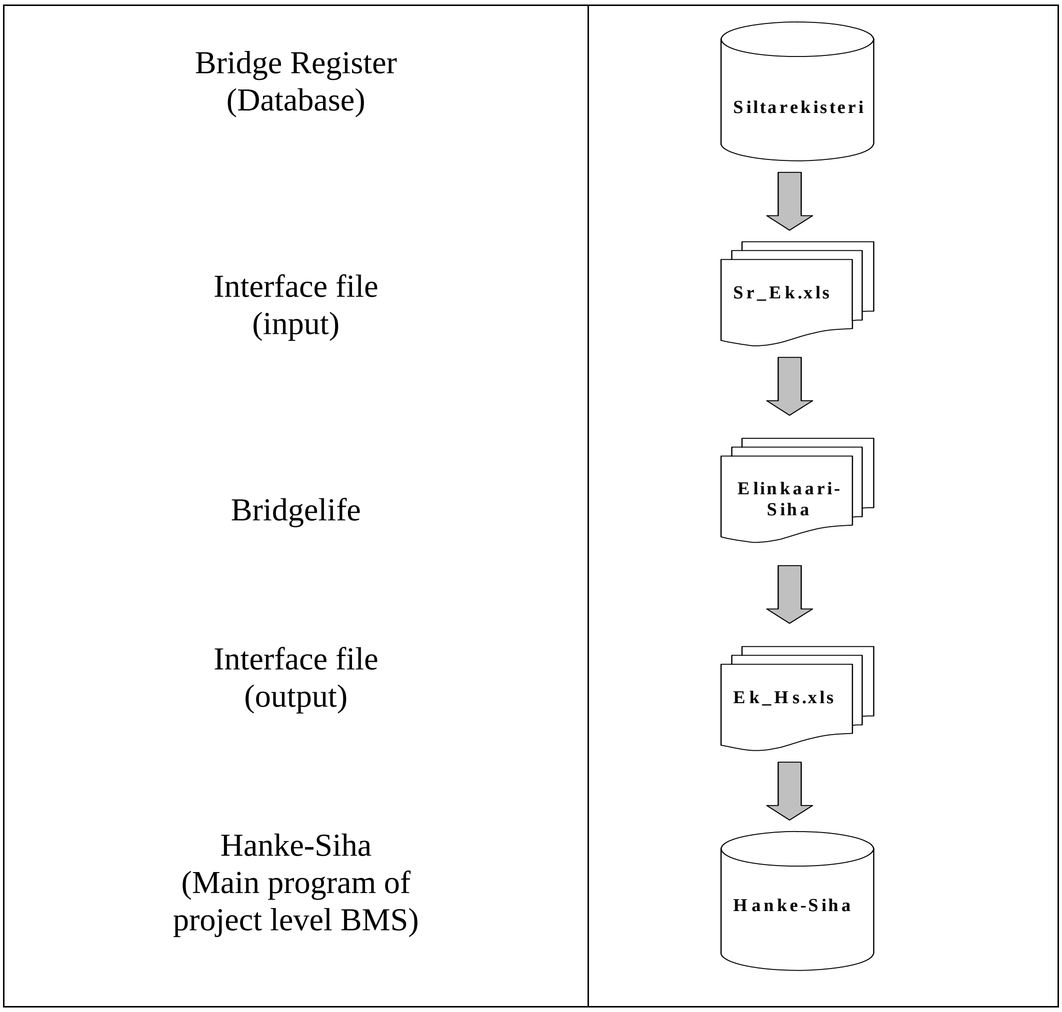


Fig. 26. The data flow between programs Bridgelife and Hanke-Siha (figure Inframan Oy).

3.3.2 The interface file produced by Bridgelife for Hanke-Siha

Program ”Bridgelife” produces the interface file EK_HS.xls for Hanke-Siha. The interface file consists of two data tables. One of the, ”EK_Silta”, contains the bridge specific data and the other ”EK_Rakosa” contains the component specific data. In the following the structure of these data tables is presented in the form of examples.

EK_Silta

Bridge_id	Action	Year	Delay_cost	Next_project	Next_rehabil
2253	11	2026	398	2122	
8061	11	2005	169	2013	2020
8066	11	2020	7	2023	2023
8169	11	2065	197	2077	
8268	11	2019	18	2023	2023
8284	11	2021	4	2024	2024
8344	12	2019	1831	2059	2060
8351	11	2021	29	2024	2024
8375	11	2069	448		
8415	11	2005	54	2016	2024
8453	12	2024	68	2072	2072
8473	12	2024	1256	2072	2072
8499	12	2010	19032	2030	2038
8528	11	2021	291	2038	
8607	11	2013	11	2015	2015
150718	12	2024	311	2070	2072

EK_Rakosa

Bridge_id	Compon_code	Action_code	Cost
2253	106	102	25922
8061	201	116	5255
8061	113	116	243
8061	114	116	147
8061	113	116	219
8066	110	603	846
8066	106	603	212
8066	109	603	282
8169	304	102	29352
8268	110	603	650
8268	110	603	690
8268	106	603	619
8268	106	603	656
8268	109	603	1060
8268	109	603	1115
8284	110	603	257
8284	109	603	425
8344	301	701	68523
8344	301		125565
8344	301	105	13850
8344	301	701	827
8344	301		1516
8344	301	105	148
8344	301	701	11686
8344	301		21415
8344	301	105	2236
8351	110	603	389
8351	106	603	1073

Bridge_id	Compon_code	Action_code	Cost
8351	106	603	766
8351	109	603	1086
8375	201	102	12904
8375	105	102	8720
8375	105	102	9343
8375	304	102	44206
8415	108	116	238
8415	117	116	1423
8415	117	116	1450
8453	301	701	2278
8453	301		4174
8453	301	105	627
8473	301	701	32420
8473	301		59409
8473	301	105	9501
8473	301	701	2963
8473	301		5430
8473	301	105	792
8499	301	701	147963
8499	301		271137
8499	301	105	15390
8499	301	701	1201
8499	301		2202
8499	301	105	138
8499	301	701	37594
8499	301		68891
8499	301	105	4313
8499	201	102	184799
8499	110	603	313
8499	110		1375
8499	106	603	2181
8499	109	603	778
8499	104	102	79683
8499	108	102	9663
8499	113	102	5906
8499	114	102	2765
8499	302	102	222173
8499	302	102	222173
8499	303	102	30992
8499	309	102	2251
8528	110	603	300
8528	106	603	1158
8528	106	603	1101
8528	109	603	324
8528	113	102	5233
8528	114	102	4112
8607	110	603	707
8607	106	603	237
8607	109	603	1745
150718	301	701	17459
150718	301		31993
150718	301	105	4208

3.4 DECISION TREES

The three decision trees used by program Bridgelife version 1.1. are presented graphically in figures 27, 28 and 29. The decision trees are:

- general decision tree for concrete bridge components (takes into account coatings and other protection methods of components)
- decision tree of bridge deck (takes into account the special repair actions for the deck)
- decision tree for bearing plane (takes into account the degradation effect of leaking expansion joints).

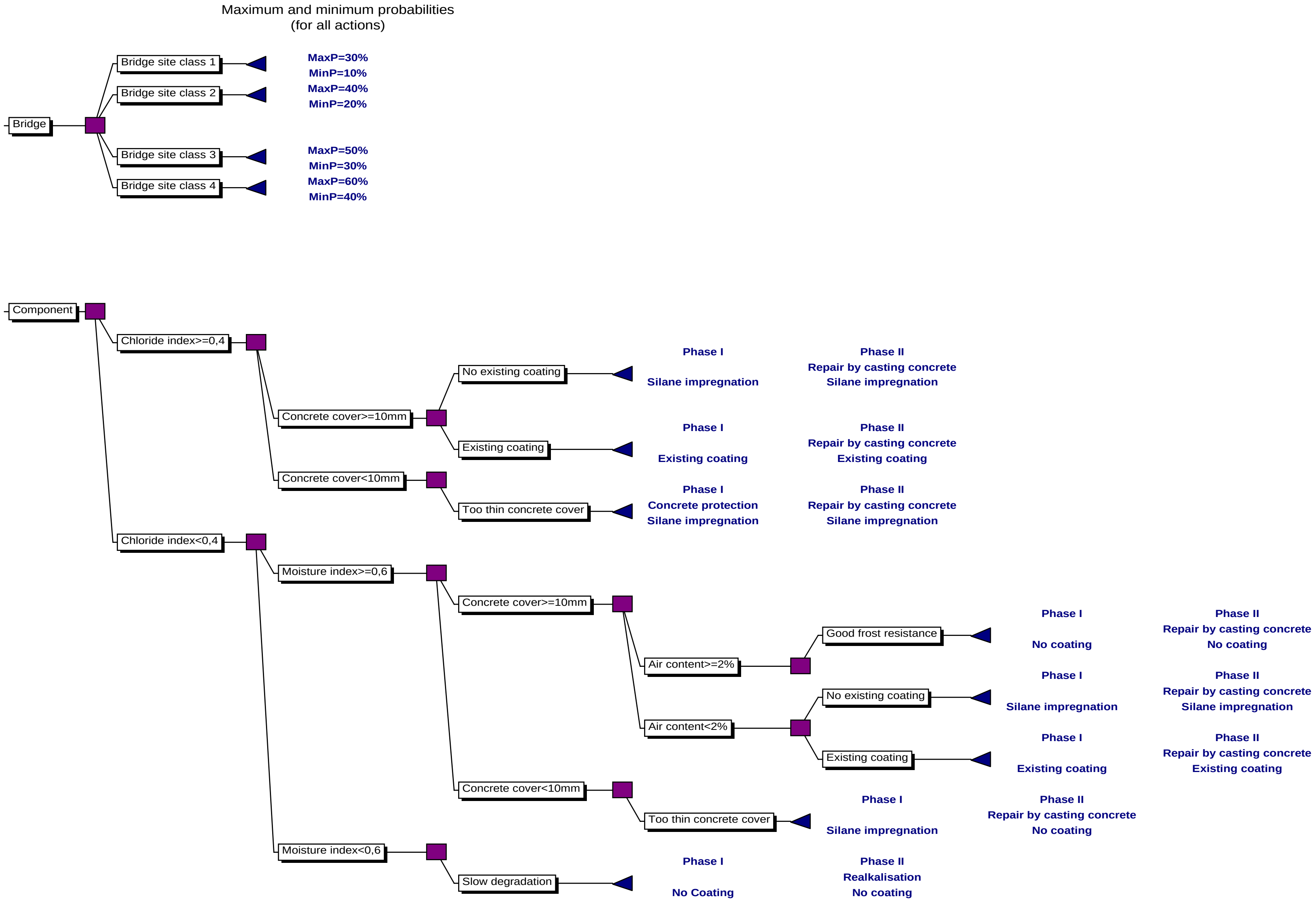


Fig 27. General decision tree for concrete structures.

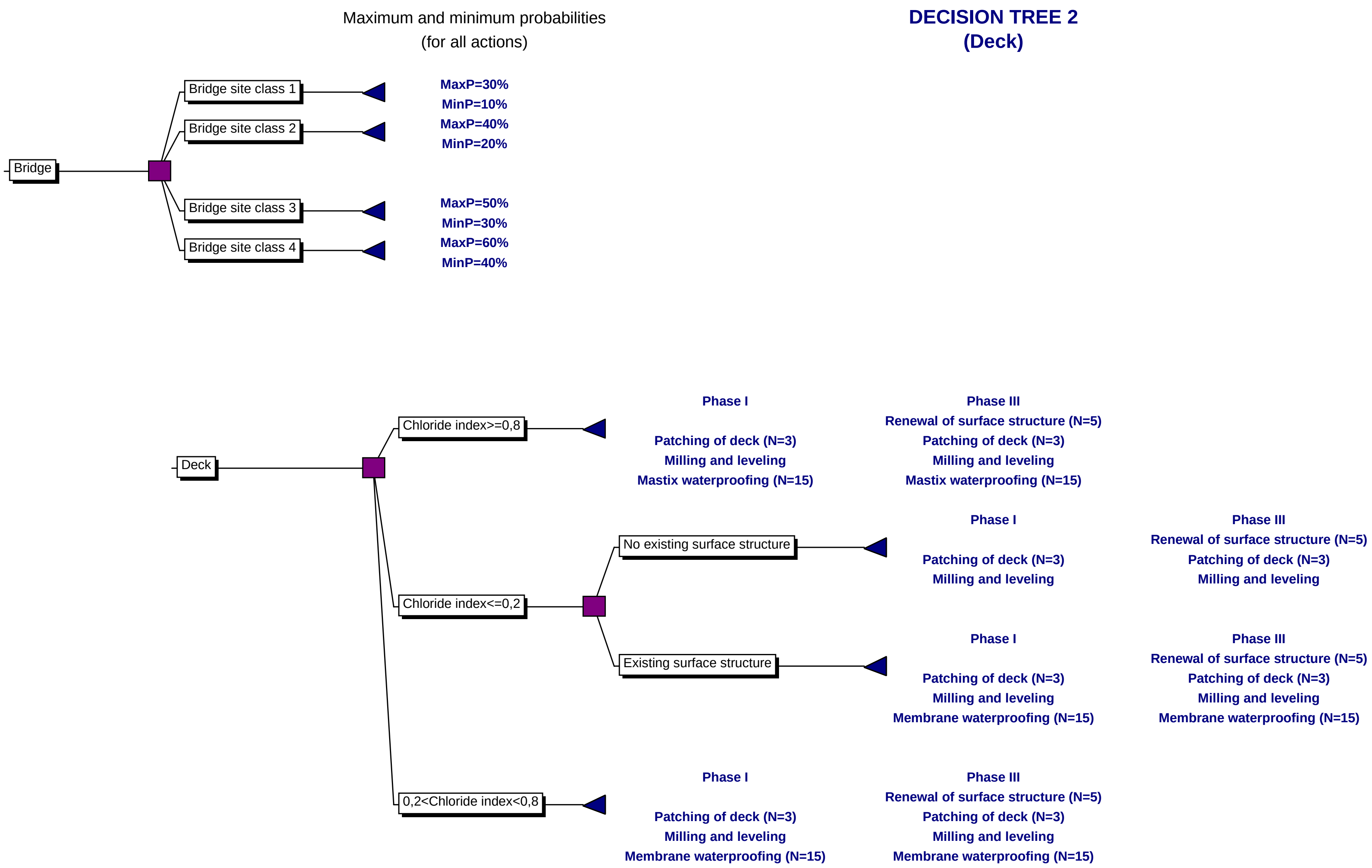


Fig. 28. Decision tree of deck.

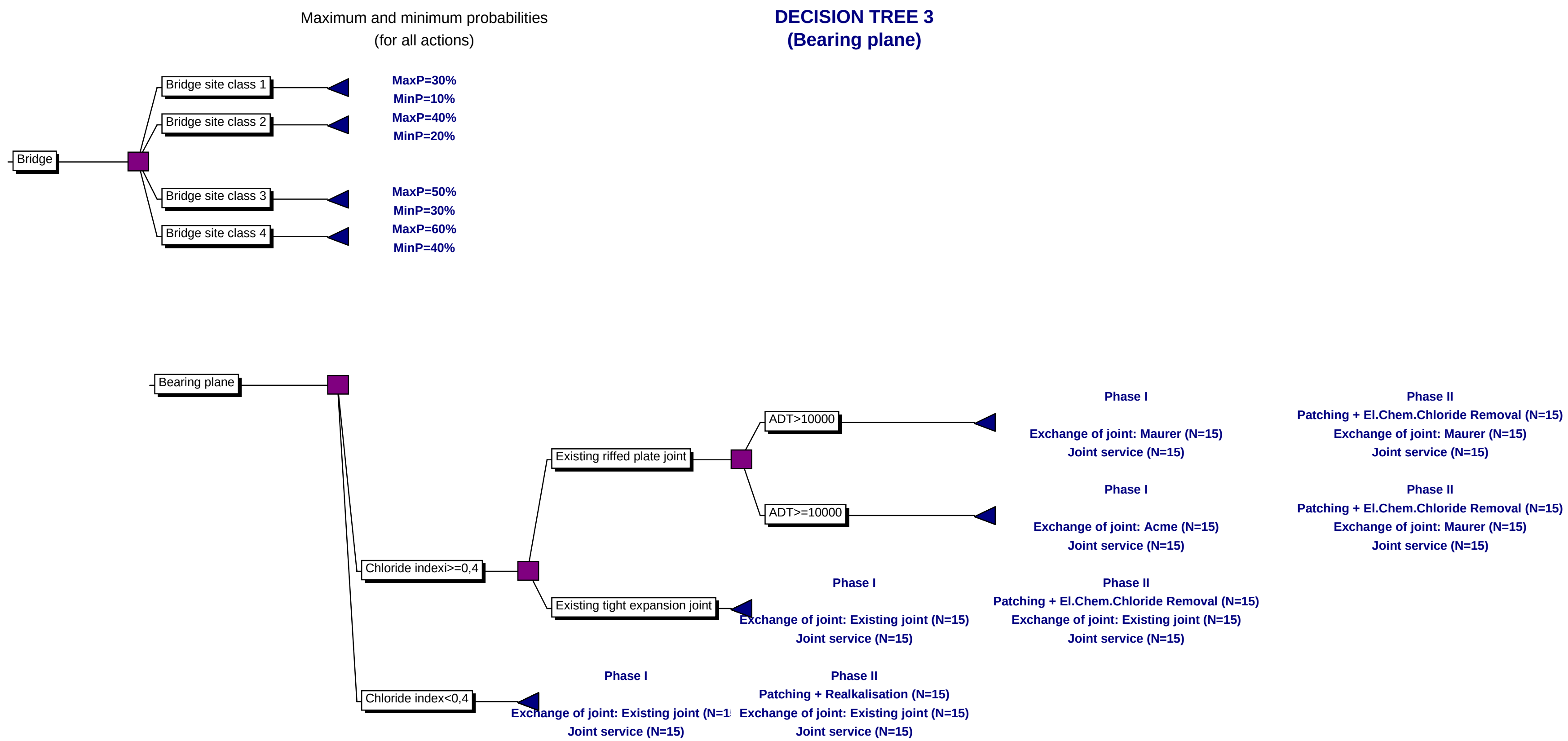


Fig 29. Decision tree of bearing plane.

3.5 THE PAPER PRINT FOR SERVICE LIFE DESIGN

The paper print for Service Life Decign is started by pressing the button ”Paper print” on the “Service Life Design” display. An example of the paper print is presented below.

SERVICE LIFE DESIGN							
Bridgelife	9.8.2006						
Component		201	Edge beam				
Design Service Life		30	years				
Exposure data							
Geographical situation		1	Coastal Finland				
Purpose of use		12	Cross roads bridge				
Exposure stress		12	Urban				
Maintenance class of the road		12	1-road superways ADT 6000…12000				
Maintenace class of the crossing road		15	ADT 350…1500				
Component data							
Cement		12	CEM II/A-S				
Nominal strength, MPa		40	MPa				
Air content		4	%				
Concrete cover, mm		35	mm				
Condition state distribution	CondSt	0	1	2	3	4	
	%	100	0	0	0	0	
Protection data							
Protection 1		Yes					
Protection Action		9	Silan impregnation (116)				
Limit condition state		3					
Max allowable probability		40	%				
Max number of sequential protections		1					
Protection 1 patching		No					
Limit condition state							
Max allowable probability			%				
Max number of patchings (protection 1)							
Protection 2		Yes					
Protection Action		43	Filling of cracks (110)				
Limit condition state		3					
Max allowable probability		40	%				
Max number of sequential protections		1					
Protection 2 patching		No					
Limit condition state							
Max allowable probability			%				
Max number of patchings (protection 2)							
Level of Safety		90	%				
Surface Damage							
Predicted Service Life		35	years				
Halkeamavauriot							
Predicted Service Life		#N/A	years				

On the paper print the following data of the designed component is presented: (1) Identification data (2) Design service life (3) Exposure data (4) Material data (5) Structural data (6) Condition data (7) Protection data (8) Required safety level (9) Predicted service life with respect to ”surface damage” and (10) Predicted service life with respect to “Crack corrosion”. In the example the predicted service life with respect to crack corrosion is infinitely long because of filling of the cracks. This causes the sign #N/A in the paper print.

References

1. Söderqvist M-K. and Vesikari E., "Generic Technical Handbook for a Predictive Life Cycle Management System of Concrete Structures (LMS)", *Lifecon GIRD-CT-2000-00378 Lifecon Deliverable D1.1*, final report, Dec 2003. 170 p. http://lifecon.vtt.fi/
2. Vesikari E., "Statistical Condition Management and Financial Optimisation in Lifetime Management of Structures." Part 1: "Markov Chain Based Life Cycle Cost (LCC) Analysis". Part 2: "Reference Structure Models for Prediction of Degradation", *Lifecon GIRD-CT-2000-00378 Lifecon Deliverable D2.2*, final report, Dec 2003. 113 p. http://lifecon.vtt.fi/
3. European Cement Standard EN 197-1 : 2001 Cement - Part 1 : Composition, Specifications and Conformity Criteria for Common Cements.

PART II: CALCULATION PRINCIPLES

1 General

The basic idea of the program “Bridgelife” is to combine a Markov Chain based condition analysis with a life cycle cost analysis and a life cycle assessment (ecology) analysis. Starting from the initial condition state distribution of a component a statistical condition analysis covering the whole design period is performed. The optimal MR&R (maintenance, repair and rehabilitation) actions are automatically specified by the help of decision trees. The timings of MR&R actions are automatically triggered by a condition guarding system which is built over the Markov Chain based condition analysis. Whenever the predefined maximum allowable probability of exceeding the limit condition state are attained the system triggers a MR&R action /1, 3/.

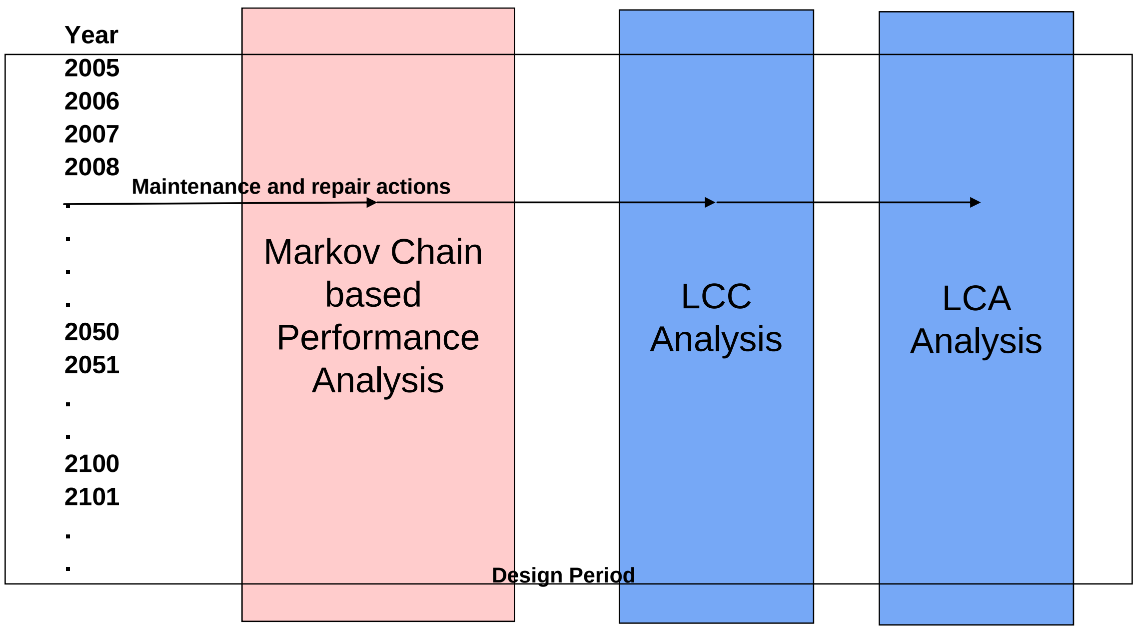


Fig. 1. Principle of combining the Markov Chain based Condition (Performance) analysis with a LCC analysis and a LCA analysis.

2 Markov Chain based Condition analysis

The Markov Chain method is a mathematical framework based on probability calculus and vector algebra. In the condition analysis of structural components is used for predicting the future condition of structures over a certain time frame. The condition is presented in the form of condition vectors i.e. frequency distributions based on a predefined set of condition states. The annual changes in the condition state distributions are predicted by matrix multiplications using transition probability matrices.

The Markov Chain method as such does not contain any information on the rate of degradation of structures. However, if such data is available in any form it can usually be transferred into transition probabilities of the Markov Chain degradation matrices so that the results of the Markov Chain based condition analysis corresponds closely the original information. Markov Chain transition probabilities have also been proved to be suitable for modelling the action effects of various MR&R actions. The action effect models are necessary because the condition analysis must cover – not only the period up to the next repair of the structure – but over the whole design period which may comprise of many sequential MR&R actions of different types.

The following advantages can be gained by the Markov Chain based condition analysis:

- Fully probabilistic reproduction of the condition of a structure over the time frame
- Capability of triggering actions based on the reliability theory
- Capability of combining the condition related effects of both degradation and MR&R actions
- Capability of straightforward combining sequential degradation processes such as the process of depassivation by carbonation or chloride contamination and active corrosion of reinforcement
- Capability of describing parallel time dependent processes and their interaction such as degradation of a coating on a structure which also is deteriorating
- Easily attachable to a LCC analysis.
- Enables calculation of risk costs and costs that depend on the condition of the structure.

In the following a description on the basics of the Markov Chain method and its application to the condition analysis of structural components is given.

2.1 BASICS OF MARKOV CHAIN MODELLING

The Markov Chain method evaluates the condition of structures as condition state distributions at each year t. A condition state distribution expresses the relative proportions (=fractions) of structures being at the defined condition states. A condition state distribution is exemplified in the following table.

Table 1. Condition state distribution (Example).

State	0	1	2	3	4
Fraction	w_0	w_1	w_2	w_3	w_4
Example of fraction	0,25	0,35	0,25	0,1	0,05

When studying the condition of structures at the network level the fractions refer to the surface area (sometimes length or other functional unit) of all structures or structural parts belonging to a network of structures. At the object level the fractions refer to the surface area (or other functional unit) of one structure or a structural part. When predicting the condition of structures by the Markov Chain method the condition state vector is interpreted as expressing the probability of a structure or structural part to be at any of the condition states in the future. The sum of all fractions in a condition state vactor must always be 1.

The number of condition states is not restricted. In the following examples of the Markov Chain calculus the number of states is assumed to be five consisting of states 0, 1, 2, 3 and 4. The condition state 0 represents the best and 4 the poorest condition. The condition state 3 defines usually the limit state of service life that is the state at which the structure should normally be repaired.

The changes in condition states as a result of both degradation and MR&R actions are evaluated by transition probability matrices. The condition state distribution of each year is obtained by multiplying the condition state vector of the previous year by the transition probability matrix. Mathematically the principle is presented in Equation 1. By repeated multiplication the condition state distributions can be predicted over time up to several years or even tens of years.

$$W(t) = W(t-1) * P \tag{1}$$

where
W(t) is condition state distribution of year t and
P transition probability matrix

There are two kinds of transition probability matrices:
- Degradation matrices
- Action effect matrices.

Degradation matrices are applied in years when repair actions are not performed, i.e. the changes in the condition state distribution result only from degradation. The action effect matrices predict the condition state distribution, as it will be after the repair action. They are applied only in those years during which repair actions are performed. Accordingly, by the help of the Markov Chain it is possible to reproduce the condition of a structure during the whole time frame as a series of sequential annual condition state distributions. The treated time frame may include various maintenance and repair actions such as coatings, other predictive maintenance actions, repairs and renewals.

2.2 DEGRADATION MATRICES

Usually the form of a degradation matrix is assumed to be as the one presented in Table 2. The elements of a transition probability matrix express the probability that a structure, which at the beginning of a year was at condition state i (vertical direction), will be at the end of the year at condition state j (horizontal direction).

It has been assumed in the table that within one year the structure either stays at the same condition state where it was at the beginning of that year or it drops to the next state, i.e. dropping more than 1 state in a year is not possible. Accordingly, most of the transition probabilities are 0. Only the diagonal probabilities, i.e. the probabilities that a structure stayes at the same condition state and the probabilities next to the right of them expressing the probability that the structure will be transited to the next state during a year, are non-zero elements. The sum of transition probabilities in each row must be 1 ($p_{i;i} + p_{i;i+1} = 1$).

Table 2. Transition probability matrix for degradation (5 state system).

State	0	1	2	3	4
0	p_{00}	p_{01}	0	0	0
1	0	p_{11}	p_{12}	0	0
2	0	0	p_{22}	p_{23}	0
3	0	0	0	p_{33}	p_{34}
4	0	0	0	0	1

The transition probabilities of degradation matrices are determined automatically from previously developed degradation model functions by special conversion methods. So the information included in the material, structural and environmental parameters of the model functions are automatically transferred to the transition probabilities of degradation matrices.

The "drop-from-state" transition probabilities, $p_{i,i+1}$, can be deduced from the scaled degradation model functions by derivation of the model function and determination of the average value of the derivative within the interval of the states i and i+1 /2/.

$$p_{i;i+1} = DoD'_{i;i+1} = \left(\frac{\partial(DoD(t))}{\partial t}\right)_{i;i+1} \tag{2}$$

where

$p_{i;i+1}$ is	transition probability from stati to state i+1
DoD(t)	a scaled degradation function. DoD is “degree of damage” and is considered to be the same as condition state.

The average value of the derivative can be determined either by calculating the value of the derivative in several points within the range i; i+1 or by determining the value of the derivative in a point that is proved to optimally represent the average.

The "Remain-in-state" transition probabilities, $p_{i;i}$, can be determined by subtracting the corresponding "drop-from-state" probability from 1.

$$p_{i;i} = 1 - p_{i;i+1} \tag{3}$$

At the lower right corner of the matrix the value of the probability element is always 1 as the structures in the highest possible condition state always stay at the same condition state.

The condition state vector after *n* years is predicted by multiplying the initial condition state vector, W(0), by the transition matrix n times in the row, as shown in the example of Figure 1. In this example the limit condition state of service life has been defined to be 3 (DoD = 3). The state 4 is assumed to be a "terminal state", i.e. an extra state where all structures finally end up. All structures in this case start off in perfect condition, so the initial damage index distribution is | 1, 0, 0, 0, 0 |.

Transition probability matrix

State	0	1	2	3	4
0	0.61	0.39	0	0	0
1	0	0.74	0.26	0	0
2	0	0	0.82	0.18	0
3	0	0	0	0.91	0.09
4	0	0	0	0	1

Year	State 0	1	2	3	4	Average DoD
0	1.000	0.000	0.000	0.000	0.000	0.00
1	0.610	0.390	0.000	0.000	0.000	0.39
2	0.372	0.527	0.101	0.000	0.000	0.73
3	0.227	0.535	0.220	0.018	0.000	1.03
4	0.138	0.484	0.319	0.056	0.002	1.30
5	0.084	0.412	0.388	0.109	0.007	1.54
6	0.052	0.338	0.425	0.169	0.016	1.76
7	0.031	0.270	0.437	0.230	0.032	1.96
8	0.019	0.212	0.428	0.288	0.052	2.14
9	0.012	0.165	0.406	0.339	0.078	2.31
10	0.007	0.126	0.376	0.382	0.109	2.46
11	0.004	0.096	0.341	0.415	0.143	2.60
12	0.003	0.073	0.305	0.439	0.181	2.72
13	0.002	0.055	0.269	0.454	0.220	2.84
14	0.001	0.041	0.235	0.462	0.261	2.94
15	0.001	0.031	0.203	0.463	0.303	3.04
16	0.000	0.023	0.175	0.458	0.344	3.12
17	0.000	0.017	0.149	0.448	0.385	3.20
18	0.000	0.013	0.127	0.434	0.426	3.27
19	0.000	0.010	0.107	0.418	0.465	3.34
20	0.000	0.007	0.091	0.400	0.502	3.40
21	0.000	0.005	0.076	0.380	0.538	3.45
22	0.000	0.004	0.064	0.360	0.573	3.50
23	0.000	0.003	0.053	0.339	0.605	3.55
24	0.000	0.002	0.044	0.318	0.635	3.59
25	0.000	0.002	0.037	0.297	0.664	3.62
26	0.000	0.001	0.031	0.277	0.691	3.66
27	0.000	0.001	0.026	0.258	0.716	3.69
28	0.000	0.001	0.021	0.239	0.739	3.72
29	0.000	0.000	0.018	0.221	0.760	3.74
30	0.000	0.000	0.015	0.205	0.780	3.77
31	0.000	0.000	0.012	0.189	0.799	3.79
32	0.000	0.000	0.010	0.174	0.816	3.81
33	0.000	0.000	0.008	0.160	0.832	3.82
34	0.000	0.000	0.007	0.147	0.846	3.84
35	0.000	0.000	0.006	0.135	0.859	3.85
36	0.000	0.000	0.005	0.124	0.871	3.87
37	0.000	0.000	0.004	0.114	0.883	3.88
38	0.000	0.000	0.003	0.104	0.893	3.89
39	0.000	0.000	0.003	0.095	0.902	3.90
40	0.000	0.000	0.002	0.087	0.911	3.91
41	0.000	0.000	0.002	0.080	0.919	3.92
42	0.000	0.000	0.001	0.073	0.926	3.92
43	0.000	0.000	0.001	0.067	0.932	3.93
44	0.000	0.000	0.001	0.061	0.938	3.94
45	0.000	0.000	0.001	0.055	0.944	3.94
46	0.000	0.000	0.001	0.051	0.949	3.95
47	0.000	0.000	0.001	0.046	0.953	3.95
48	0.000	0.000	0.000	0.042	0.957	3.96
49	0.000	0.000	0.000	0.038	0.961	3.96
50	0.000	0.000	0.000	0.035	0.965	3.96

Figure 1. Calculation of sequential condition state distributions by the Markov Chain method.

The expectation value of the degree of damage (= expected average DoD) is obtained by multiplying the scale vector R = ¦ 0, 1, 2, 3, 4 ¦ by the condition state distribution, as shown in Equation 4.

$$E(t) = W(t) * R \qquad (4)$$

where

E(t) is expectation value for the degree of damage (=average)

R scale vector comprising of the numerical values of condition states

The probability density functions and the cumulative probability functions for the states 0...4 are depicted in Figures 2 and 3 according to the calculations in Figure 1.

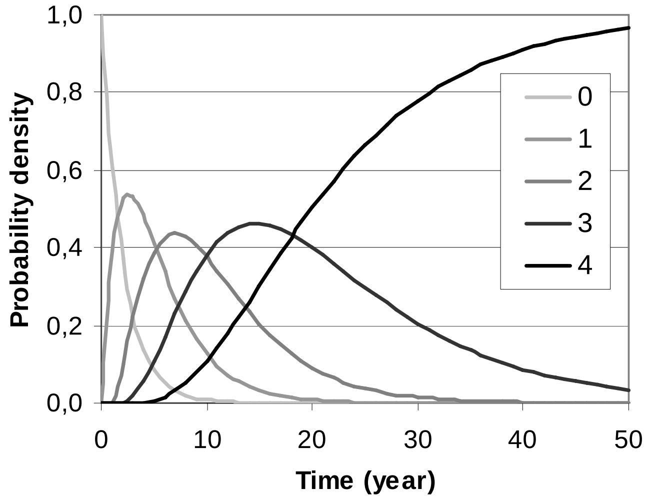


Figure 2. Probability density functions for condition states (=degrees of damage) 0 - 4 calculated by the Markov Chain method.

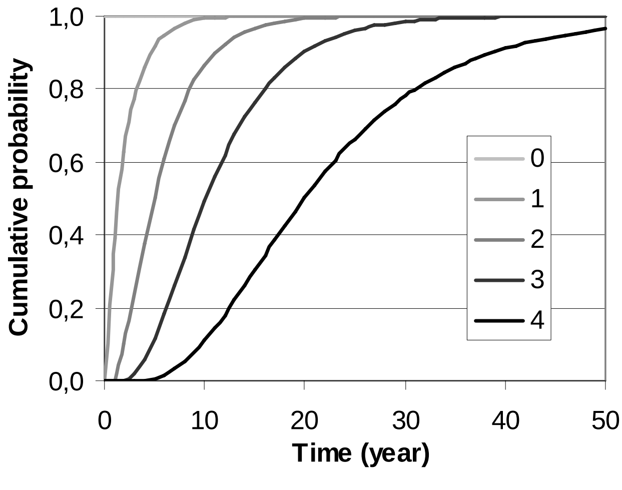


Figure 3. Cumulative probability functions for degrees of damage 0 - 4 determined by the Markov Chain method.

2.3 ACTION EFFECT MATRICES

The action effect matrices are built individually for each repair action taking into account the probable changes in the condition of the structure as a result of the action and the risk of failure during repair. Thus the condition state distribution of the structure after a repair action is not necessarily the same as that for a new structure.

The general appearance of an action effect matrix is as shown in Table 5. As it is assumed that the condition state of a structure is always improved or at least remains the same as a result of a MR&R action, all the probability elements above the diagonal are 0. Other elements may have a value between 0...1. Again the sum of transition probabilities in each row must be 1. Usually heavy repair actions bring the structures close to the perfect condition so that the elements in the first column of the matrix are near 1 and the others near 0.

Table 3. Transition probability matrix for MR&R action effects (5 state system).

State	0	1	2	3	4
0	p_{00}	0	0	0	0
1	p_{10}	p_{11}	0	0	0
2	p_{20}	p_{21}	p_{22}	0	0
3	p_{30}	p_{31}	p_{32}	p_{33}	0
4	p_{40}	p_{41}	p_{42}	p_{43}	p_{44}

Much data is lacking in this area as very little research work has been done for studying the condition-related effects of various repair actions. So there are usually no convertion methods used for action effect matrices as were for degradation matrices. In practice the transition probabilities of action effect matrices are usually determined based on expert evaluation (Delphi study).

A typical action effect matrix can be seen on top of Figure 4. The purpose of Figure 4 is to visualise the action effects in a Markov Chain process. The calculation table is programmed so that a repair is done every time when signed by 1 in the column at the left side of the figure. The action effects can be readily seen in the condition state distributions and the average DoD curve presented in Figure 5.

Transition probability matrix of repair

State	0	1	2	3	4
0	1	0	0	0	0
1	0.95	0.05	0	0	0
2	0.92	0.05	0.03	0	0
3	0.9	0.05	0.03	0.02	0
4	0.88	0.05	0.03	0.02	0.02

Transition probability matrix of degradation

State	0	1	2	3	4
0	0.61	0.39	0	0	0
1	0	0.74	0.26	0	0
2	0	0	0.82	0.18	0
3	0	0	0	0.91	0.09
4	0	0	0	0	1

Repair	Year	State 0	1	2	3	4	Average DoD
	0	1.000	0.000	0.000	0.000	0.000	0.00
	1	0.610	0.390	0.000	0.000	0.000	0.39
	2	0.372	0.527	0.101	0.000	0.000	0.73
	3	0.227	0.535	0.220	0.018	0.000	1.03
	4	0.138	0.484	0.319	0.056	0.002	1.30
	5	0.084	0.412	0.388	0.109	0.007	1.54
	6	0.052	0.338	0.425	0.169	0.016	1.76
	7	0.031	0.270	0.437	0.230	0.032	1.96
	8	0.019	0.212	0.428	0.288	0.052	2.14
	9	0.012	0.165	0.406	0.339	0.078	2.31
	10	0.007	0.126	0.376	0.382	0.109	2.46
	11	0.004	0.096	0.341	0.415	0.143	2.60
	12	0.003	0.073	0.305	0.439	0.181	2.72
	13	0.002	0.055	0.269	0.454	0.220	2.84
	14	0.001	0.041	0.235	0.462	0.261	2.94
1	15	0.902	0.050	0.029	0.014	0.005	0.17
	16	0.550	0.389	0.037	0.018	0.007	0.54
	17	0.336	0.502	0.131	0.023	0.008	0.87
	18	0.205	0.502	0.238	0.045	0.010	1.15
	19	0.125	0.452	0.326	0.084	0.014	1.41
	20	0.076	0.383	0.385	0.135	0.022	1.64
	21	0.046	0.313	0.415	0.192	0.034	1.85
	22	0.028	0.250	0.422	0.249	0.051	2.05
	23	0.017	0.196	0.411	0.303	0.074	2.22
	24	0.011	0.152	0.388	0.349	0.101	2.38
	25	0.006	0.116	0.357	0.388	0.132	2.52
	26	0.004	0.089	0.323	0.417	0.167	2.65
	27	0.002	0.067	0.288	0.438	0.205	2.78
	28	0.001	0.051	0.254	0.450	0.244	2.88
1	29	0.903	0.050	0.028	0.014	0.005	0.17
	30	0.551	0.389	0.036	0.018	0.006	0.54
	31	0.336	0.503	0.131	0.023	0.008	0.86
	32	0.205	0.503	0.238	0.044	0.010	1.15
	33	0.125	0.452	0.326	0.083	0.014	1.41
	34	0.076	0.383	0.385	0.134	0.021	1.64
	35	0.047	0.313	0.415	0.191	0.033	1.85
	36	0.028	0.250	0.422	0.249	0.051	2.04
	37	0.017	0.196	0.411	0.303	0.073	2.22
	38	0.011	0.152	0.388	0.349	0.100	2.38
	39	0.006	0.117	0.358	0.388	0.132	2.52
	40	0.004	0.089	0.324	0.417	0.167	2.65
	41	0.002	0.067	0.288	0.438	0.204	2.77
	42	0.001	0.051	0.254	0.450	0.243	2.88
	43	0.001	0.038	0.221	0.456	0.284	2.98
	44	0.001	0.029	0.191	0.454	0.325	3.07
1	45	0.899	0.050	0.029	0.016	0.007	0.18
	46	0.548	0.388	0.037	0.019	0.008	0.55
	47	0.334	0.501	0.131	0.024	0.010	0.87
	48	0.204	0.501	0.238	0.046	0.012	1.16
	49	0.124	0.450	0.325	0.084	0.016	1.42
	50	0.076	0.382	0.384	0.135	0.024	1.65

Figure 4. Action effects in a Markov Chain lifetime table.

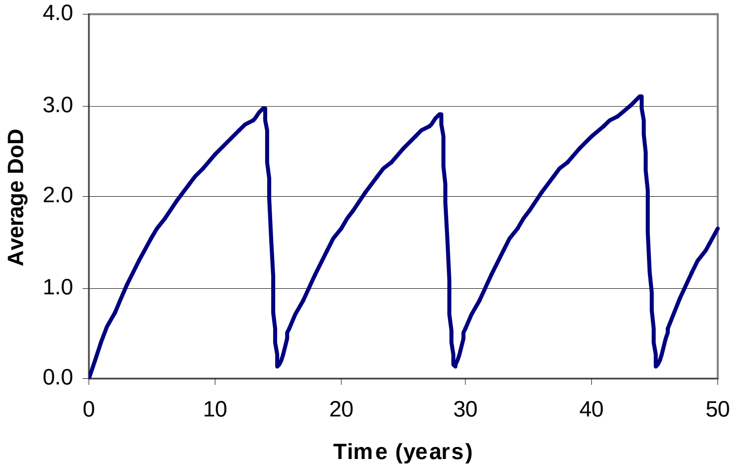


Figure 5. The average DoD with time showing the effects of repair on the condition of a structure.

A repair action may also have an impact on the rate of degradation after the repair. If the rate of degradation is expected to be changed after a MR&R action the degradation matrix is changed respectively.

2.4 MODELLING OF THE ACTION EFFECTS OF COATINGS

When applying coatings and other preventive maintenance measures the condition state of the structure is not considered to be changed at all but the rate of further degradation is reduced. So no action effect matrix is applied in connection of preventive maintenance actions but the degradation matrix is changed according to the expected rate of degradation. The effects of coatings on the condition of the structure depend on the condition of the coating /4/.

Coatings have both direct and indirect effects on the condition state of a structure. The direct effects are a result of the physical barrier which retards the penetration of aggressive agents, such as CO_2 and chlorides, into the concrete structure. The indirect effects result from the changed moisture content in the structure because of the coating as the moisture content has a remarkable effect on the degradation rate. The model of a degradation matrix which takes into account the direct effects of a coating to the degradation rate of a structure is presented in Table 6.

Table 4. The assumed form a degradation matrix for a coated structure.

State	0	1	2	3	4
0	$1-p_c \cdot p_{01}$	$p_c \cdot p_{01}$	0	0	0
1	0	$1-p_c \cdot p_{12}$	$p_c \cdot p_{12}$	0	0
2	0	0	$1-p_c \cdot p_{23}$	$p_c \cdot p_{23}$	0
3	0	0	0	$1-p_c \cdot p_{34}$	$p_c \cdot p_{34}$
.	0	0	0	0	1

For more detailed information on the modelling of the condition-related effects of coatings using the Markov Chain method, see Reference /2/. As the condition and the protection properties of coatings are time dependent the condition of the coating is first modelled by the Markov Chain and then the changes in the condition of the structure are determined taking into account the concurrent condition state of the coating. So the transition probabilities of the structure are not any more constant but are dependent on the condition of the coating. Figure 11 shows the result of calculation as an example.

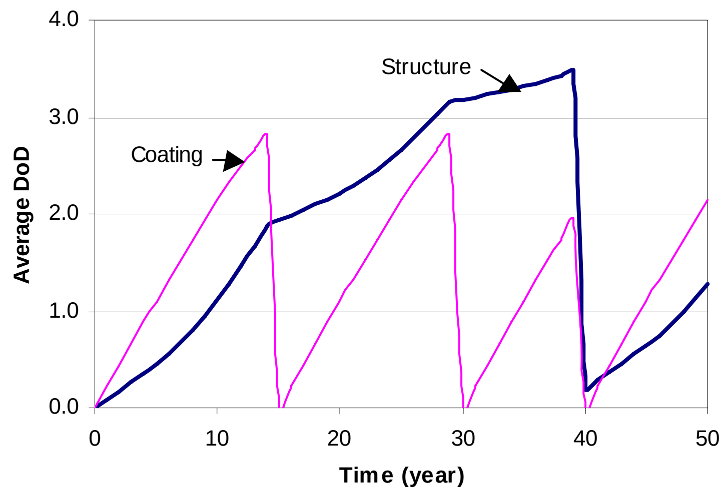


Figure 6. Average DoD of the coating and the structure (example).

3 Combined LCP-, LCC- and LCA-Analysis

Working on the "life cycle principle" means that the profitability of optional maintenance strategies is evaluated by the results of life cycle analyses. Not only MR&R costs but also the user costs and environmental costs, i.e. environmental impacts are determined by the life cycle principle and are considered in the decision making of maintenance strategies.

The principles of life cycle cost calculations with predefined MR&R action profiles are well known and described in international standards like ISO 15686-5 /5/ and ASTM E 917 /6/. However, the traditional procedure of cost calculation with predefined action profiles could obviously not serve as the basis for a life cycle management system. Rather it is the task of the management system to specify the actions and to define the timings of actions using appropriate degradation models. So the calculation methods for the life cycle cost analyses in a life cycle management system must be more advanced and more automatic than those in a conventional life cycle cost analysis.

A Markov Chain based life cycle cost analysis is actually a combination of a life cycle performance (LCP), a life cycle cost (LCC) and a life cycle ecology (LCE) analysis. It integrates the Markov Chain based condition analysis to a conventional life cycle analysis framework. From the material resources used during the MR&R actions it determines also the life cycle ecological consequences in the form of environmental impacts.

3.1 GENERAL PRINCIPLES

The idea of the Markov Chain based LCC analysis is to combine the Markov Chain lifetime table with a traditional LCC calculation table. The timings of MR&R actions can be defined based on the Markov Chain models and an automatic condition guarding system for triggering actions. The life cycle costs can then be determined using conventional calculation methods. An environmental impact analysis can also be combined into the same composition of analyses.

In a Markov Chain LCC analysis the MR&R actions are timed based on predefined condition requirements. An action is automatically triggered when the maximum allowable probability for exceeding the predefined limit state is overridden. Every MR&R action causes costs which are summed up. Other costs such as user costs and environmental costs (impacts) can be determined in the same way and integrated in special cost counters attributed to them. The final purpose of the Markov Chain based LCC analysis is to find the most feasible and economically most effective maintenance strategy to upkeep the structures taking into account both MR&R costs, user costs and environmental impacts. It takes an optimisation problem where the user seeks to find the most effective MR&R action profile for each structural part and for the defined period of time.

In the Markov Chain based LCC analysis the whole MR&R action profile pertaining to the given time frame is reproduced as a series of annual condition state distributions. There are two ways for specification of MR&R actions and definition of timings of them: manual and automatic. In a manual analysis the definition of MR&R actions are done manually. In principle a designer can specify whatever actions to be applied at any time during the time frame. However, even in a manual analysis in which the MR&R actions are specified manually the timing of actions may be based on the condition analysis and automatic triggering of actions. In a fully automatic analysis system (which aims at automatic life cycle planning) the MR&R actions are specified using the decision tree method. The decision tree contains pre-optimised MR&R action profiles for each case. It selects the optimised MR&R action profile based on the material properties, environmental burdens and possible special requirements of the structural part.

A life cycle cost analysis cannot be conducted right away for the whole building or infrastructure if the environmental conditions, materials and structural features in its parts vary. That is why the building or infrastructure is first divided into components and the life cycle cost analyses are conducted for each component separately. The answers related to the whole building or infrastructure can then be obtained by summing up the analysis results of components.

The life cycle cost analyses can be used both in object level and in network level studies. At the object level the LCC analysis is used for life cycle design of specific components and objects. Specific parameter values of structures (obtained from database) are used in these calculations. The purpose of such analyses is to find out the optimal MR&R action profiles for structural component and to find the optimal project profile for the object.

At the network level the purpose is to use the LCC analysis results for strategic planning of MR&R activities and to make short- and long term cost scenarios for the future. The structural parts are treated statistically as populations of structural parts. The calculations are conducted using average values of the material, structural and environmental parameters pertaining to the network or a subnetwork of structures. The purpose is to find the optimal maintenance strategy for structures for varying environmental conditions and for varying material and structural properties. Typically answers for the following questions can be obtained: Is it cost effective to protect the structures by coatings or other protection methods? Which repair methods should be used? In which condition state should the structure be repaired and in which condition state should the coatings or other protections be renewed to minimise the life cycle costs?

3.2 SPECIFICATION OF MR&R ACTIONS

For both the manual and the automatic analyses methods each MR&R action must be specified. The specification of actions is done by answering the following questions.

Table 5. Definition of actions.

1	Is the MR&R action group used during the design period?	Yes/no
2	Which MR&R system?	Code of the MR&R system within the MR&R action group
3	Limit condition state?	Limit state for the action, e.g. 3 or 4
4	Maximum allowable probability for exceeding the limit state?	Probability as %. Exceeding the given percentage will trigger the action.
5	Maximum number of repeated actions?	Number of allowable repetitions of an action before a heavier action.

The action groups mean MR&R action categories composed of similar MR&R systems. For concrete structures the MR&R actions groups may be the following:

- Coating
- Patching of coating
- Protection with concrete overlay
- Patching of concrete protection
- Patching of structure
- Repair of structure
- Renovation of structure.

Each MR&R action group contains several repair systems or methods. Accordingly, the group of coatings is comprised of several coating systems. The concrete protection group refers to methods in which a layer of shotcrete, conventional concrete or cement mortar is applied on the whole surface of the structure. Cathodic protection methods with a net anode embedded in a layer of concrete on the original structure is also included in this group of actions.

The group of structural repairs refers to major repair actions which improve the condition of the structural part. In concrete structures the structural repairs refer to actions by which the concrete around the reinforcement is renewed. This can be done by removing and replacing concrete around the steel bars by mechanical repair methods. Electrochemical methods such as realkalisation and chloride extraction are included in this group as the concrete environment around the reinforcement is renewed by realkalisation or removal of chlorides.

Patching means partial repair of the most attacked areas of the structure. Patching may refer also to partial repair of a coating or other protection. The methods of structural patching are comparable to the structural repair in that they also change the environment around the reinforcement. However, this is done only locally and the other parts of the structure remain unchanged. So patching is not considered to start a new service life but only to extend the on-going service life.

Renovation refers to complete replacement of a component by a new one, so this group consists of methods for renovation. The component can be reconstructed at site or a new prefabricated element can be installed at the place of the old component.

The data related to specific MR&R action systems are presented in Table of MR&R systems. The MR&R systems are arranged in the table according to action groups and they can be referred to by their code numbers. For example in the case of the coating group the code number refers to a specific coating system with defined materials and material thicknesses. In the case of concrete protection group it refers to specific concrete or cathodic protection systems with defined materials, thicknesses and techniques.

The maximum allowable probability sets the maximum limit for the probability of exceeding the limit state. In object level studies one can interpret it as expressing the maximum allowable fraction of the surface area of a component to be at the limit state or in still worse condition. In network level studies it means the maximum portion of structures which can be tolerated at the limit state or in still a worse condition. The MR&R actions for structures are automatically triggered when the maximum allowable probability for the defined limit state is exceeded.

Maximum number of repeated actions sets a limit to the number of the same MR&R action during the design phase. For instance the number of repairs or recoatings can be limited. In the case of coatings the counter starts from zero every time when the component is repaired and in the case of repairs the repair counter starts from zero when the component is replaced by a new one.

The life of a component is considered to be composed of three phases for which the MR&R actions may be specified independently as follows.

Phase I — Residual service life of the component. All actions of protection and patching are defined until the end of the on-going service life.

Phase II — From the end of the residual service life to the end of the residual life cycle of the component. The repair methods are defined until the end of the life cycle of the component. The patching and protection methods for this period of time can be defined in another way than for the on-going service life. This is necessary as the need of protection may be changed after the repair.

Phase III — From the end of the on-going life cycle to the end of the last life cycle. The methods of renovation are defined. For this period of time the repair methods can be newly defined as also the patching and protection methods.

The division of the life of a component is presented graphically in Figure 12. The life of a component can be described as a combination of nested arches which represent the lives of actions.

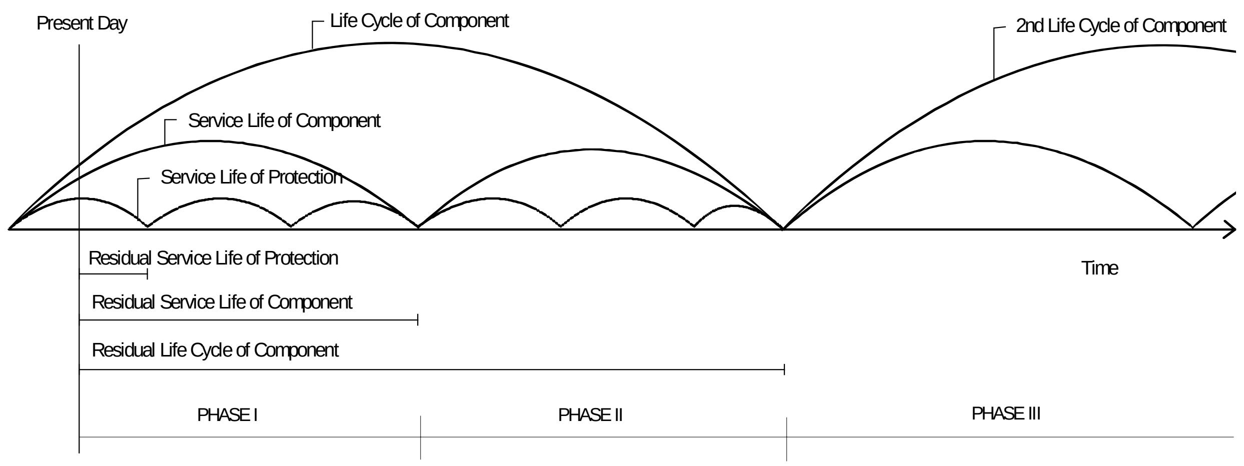


Figure 7. Division of the life of a component into phases.

Several action groups can be selected for the same design phase with appropriate limitations. So it is possible to apply for example coating together with structural repair or coating and concrete protection together with structural repair. However in the design phase I no repair is possible and in the design phase II no renovation is possible to select.

As a component can be repaired completely without replacing the whole component by a new one a new service life of the component is considered to start from the repair. Possibly many consecutive repairs can even be accepted before the component must be replaced. Thus the life cycle of a component is not considered to end until it is completely renovated or replaced by a new one. Accordingly a structural repair generates a new service life and a renovation or replacement generates a new life cycle for the component.

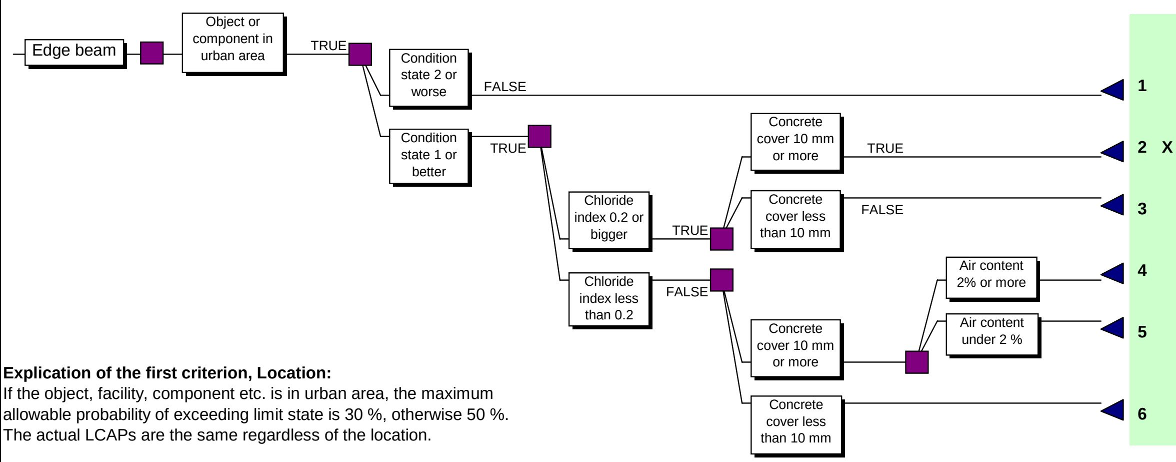
3.3 SPECIFICATION OF MR&R ACTIONS BY A DECISION TREE

The MR&R actions for a component can be specified automatically by a decision tree. The MR&R action profiles specified by a decision tree have been previously optimised by manually defined LCC analyses and risk analyses. The selection of a MR&R action profile for a particular component is done by the decision tree run during which several decision criteriae related to the specific properties, environmental conditions and requirements of the component are evaluated. However, only the types of MR&R actions are defined by the decision tree. The timing of actions is determined by the Markov Chain life cycle table and the automatic triggering of actions.

A decision tree has a "root" which forks at "nodes" representing the relevant criteria related to properties of the component, severity of environment and special requirements of the object and makes with a growing number of nodes an ever-increasing amount of "branches". The final branches after the last node are called "leaves". The optimal sets of MR&R actions are the results of the tree and are inserted in the leaves of the tree.

An example of a decision tree and its solution is presented in Figure 8. The component specific data is given at the row "distribution". The tree is active to find the correct set of MR&R actions corresponding to the given data.

Component: EDGE BEAM	Criteria: Location urban (1), not urban (0)	Condition state from 0 to 4	Chloride index from 0 to 1	Concrete cover from 0 mm to 70 mm	Air content from 0 % to 10%
Distribution:	0	1	0.5	25	2



Explication of the first criterion, Location:
If the object, facility, component etc. is in urban area, the maximum allowable probability of exceeding limit state is 30 %, otherwise 50 %. The actual LCAPs are the same regardless of the location.

Recommended actions (= different possible Life Cycle Action Profiles) for edge beam				
LCAP number	**Immediate actions**	**Predicted preventive actions**	**Predictive repair actions**	
1	Nothing	Nothing	Repair at DoD 4	
2	Impregnation	Reimpregnation at DoD 3	Repair at DoD 4	X
3	Thickening of concrete cover and impregnation	Reimpregnation at DoD 3	Repair at DoD 4	
4	Nothing	Nothing	Repair at DoD 4	
5	Impregnation	Reimpregnation at DoD 3	Repair at DoD 4	
6	Thickening of concrete cover	Nothing	Repair at DoD 4	

Figure 8. Decision tree, illustrative presentation.

In a LCC analysis program the decision tree is usually attached as a subprogram. In a program code of a decision tree the branches are implemented by IF...THEN statements, which can be nested multifold.

Normally the user has no access to the decision tree. However it is possible to make the computer program such that the user can do some changes in the MR&R specifications of the decision tree.

3.4 PRINCIPLES OF CONDITION GUARDING AND TRIGGERING OF ACTIONS

In a condition controlled life cycle cost analysis the timing of actions is performed automatically. The principle of triggering actions in a Markov Chain life cycle table is presented in Figure 9. The sequential annual condition state distributions have been determined by Markov Chain on the left side of the figure. They show the probability of the component to be at any of the condition states at any time. In the middle of the figure the respective cumulative probabilities which express the probability of exceeding or being equal to any of the condition states are presented. In this example condition state 3 was selected for the limit condition state and 50 % as the maximum allowable probability for exceeding the limit condition state. If this criterion is exceeded during a year, a repair action will be performed immediately in the next year. The action effects on the condition state distribution of the structure are obtained by multiplying the condition state distribution of the year by the action effect matrix in the upper left corner. At the same time the repair costs are added in the cost counters in the right side of the figure. In other years only the increase of degradation is evaluated by the degradation matrix that is situated below the action effect matrix.

Transition probability matrix for repair action

State	0	1	2	3	4
0	1.00	0	0	0	0
1	0.95	0.05	0	0	0
2	0.92	0.05	0.03	0	0
3	0.90	0.05	0.03	0.02	0
4	0.88	0.05	0.03	0.02	0.02

LC COSTS PER UNIT AREA

Cumulative real costs	**600**	Euro/m^2
Cumulative PV costs	**221**	Euro/m^2
Average annual costs	**12.00**	Euro/m^2/year
Equalised annual costs	**9.90**	Euro/m^2/year

TOTAL LC COSTS

Cumulative real costs	**30000**	Euro
Cumulative PV costs	**11059**	Euro
Average annual costs	**600**	Euro/year
Equalised annual costs	**495**	Euro/year

Transition probability matrix for degradation

State	0	1	2	3	4
0	0.330	0.670	0	0	0
1	0	0.662	0.338	0	0
2	0	0	0.765	0.235	0
3	0	0	0	0.814	0.186
4	0	0	0	0	1

REPAIR CRITERIA

Limit state	3	(2 or 3)
Max Proba	0.5	(0.01-0.99)

Year	Condition state distributions State (DoD) 0	1	2	3	4	Average DoD	Cumulative distributions State (DoD) 0	1	2	3	4	Condition fulfilled	LC costs real	Discount factor	LC costs discounted
0	1.000	0.000	0.000	0.000	0.000	0.00	1.000	0.000	0.000	0.000	0.000		0	1.000	0
1	0.330	0.670	0.000	0.000	0.000	0.67	1.000	0.670	0.000	0.000	0.000		0	0.962	0
2	0.109	0.664	0.227	0.000	0.000	1.12	1.000	0.891	0.227	0.000	0.000		0	0.925	0
3	0.036	0.513	0.398	0.053	0.000	1.47	1.000	0.964	0.451	0.053	0.000		0	0.889	0
4	0.012	0.363	0.478	0.137	0.010	1.77	1.000	0.988	0.625	0.147	0.010		0	0.855	0
5	0.004	0.248	0.488	0.224	0.035	2.04	1.000	0.996	0.748	0.259	0.035		0	0.822	0
6	0.001	0.167	0.457	0.297	0.077	2.28	1.000	0.999	0.832	0.374	0.077		0	0.790	0
7	0.000	0.111	0.406	0.350	0.132	2.50	1.000	1.000	0.888	0.482	0.132		0	0.760	0
8	0.000	0.074	0.348	0.380	0.197	2.70	1.000	1.000	0.926	0.578	0.197	1	0	0.731	0
9	0.907	0.050	0.028	0.012	0.004	0.16	1.000	0.093	0.043	0.015	0.004		100	0.703	70
10	0.300	0.640	0.038	0.016	0.006	0.79	1.000	0.700	0.060	0.022	0.006		100	0.676	70
11	0.099	0.624	0.246	0.022	0.009	1.22	1.000	0.901	0.277	0.031	0.009		100	0.650	70
12	0.033	0.479	0.399	0.076	0.013	1.56	1.000	0.967	0.488	0.089	0.013		100	0.625	70
13	0.011	0.339	0.467	0.156	0.027	1.85	1.000	0.989	0.650	0.183	0.027		100	0.601	70
14	0.004	0.232	0.472	0.237	0.056	2.11	1.000	0.996	0.765	0.293	0.056		100	0.577	70
15	0.001	0.156	0.439	0.304	0.100	2.35	1.000	0.999	0.843	0.404	0.100		100	0.555	70
16	0.000	0.104	0.389	0.351	0.157	2.56	1.000	1.000	0.896	0.507	0.157	1	100	0.534	70
17	0.910	0.050	0.027	0.010	0.003	0.15	1.000	0.090	0.040	0.013	0.003		200	0.513	122
18	0.301	0.642	0.037	0.015	0.005	0.78	1.000	0.699	0.057	0.020	0.005		200	0.494	122
19	0.099	0.626	0.246	0.021	0.008	1.21	1.000	0.901	0.274	0.028	0.008		200	0.475	122
20	0.033	0.481	0.400	0.075	0.012	1.55	1.000	0.967	0.486	0.086	0.012		200	0.456	122
21	0.011	0.340	0.469	0.155	0.025	1.84	1.000	0.989	0.649	0.180	0.025		200	0.439	122
22	0.004	0.232	0.473	0.236	0.054	2.11	1.000	0.996	0.764	0.291	0.054		200	0.422	122
23	0.001	0.156	0.441	0.304	0.098	2.34	1.000	0.999	0.843	0.402	0.098		200	0.406	122
24	0.000	0.104	0.390	0.351	0.155	2.56	1.000	1.000	0.896	0.506	0.155	1	200	0.390	122
25	0.910	0.050	0.027	0.010	0.003	0.15	1.000	0.090	0.040	0.013	0.003		300	0.375	159
26	0.301	0.642	0.037	0.015	0.005	0.78	1.000	0.699	0.057	0.020	0.005		300	0.361	159
27	0.099	0.626	0.246	0.021	0.008	1.21	1.000	0.901	0.274	0.028	0.008		300	0.347	159
28	0.033	0.481	0.400	0.075	0.012	1.55	1.000	0.967	0.486	0.086	0.012		300	0.333	159
29	0.011	0.340	0.469	0.155	0.025	1.84	1.000	0.989	0.649	0.180	0.025		300	0.321	159
30	0.004	0.232	0.473	0.236	0.054	2.11	1.000	0.996	0.764	0.291	0.054		300	0.308	159
31	0.001	0.156	0.441	0.304	0.098	2.34	1.000	0.999	0.843	0.402	0.098		300	0.296	159
32	0.000	0.104	0.390	0.351	0.155	2.56	1.000	1.000	0.896	0.506	0.155	1	300	0.285	159
33	0.910	0.050	0.027	0.010	0.003	0.15	1.000	0.090	0.040	0.013	0.003		400	0.274	187
34	0.301	0.642	0.037	0.015	0.005	0.78	1.000	0.699	0.057	0.020	0.005		400	0.264	187
35	0.099	0.626	0.246	0.021	0.008	1.21	1.000	0.901	0.274	0.028	0.008		400	0.253	187
36	0.033	0.481	0.400	0.075	0.012	1.55	1.000	0.967	0.486	0.086	0.012		400	0.244	187
37	0.011	0.340	0.469	0.155	0.025	1.84	1.000	0.989	0.649	0.180	0.025		400	0.234	187
38	0.004	0.232	0.473	0.236	0.054	2.11	1.000	0.996	0.764	0.291	0.054		400	0.225	187
39	0.001	0.156	0.441	0.304	0.098	2.34	1.000	0.999	0.843	0.402	0.098		400	0.217	187
40	0.000	0.104	0.390	0.351	0.155	2.56	1.000	1.000	0.896	0.506	0.155	1	400	0.208	187
41	0.910	0.050	0.027	0.010	0.003	0.15	1.000	0.090	0.040	0.013	0.003		500	0.200	207
42	0.301	0.642	0.037	0.015	0.005	0.78	1.000	0.699	0.057	0.020	0.005		500	0.193	207
43	0.099	0.626	0.246	0.021	0.008	1.21	1.000	0.901	0.274	0.028	0.008		500	0.185	207
44	0.033	0.481	0.400	0.075	0.012	1.55	1.000	0.967	0.486	0.086	0.012		500	0.178	207
45	0.011	0.340	0.469	0.155	0.025	1.84	1.000	0.989	0.649	0.180	0.025		500	0.171	207
46	0.004	0.232	0.473	0.236	0.054	2.11	1.000	0.996	0.764	0.291	0.054		500	0.165	207
47	0.001	0.156	0.441	0.304	0.098	2.34	1.000	0.999	0.843	0.402	0.098		500	0.158	207
48	0.000	0.104	0.390	0.351	0.155	2.56	1.000	1.000	0.896	0.506	0.155	1	500	0.152	207
49	0.910	0.050	0.027	0.010	0.003	0.15	1.000	0.090	0.040	0.013	0.003		600	0.146	221
50	0.301	0.642	0.037	0.015	0.005	0.78	1.000	0.699	0.057	0.020	0.005		600	0.141	221

Figure 9. Principles for the determination of condition state distributions, triggering of actions and calculation of life cycle costs /1, 3/.

Many kinds of maintenance and repair actions can be included in a life cycle of a structure. So Figure 14 is inadequate to represent the whole life cycle cost analysis. For instance the degradation of a concrete structure can be retarded by applying an extra layer of concrete or a coating on the structure. However, both the extra layer of concrete and the coating deteriorate themselves. So before evaluation of their effect on the condition of the structure, the condition of the concrete layer and the coating must be first evaluated. In practice three lifetime tables of the form presented in Figure 10 are needed:

- Table of coatings
- Table of extra concrete layer
- Table of the structure.

These tables are connected to each other by rules and formulas, which take into account the mutual condition-related effects, as schematically presented in Figure 10.

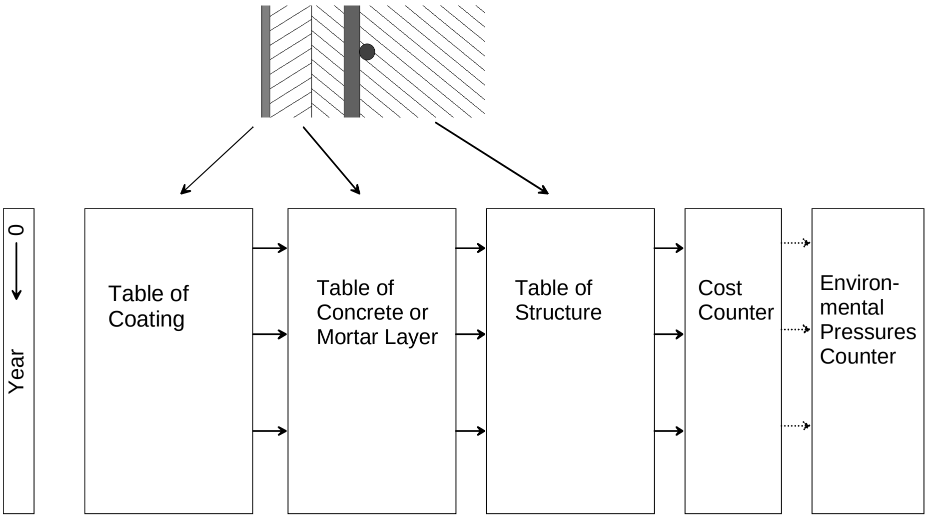


Figure 10. Tables of coating, concrete or mortar layer and the structure connected to each other and counters for costs and environmental impacts.

3.5 METHODS OF COUNTING COSTS

General

The costs are counted by the cost counters obeying the ISO whole life costing principles /5/. The cost counters get their information from the Markov Chain life cycle table (types and timings of MR&R actions) and the table of the MR&R systems (unit costs for MR&R actions etc.). The task of the cost counters is to collect and summarise the costs from the total time frame. The costs are understood here to cover MR&R costs, user costs and environmental impacts.

MR&R Costs

The MR&R costs are comprised of real maintainance costs such as costs of coating, protection, patching, repair, rehabilitation, renovation etc..

The unit costs of MR&R actions are usually based on statistical data from earlier executed MR&R projects. In some cases the costs depend on the extent of the repair, i.e. the area of repair and the depth of concrete that is replaced from the structure. The unit costs may also depend on the general condition of the structure. Then a single value is not justified for unit costs but a model formula that determines the unit costs as a function of the relevant parameters is applied instead. An example of such a model formula is given in Equation 5:

$$UnitCost = UnitCost_0 \cdot C_{depth} \cdot C_{area} \cdot C_{cond} \qquad (5)$$

where:

Unit Cost is	unit costs of a MR&R action, Euro/m^2
$UnitCost_0$	unit cost of a MR&R action with respect to the minimum depth and the minimum area of repair, Euro/m^2
C_{depth}	coefficient depending on the depth of repair
C_{area}	coefficient depending on the area of repair
C_{cond}	coefficient depending on the condition of the structure at the moment of repair.

User Costs

In some types of infrastructure, such as bridges, the user costs are included in the decision making on maintenance strategy. For bridges three kinds of road user costs (RUC) can be identified /8/:

- additional road user costs due to restricted traffic for restricted axle loads and inadequate bridge geometry
- additional road user costs due to MR&R works (delays)
- risk costs due to failure of a bridge.

In a management system of bridges the additional road user costs due to MR&R actions are of special interest. These costs may result from the following reasons:

- reduced speed (traffic sign)
- diversion
- signal regulation.

The road user costs as a result of the increased travel time (for MR&R works) can be determined by the following formula:

$$RUC = I \cdot \%_{car} \cdot \Delta t \cdot TDC_{car} + I \cdot \%_{truck} \cdot \Delta t \cdot TDC_{truck} \qquad (6)$$

where

RUC	road user costs, Euro/ day
I	average daily traffic (ADT)
$\%_{car}$, $\%_{truck}$	percentage of traffic for cars and trucks
Δt	increased travel time due to the maintenance works (for traffic sign, diversion or signal regulation, h
TDC_{car}, TDC_{truck}	time dependent unit costs for cars and trucks, Euro/h

In the case of diversion the road user costs due to the increased driving length must be added to the road user costs. They are determined by the following formula:

$$RUC = I \cdot \%_{car} \cdot \Delta L \cdot DDC_{car} + I \cdot \%_{truck} \cdot \Delta L \cdot DDC_{truck} \qquad (7)$$

where

ΔL is increased driving length due to the diversion, km

DDC_{car}, DDC_{truck} driving dependent unit costs for cars and trucks, Euro/km

The above-presented equations refer to the road user costs per day. So the total road user costs depend on the total time of the repair work. The total costs per unit area (or other functional unit) can be determined as the product of the user costs per day and the repair time. The repair time may be evaluated based on the production rate of the work [m^2/day] for each MR&R action system and the area of repair as follows:

$$t_r = \frac{A}{a_r} \qquad (8)$$

where:

t_r is	repair time, d
A	area of repair, m^2
a_r	production rate of the MR&R system applied, m^2/d.

This calculation method is not indisputable as in practice several works for several components can be performed at the same time. However, this offers one solution for the problem of addressing user costs for components.

Environmental Impacts

The purpose of the environmental impact analysis is to provide the decision-makers with comparative data on the environmental impacts of various optional MR&R action profiles. This data is used as one attribute in the optimisation of the maintenance strategy for structures.

As a starting point of the environmental impact analysis it is assumed that the environmental profiles for the used materials are available. The profiles should at least consist of the following variables:

Resources of energy [MJ]
- Renewable energy
- Non-renewable energy

Emissions into air [kg], [g] or [mg]
- CO_2
- SO_2
- NO_x
- Particles
- CH_4
- Non-methane VOC

Non-renewable raw materials [kg]
- mineral raw materials

The results of the environmental profiles are normally given per mass units, [kg]. So the profiles must be converted into functional units, usually squaremeters, to know their consumption on the surface of structures. To do this each environmental variable is divided by the coverage [m^2/kg] of the material.

The emissions related to MR&R actions have many kinds of ecological impacts. The following classification of impacts is normally used:
- Climate change
- Acidification
- Formation of photo-chemical ozone
- Ecotoxity
- Heavy metals
- Cancerous materials
- Effect on biodiversity

The first three environmental impact classes have usually been applied in the analyses of the construction sector.

There are several methods developed for the evaluation of the total environmental impact. However, there is no general agreement on the methods as yet. In the following only the Swedish Environmental Priority Strategy (EPS) -method is presented /**Error! Reference source not found.**/. The environmental indicator in this method is Environmental Load Unit (ELU) which is defined in Euro as follows:

$$ELU[Euro] = 1.557 \cdot CH_4\,[kg] + 0.191 \cdot CO\,[kg] + 0.0635 \cdot CO_2\,[kg] + 0.00707 \cdot particles\,[kg] + 3.4 \cdot (C_xH_y - CH_4)\,[kg] + 0.395 \cdot NO_x\,[kg] + 0.0545 \cdot SO_x\,[kg] \qquad (9)$$

The principle for calculating the sum of environmental impacts from MR&R actions during the treated time frame is the same as that for life cycle costs. The environmental impacts per functional units like m^2, m etc. for each MR&R action are determined in the MR&R system tables. The total impacts for MR&Rs action can be determined by multiplying the unit area based impacts by the total rapair area. The impacts of the whole treated time frame are determined in the cost counters by summing up all the impacts of the design period.

Methods of Discounting

The life cycle costs are determined according to the principles of the standard ISO 15686 Part 5, Whole life costing /**Error! Reference source not found.**/. Accordingly the costs are determined as:

- Real costs
- Discounted costs (present value costs).

The total real costs are determined by simply summing up the MR&R action costs throughout the treated time as presented by Equation 10. No discounting is used:

$$C_R = \sum_{i=0}^{t} \sum_{j=1}^{n_i} C_{j;i} \qquad (10)$$

where:

C_R is	the total real costs from the treated time frame, Euro/m^2
$C_{j;i}$	costs of the j^{th} maintenance action in year i, Euro/m^2
n_i	number of maintenance action in year i
t	number of years in the time frame (length of the span in years).

Discounted, i.e. present value (PV) costs refer to maintenance costs discounted to the present day by the discount factor. As the discount factor diminishes with time the present value costs of actions scheduled near to the start of the time frame are greater than the present value costs of respective actions scheduled later in the time frame. The total present value costs are calculated from the Equation 11:

$$C_{PV} = \sum_{i=0}^{t} \sum_{j=1}^{n_i} C_{j;i} \frac{1}{(1+r)^i} \qquad (11)$$

where:

C_{PV} is	total present value costs from the treated time frame, Euro/m^2
r	discount rate.

To compare different maintenance strategies it is advisable to redistribute the sum of life cycle costs evenly into annual costs. This can be done based either on real costs or present value costs. So two kinds of annual costs are defined:

- Average annual costs
- Equalised annual costs.

The average annual costs are defined as the total real costs divided by the number of years in the time frame, Equation 12:

$$A_A = \frac{C_R}{t} \tag{12}$$

where:
A_A is average annual costs, Euro/m^2/year.

The equalised annual costs are determined by multiplying the total present value costs by the annuity factor, Equation 13:

$$A_E = C_{PV} \cdot \frac{r(1+r)^t}{(1+r)^t - 1} \tag{13}$$

where:
A_E is equalised annual costs, Euro/m^2/year.

The equalised annual costs depend on how the maintenance actions are scheduled within the time frame. Maintenance actions scheduled near to the start of the time frame increase the equalised annual costs more than those scheduled later in the time frame. This feature is emphasised with increasing discount rate.

4 Life Cycle Cost Analysis Process

The total life cycle cost analysis process is presented schematically in Figure 11. The phases of the analysis are the following:

1. Specication of the initial data
2. Analysis process
3. Presentation of results

Figure 16 shows also schematically the structure of the life cycle analysis program. The program consists of several tables: (1) Tables of object and component specific data (2) Tables of MR&R systems (3) Tables for definition of actions (4) Markov Chain life cycle analysis tables (5) Tables for counting costs and (6) Tables of results. In the following the analysis process is described in more detail.

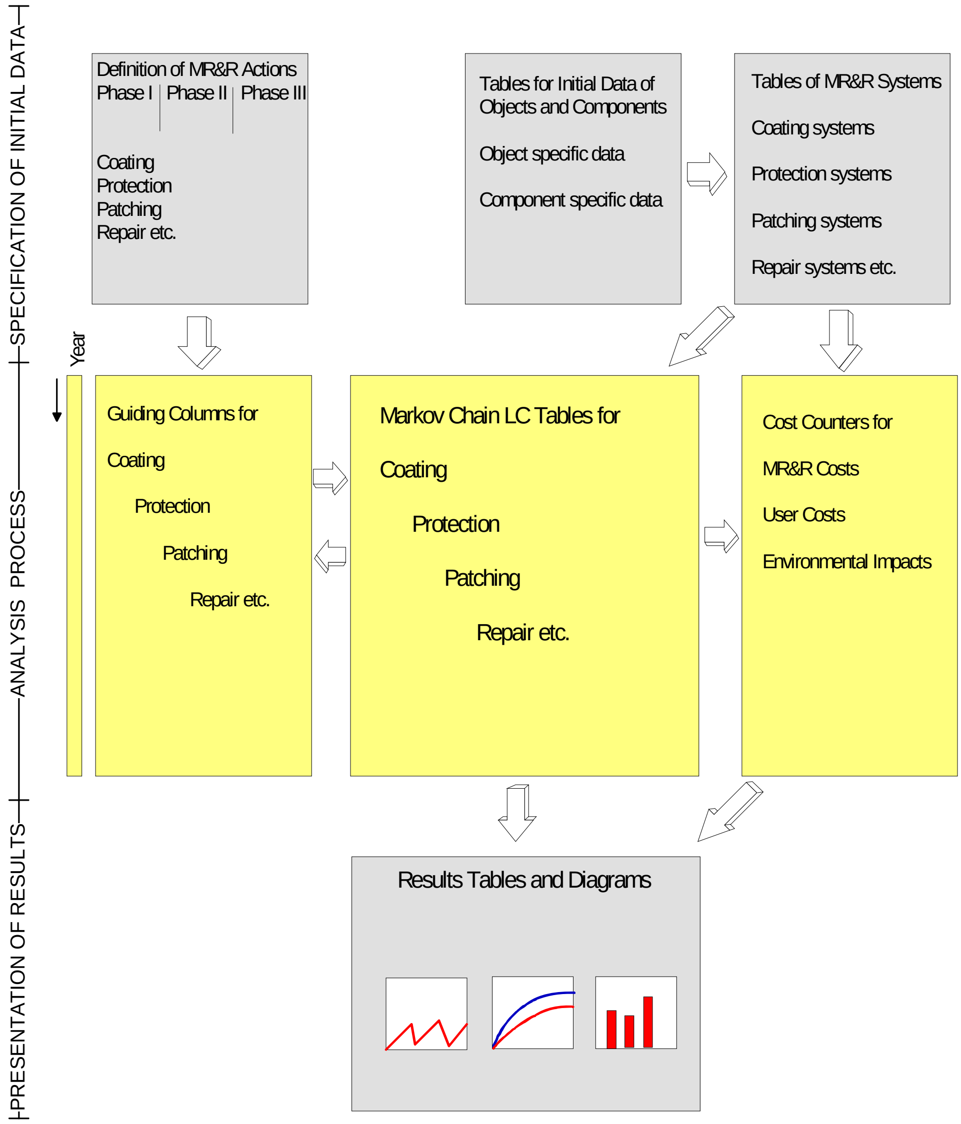


Figure 11. General layout of a life cycle cost analysis process.

4.1 SPECIFICATION OF INITIAL DATA

When the LCC analysis computer program is started the following initial data are asked to be specified by the user (in the screen):

- time frame of the analysis
- discount rate
- object
- component
- MR&R actions (unless not specified automatically by the decision tree)

The time frame (design period) of the analysis is given by the user in years. Usually the time frame is between 50 and 200 years. If it is desired to compare several optional MR&R action profiles for a component the same time frame should be used.

The chosen discount rate should be near the real rate of interest which is the nominal rate minus inflation. If the real rate of interest is used the possible inflation should not have any effect on the results. In industrial countries the real rate of interest in long term has been proved to stay between 2 and 5 %.

Next the user selects the object from the list presented on the screen. The LCC analysis program presents the list of objects according to the current initial data file. The data in the initial data file have been previously gathered from the database by special routines. If the initial data file is changed by the user another list of objects is presented on the screen.

When the user selects the object all the object specific data are assigned to the appropriate places of the analysis program. Then also a list of components pertaining to the selected object is presented. When the designer selects the component all the component specific data are assigned to the appropriate places, especially to the Tables of object and component specific data.

The object specific data contain:
- Identification data
- Measuring data
- Environmental burden data
- User cost data
- etc.

The component specific data contain:
- Identification data
- Measuring data
- Structural data
- Data on previous MR&R actions
- Inspection and condition assessment data
- etc.

The Tables of object and component specific data contain also the default values that are used in the analysis if specific data is not available. The appropriate data in the Tables of object and component specific data are then automatically assigned also to the Tables of MR&R Systems.

The Table of MR&R systems contains all data pertaining to MR&R systems (methods). Each system has a code number in the left most column of the table. The row of a specific MR&R system is identified by that code, and the data pertaining to the system is situated in the row indicated by the code number. The table of MR&R systems is more than just a store of data. All models, i.e. cost models, degradation models and action effect models, are programmed in the Table of MR&R systems. So, the system table consists of model equations and their parameters.

The MR&R actions are then specified for the selected component as explained in the previous chapter "Specification of MR&R Actions". Manual specification is needed if the optimum MR&R action profile is searched by comparing different optional profiles. Automatic specification by a decision tree is used when then optimum action profiles for each case have already been solved and the decision tree has been provided with the optimum profiles.

4.2 ANALYSIS PROCESS

The principles of the life cycle analysis process are already described. The process has been made automatic so that the user does not have to intervene during the process. The following automatic routines are performed /1, 3/:
- automatic application of object and component specific parameter data for degradation, action effect and cost models,
- automatic conversion of degradation models into Markov Chain transition probabilities,
- automatic definition of actions by the decision tree (unless manually defined),

- automatic arrangement of the guiding columns (ref. Figure 16) according to the specified MR&R action profile,
- automatic determination of the annual condition state distributions in the Markov Chain life cycle table,
- automatic timing of actions,
- automatic calculation of life cycle costs, user costs and environmental impacts, and
- automatic presentation of the analysis results in tables and diagrams.

4.3 RESULTS OF LIFE CYCLE COST ANALYSIS

The main results of a life cycle cost analysis can be compacted into a small results table. Table 6 shows the life cycle costs calculated per unit area. The annual unit costs are calculated as average annual costs and equalised annual costs.

Table 6. Results of life cycle cost analysis, unit costs (example).

Unit Costs		**MR&R Costs**	**User Costs**	**Total Costs**	**ELU**
Cumulative Real Costs,	Euro/m^2	2114	455	2568	1.83
Cumulative PV Costs,	Euro/m^2	98	18	115	
Average Annual Costs,	Euro/m^2/year	8.46	1.82	10.27	0.01
Equalised Annual Costs,	Euro/m^2/year	3.91	0.70	4.61	

The true component costs are obtained by multiplying the unit cost by the surface area of the component. If, for example, the surface area of the component is 166 m^2 and the unit costs are those presented in Table 8, the true costs are presented in Table 7.

Table 7. Results of life cycle cost analysis, true component costs (example).

Unit Costs		**MR&R Costs**	**User Costs**	**Total Costs**	**ELU**
Cumulative Real Costs,	Euro	350905	75460	426365	303
Cumulative PV Costs,	Euro	16235	2910	19146	
Average Annual Costs,	Euro/year	1404	302	1705	1
Equalised Annual Costs,	Euro/year	649	116	766	

As can be seen from the results in Tables 6 and 7, the ELU costs calculated based on the EPS method are small as compared to both the MR&R costs and user costs.

The design period was in this case 250 years. The condition of the structure changes during this time is as depicted in Figures 12 and 13.

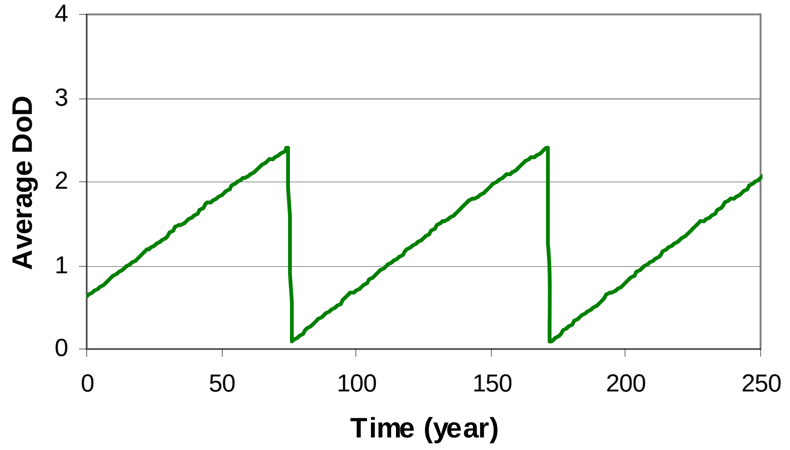


Figure 12. Average Degree of Damage as a function of time.

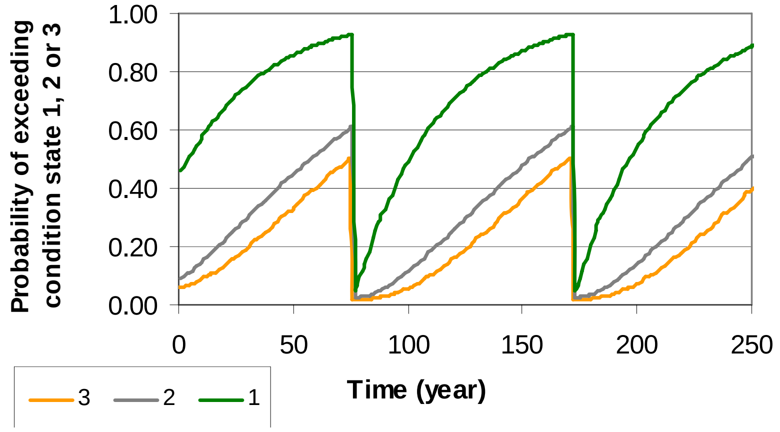


Figure 13. Probability of exceeding the condition state 1, 2 and 3 as a function of time.

In this example the maximum allowable probability of exceeding the condition state 3 (= limit state) was 50 %. From Figure 13 one can observe that the repair was triggered immediately every time when this limit was exceeded.

The costs can also be presented as a function time. Figure 14 shows the cumulative MR&R costs per unit area as real costs and present value costs. The MR&R costs in this case were composed of structural repair cost and coating costs.

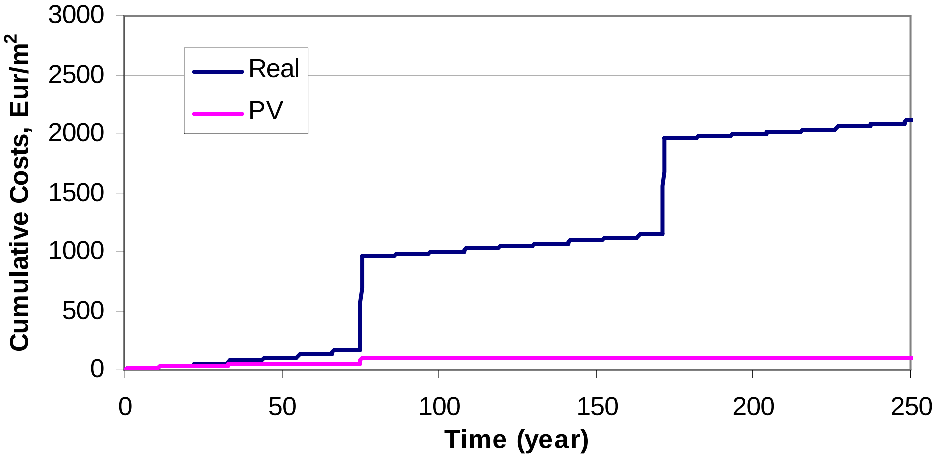


Figure 14. MR&R costs per unit area presented cumulatively as a function of time.

Figure 15 shows the cumulative MR&R costs and user costs per unit area.

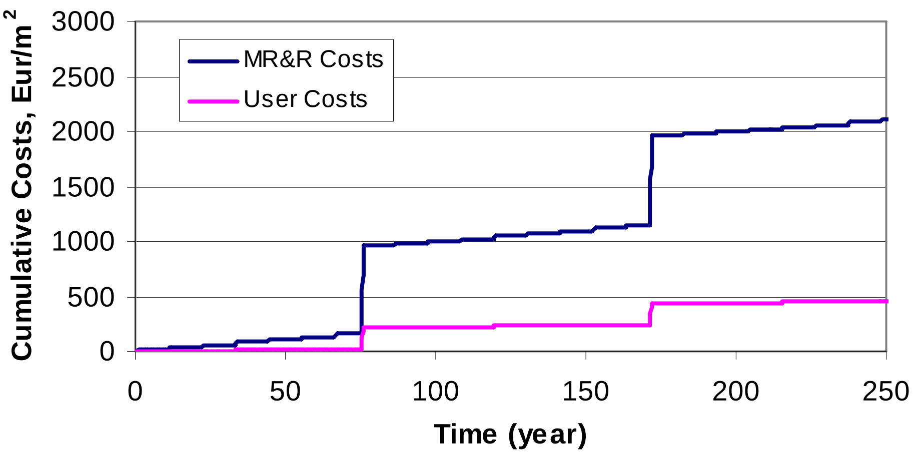
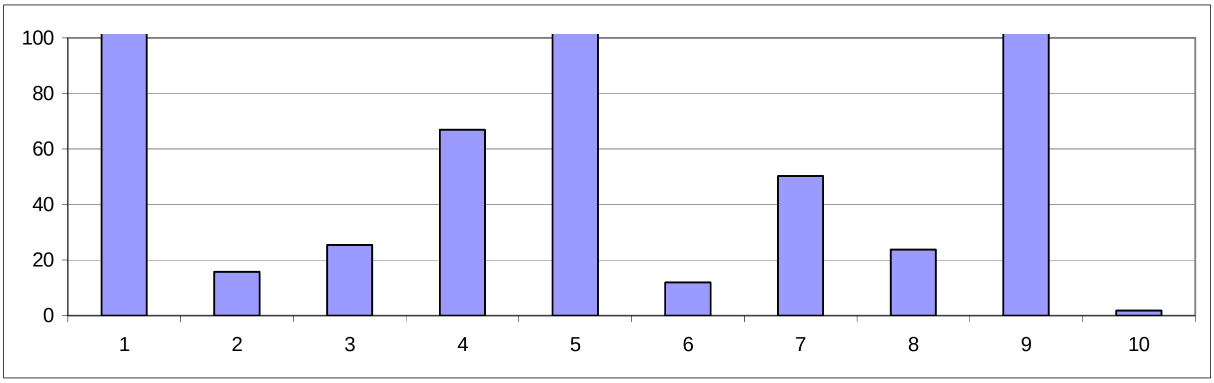


Figure 15. MR&R and user costs per unit area as a function of time.

The environmental impact analysis results can be itemised as presented in Figure 16.



1	2	3	4	5	6	7	8	9	10
Non-renewable	Renewable	CO_2	SO_2	NO_X	Particles	CH_4	VOC	Mineral raw mateials	ELU
MJ/m^2	MJ/m^2	kg/m^2	g/m^2	g/m^2	g/m^2	g/m^2	g/m^2	kg/m^2	Eur/m^2
586.15	15.72	25	66.96	120.28	12.03	50.29	23.83	135.50	1.83

Figure 16. The environmental impact analysis itemised for various items of impact.

Advanced LC Analyses Programs for Object level and Network level Use

In different variations of the life cycle analysis programs additional features may be added in the program routine. Such extended analysis programs are those specially designed for the use of the Object level and the Network level management systems.

Life Cycle Planning Program for the Object Level Management

In a Life Cycle Planning Program for the object level use all components of an object are analysed one after another and the MR&R actions pertaining to different components of an object are reorganised into “projects”. By projects we mean here groups of MR&R actions that are scheduled to the same year for the same object. Instead of project planning one could rather call it life cycle planning as not only the next coming project is planned but all the projects during the whole life frame are planned at the same time. The planning is done automatically but the program allows manually defined changes to the plans.

The reason for reorganising the MR&R actions into projects is that the optimal timings for various actions (for various components) will scatter too much. Project planning based only on the optimal timing of actions would result in too many small projects to be executed for the same object. That would be annoying for both maintainers and users. So the optimisation in the preliminary project planning is performed from a wider perspective than in the component level optimisation. As a result of proper object level planning in which the single MR&R actions are combined into reasonable groups, economic savings can be won by synergy profit.

From many possible ways of combining actions into projects only one is presented here. It is effective and probably also the fastest method, as it does not require a separate computer run. The combination of actions into projects can be performed already in connection with the first component level runs provided that a reasonable order in the analyses of components is used.

This method of combination is based on definition of both the minimum and the maximum probability for exceeding the limit state. In an optimal timing of MR&R actions the timing is always triggered according to the maximum allowable probability. Now the action is triggered latest at the maximum probability but it can be triggered earlier if it seems reasonable from the view point of the project level planning. Accordingly the action is triggered if there is a previously defined action time (for any action in any component of the same object) and if the minimum allowable probability is exceeded. The minimum allowable probability is defined in the decision tree for this type project planning.

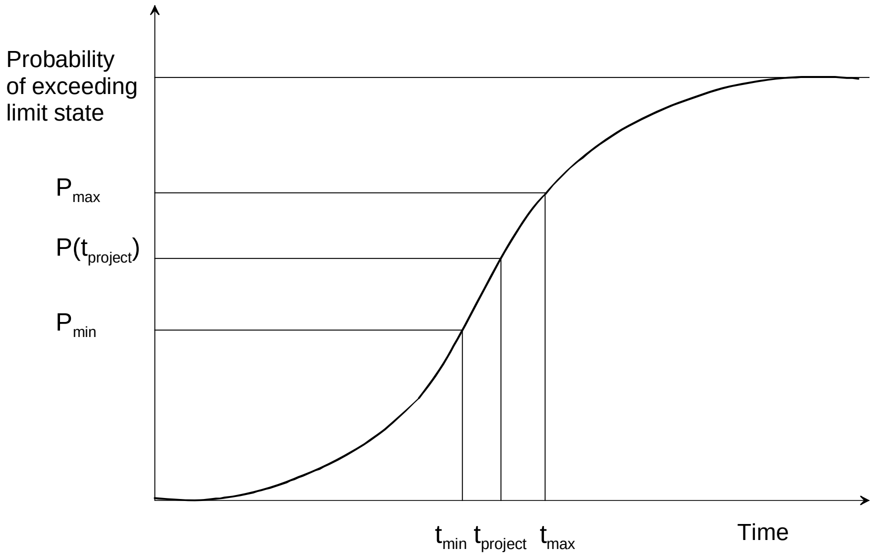


Figure 17. Principle of triggering actions.

The specification and timing of actions is performed for each component consecutively in the order of their relative importance. The timings of actions for the first component are defined at their optimal timings corresponding to the maximum probability. However, for the following components the timings of actions may be advanced from their optimal timings provided that any MR&R action (for any of the previously analysed components) was scheduled earlier than the optimal timing and the specified minimum probability is exceeded. The system still guarantees that the higher limit for exceeding the limit state is never overridden.

For the purpose of project planning a new row is added in the MR&R action definitions (ref. Table 7).

Table 8. Revised table for definition of actions.

1	Is the MR&R action group used during the design period?	Yes/no
2	Which MR&R system?	Code of the MR&R system within the MR&R action group
3	Limit condition state?	Limit state for the action, e.g. 3 or 4
4	*Minimum allowable probability for exceeding the limit state for accepting the timing of action?*	*Probability as % (exceeding the given percentage allows timing of the action to equal with a previously defined timing of any action for the same object)*
5	Maximum allowable probability for exceeding the limit state?	Probability as % (exceeding the given percentage will trigger the action *unless not triggered by the previous condition*)
6	Maximum number of repeated actions?	Number of allowable repetitions of an action before a heavier action.

Program for Cost Scenarios at Network Level

In an analysis program for cost scenarios at the network level the calculation procedures are essentially the same as those in the object level program. However the project design as presented above is not performed. The distribution of objects into components is preferably the same as that in the object level but the surface of components comprises the total surface area of all components in the treated network or subnetwork. The total network is devided into subnetworks according to the decision tree definitions so that all components of the same type with the same definition of actions can be treated in the same analysis.

Another difference in the network level procedure as compared to the object level procedure is in the mathematical way how the triggering of actions is responded. In an object level analysis the response is that the action is performed and the condition state distribution is completely changed according to the action effect matrix. However, in the network level analysis only the fraction which overrides the maximum allowable probability is considered to be repaired, thus resulting in smaller but more frequent changes in the condition state distribution. The reason for this is that the network level changes in the condition distribution are statistical not individual as at the object level.

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