LIFECON DELIVERABLE D5.2

Methodology and data for calculation of life cycle costs (LCC) of maintenance and repair methods and works

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Lifecon Deliverables

Deliverable No	Title of the Deliverable
D1.1	Generic technical handbook for a predictive life cycle management system of concrete structures (Lifecon LMS)
D1.2	Generic instructions on requirements, framework and methodology for IT-based decision support tool for Lifecon LMS
D1.3	IT-based decision support tool for Lifecon LMS
D2.1	Reliability based methodology for lifetime management of structures
D2.2	Statistical condition management and financial optimisation in lifetime management of structures • Part 1: Markov chain based LCC analysis • Part 2: Reference structure models for prediction of degradation
D2.3	Methods for optimisation and decision making in lifetime management of structures • Part I: Multi attribute decision aid methodologies (MADA) • Part II: Quality function deployment (QFD) • Part III: Risk assessment and control
D3.1	Prototype of condition assessment protocol
D3.2	Probabilistic service life models for reinforced concrete structures
D4.1	Definition of decisive environmental parameters and loads
D4.2	Instructions for quantitative classification of environmental degradation loads onto structures
D4.3	GIS-based national exposure modules and national reports on quantitative environmental degradation loads for chosen objects and locations
D5.1	Qualitative and quantitative description and classification of RAMS (Reliability, Availability, Maintainability, Safety) characteristics for different categories of repair materials and systems
D5.2	Methodology and data for calculation of life cycle costs (LCC) of maintenance and repair methods and works
D5.3	Methodology and data for calculation of LCE (Life Cycle Ecology) in repair planning
D6.1	Validation of Lifecon LMS and recommendations for further development

Keywords: Life Cycle Cost (LCC), LCC analysis, Discounted cost, Present value (PV)

Abstract

Life cycle cost (LCC) is the total discounted monetary cost of owning, operating, maintaining, and disposing of a building, building system or infrastructure over a period of time. LCC analysis can be used to evaluate and compare different MR&R (maintenance, repair and rehabilitation) methods, the calculations are made over the whole service life of a building or a structure and the relevant costs are converted to their equivalent present value. The alternative with the lowest total present value is the most economical choice.

The objective of this deliverable is to give guidelines to the decision maker how to select MR&R methods on LCC basis. Preliminary selection of applicable MR&R methods can be made when the degradation mechanism is known. The matrixes in appendices A and B help in this task.

When the applicable MR&R methods are chosen, the equations of LCC are relatively straightforward and simple. As is the case with most evaluation techniques, the real challenge lies in making unbiased assumptions, which produce fair comparisons of alternate designs. In appendix C a fictitious LCC case is presented to illuminate the calculation system and the methodology.

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1 Introduction

LCC analysis (Life-cycle cost analysis) can succinctly be defined as: "the total discounted monetary cost of owning, operating, maintaining, and disposing of a building, building system, infrastructure etc. over a period of time" /5/.

LCC analysis is an economic evaluation technique. It is appropriate for comparison of alternative designs with differing cost expenditures over the project life. Calculations are made which convert all relevant costs to their equivalent present value. The alternative with the lowest total present value is the most economical or least cost approach.

LCC analysis is particularly well suited to determine whether the higher initial cost of an alternative is economically justified by reductions in future costs when compared to an alternative with lower initial but higher future costs.

The equations of LCC methods are relatively straightforward and simple. As is the case with most evaluation techniques, the real challenge lies in making unbiased assumptions, which produce fair comparisons of alternative designs.

The greatest benefit is obtained from LCC analysis when it is deployed from the start of a new project. The truth is that in the planning phase the designs can be radically changed without radical increase in costs. When the facility is already there, the situation is not the same.

The latter situation is more common in Lifecon although it is possible to treat also new build. In LCC calculations for new build the initial cost part has a big effect on the analysis. In Lifecon context the MR&R (maintenance, repair and rehabilitation) cost part is emphasised and the initial cost is excluded or has a minor role, because in many cases the repayment period of the initial investment has already gone, but the concrete facility is still standing (and degrading).

The objective of this deliverable is to give guidelines to the decision maker how to select MR&R methods on LCC basis. However, it should be remembered, that in Lifecon context the decisions are not made only on cost basis (initial or LCC), but also the ecological, cultural and human conditions viewpoints are taken into account. These, many times un-quantifiable factors must be taken into consideration using some other method, e.g. MADA, QFD or RAMS /10/.

In Generic Handbook /10/ several degradation models are presented which can be used for prediction of timing of repair actions. Different maintenance and repair actions will be appropriate at different stages of degradation (and hence at different times during the lifetime of the structure).

2. Life Cycle Costing

In literature many different LCC methods are mentioned /3/, but the basic idea is always the same, "to reduce the total cost of a product or a system or an asset or human factors such as labour". The many equations for calculation of different LCC analysis cases or the extensive economic terminology of general LCC are not repeated here, but the reader is referred to references /1/, /4/ and /10/. The basics will be briefly presented also in this text.

As defined earlier, life cycle cost is the total discounted monetary cost of owning, operating, maintaining, and disposing of a building, building system, infrastructure facility over a period of time. Keeping this definition in mind, one can breakdown the LCC equation into the following three variables: the pertinent costs of ownership, the period of time over which these costs are incurred, and the discount rate that is applied to future costs to equate them with present day costs.

The first component of the LCC equation is time. Study period is the period of time over which ownership and operations expenses are to be evaluated. The study period varies, depending on owner's preferences, as mentioned in the Lifecon Generic Handbook, /10/. For governmental organisations the study period can mean the whole lifetime of the facility while for a speculative investor 10 years is a long time. In Lifecon context, the study period is normally replaced with term "design life".

´Costs` embrace all costs incurred during the study period, before and after the occupation of the facility. In Lifecon costs include for example inspections, condition surveys, yearly maintenance works, monitoring, cleaning, repairs etc. In case of new build, the initial investment would also be taken into account.

* MERGEFORMAT The third component is the discount rate, which can be defined as "the rate of interest reflecting the investor's time value of money" /5/. Basically, it is the interest rate that would make an investor indifferent as to whether he received a payment now or a greater payment at some time in the future.

The advantage of LCC is best reached when a selection of alternatives can be compared. The different MR&R methods need interventions at different intervals, so the costs are also dated at different times. To be able to compare the costs (occurring somewhere in the future), a term called present value must be introduced. The present value can be defined as "the time-equivalent value of past, present or future cash flows as of the beginning of the base year" /5/.

After defining the three components, the basic LCC equation can be expressed as follows:

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

where

$C_{j;i}$ is costs of the j^{th} maintenance action in year i

n_i number of maintenance actions in year i

t number of years in the treated time frame (in the study period)

C_{PV} sum of discounted (present value) costs from the study period

r discount rate.

Discounted 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 PV costs of actions scheduled in a late time (from the beginning of the study period) are smaller than the PV costs of the same actions scheduled near to the start of the time frame /10/. The residual value or the disposal costs of the structure should be included when comparing different alternatives.

For further interest in LCC analyses in general, a standard practice procedure and a good example of LCC calculations are presented in /1/.

3 The Life Cycle Costing (LCC) of Maintenance, Repair and Rehabilitation (MR&R) in Lifecon

3.1 LCC calculation procedure

ASTM E 917 presents a simple and logical procedure for calculating the LCC of building or building system. The same principles can be easily applied also in civil infrastructure sector. The ASTM procedure /1/, which is also the recommended Lifecon's LCC of MR&R procedure, consists of five steps:

1. Identifying objectives, alternatives, and constraints

   The system objective must be specified, and clear boundaries set. Within those boundaries, alternatives that accomplish the objective must be defined. To get advantage from LCC calculations, at least three different alternatives should be defined. It is very important to remember that each alternative should be capable of satisfying the requirements and if the decision is made on LCC basis only, then the alternative with lowest LCC is the preferred choice. Boundary or constraint can mean for example, that only MR&R actions that can be executed without foreign contractor's and their expertise, are to be considered.

2. Establishing basic assumptions for the analysis

   This includes choosing of the calculation method (consistently either present-value or annual-value calculation method), base time, study period (reflects investor's time horizon, in Lifecon normally the design life), general inflation rate, discount rate and comprehensiveness of the LCC analysis.

3. Compiling cost data

   Simplifying, this means timing of each cost as it is expected to occur during the study period. However, this phase needs a lot of expertise and knowledge and is the most crucial phase in making LCC analysis. Costs that do not have significant difference between alternatives can be omitted from the analysis where the purpose of the analysis is solely comparative. It should be remembered that the primary object of LCC analysis is to rank alternatives on LCC basis, and the secondary object is to get exact numbers!

4. Computing the LCC for each alternative

   When the cost compilation for each alternative is ready, the LCCs of the alternatives can be made comparable by using the equation (1) and its derivatives.

5. Comparing LCCs of each alternative to determine the one with the minimum LCC

   If the decision is made on LCC basis only, then the alternative with the lowest LCC is the preferred choice on economic grounds.

If the decisions (about MR&R strategy) were based only on costs, the described five steps would be enough, but in Lifecon LMS final decisions are made after taking into consideration also the human, cultural and ecological effects and factors. They can change the ranking order of the alternatives, depending on the importance and weighting of those viewpoints. LCC calculations of MR&R give, however, great impact to the final decision making.

3.2 Preliminary choice of MR&R methods for LCC analysis

ENV 1504-9:1997 offers principles and methods related to the repair of defects in reinforced concrete. These principles and methods are based on an understanding of the underlying chemical, electro-chemical and physical processes that govern various deterioration mechanisms. There are 11 principles, 6 of which are concerned primarily with defects caused by mechanical, chemical or physical actions on the concrete itself and 5 of which are specifically concerned with corrosion of reinforcement. The tables in appendix A summarise the principles and the methods by which they may be achieved. The tabulation of the principles and methods does not necessarily coincide with Lifecon degradation mechanisms, but it gives a quick overview for laypersons about MR&R of concrete facilities.

Preliminary selection of applicable MR&R methods can be made when the degradation mechanism is known and the condition of the structure is assessed. This information is obtained from the condition assessment of the structure /14/. In Lifecon six degradation mechanisms are treated: corrosion due to carbonation, sulphate attack, chloride induced corrosion, frost attack, degradation due to water and AAR (alkali-aggregate reaction). At least three different alternative repair methods should be studied /5/.

3.3 Cost Breakdown Structure (CBS)

The real challenge of successful LCC analysis lies in making unbiased assumptions, which produce fair comparisons of alternate designs or maintenance policies. As with any evaluation process, it is always easier to assess or evaluate smaller entities. For this reason it is recommended to build a Cost Breakdown Structure (CBS) for the various MR&R methods, using consistent subtitles and units to compare the costs of the different methods /2/.../8/. An example of a possible CBS for building elements or services is presented in the figure *1*.

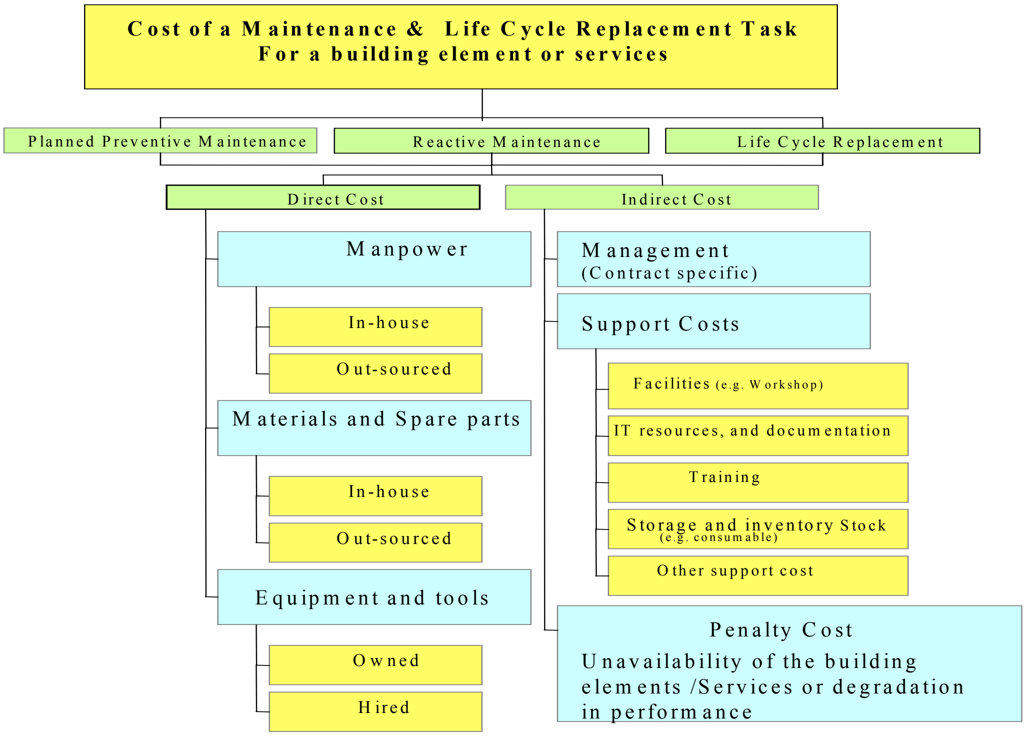

Figure 1. Cost Breakdown Structure /8/.

The factors that build up the total LCC sum of all MR&R actions, should be categorised into few subcategories (manpower, materials and spare parts etc.) that are common for all MR&R methods.

Problems arise when one wants to find information to be placed into the subcategories and the corresponding cost estimates. The variations can be huge, depending for example on the location of the facility (centre of town, backcountry...), the quality of the execution of MR&R works, the season of the year, the climate, etc. This is why no extensive, unequivocal catalogues or databases of different MR&R costs on European (or even national) level exist. However, with the help of consistent CBS the problem can be alleviated if not overcome.

First, the maintenance action or repair is divided in clear phases, which are:

- Condition survey and analysis
- Design and planning of maintenance or repair actions
- Execution of maintenance or repair actions
- Commissioning

Normally, the execution phase is the most costly one. The costs in execution phase accumulate from different elements, which are for example:

- Preparation
- Temporary support
- Repair materials (patch repair mortars and concretes, rebar coatings, bonding coatings, etc)
- Repair systems and components (for example cathodic protection system components)
- Application of the repair and/or system assembly
- Quality control
- Consequential costs (loss of production e.g. power plant, interruption to operations e.g. bridge, etc)

For the execution phase a further division should be made. A logical division is the one presented in the left side of the figure 1, because all MR&R methods require manpower, materials and equipment. In the manpower category factors that accumulate costs are e.g. management personnel costs, man hours, manpower transportation costs, special expertise of the manpower, number of people needed, etc. In the materials category total costs accumulate because of transportation costs, raw material costs, quality grade of the material, availability of the material, amount of the material, etc. The equipment category include same kind of subdivisions, namely transportation costs, hiring costs, availability costs etc. Quality assurance (or control) and consequential costs must not be forgotten from the CBS.

The Cost Breakdown Structure can be made in matrix form for example using spreadsheets. In appendix B an example is presented of LCC-table for gathering cost estimates for different MR&R methods. The table collects the costs of the execution phase, because it is the predominant one and the main distinctions in costs between different MR&R methods result from this phase. In the table the usual MR&R methods for the six Lifecon degradation mechanisms are addressed.

The MR&R execution cost matrix in appendix B is built for one intervention (at a certain time and at a certain location), divided in preparation, execution and finishing. The table is an illustrative outcome page, where the commensurate unit is Euro. The calculation routines are executed elsewhere. The number of cost elements can be added, according to the accuracy of analysis. Also, new methods can be added or removed, according to end user's needs, to general development of the methods etc.

The number (and possible combinations) of interventions during study period, estimates of discount rates etc. will be taken into account in other following phases of the analysis. The whole LCC analysis procedure can easily be executed on the same spreadsheet, the difficulty is in getting reliable information for the estimates, and after that keeping the table updated. Logically, the other MR&R phases (condition survey, planning of actions and commissioning) can also be broken down to matrix form, and the corresponding cost estimates given.

When all the factors in CBS have been given a cost, time and discount rate estimates, the calculation of LCC is performed using the equation 1, and consequently a comparison between the MR&R methods can be made. One very important thing must not be forgotten when making LCC comparisons: the study period must be same for each alternative.

The LCC matrix of appendix B is for one facility and one intervention in present time. The Lifecon LMS will incorporate the LCC component to provide the overall optimum strategy for the management of the structure (strategic planning, estimation of network level intervention intervals, coupling with other analyses etc.).

Cost estimates are usually based on current costs, i.e neglecting the effect of economic inflation on prices. The discount rate is correspondingly taken net of inflation.

3.4 Difficulties in filling in the CBS (information for intrigued reader)

When the CBS is ready, it should be easier to give cost estimates to the factors. But, as mentioned before, local micro and macro conditions (climate, general cost level, local workmanship...) have huge impact on the unit costs, thus complicating the creation of universal cost catalogue.

However, the major difficulty is caused by the factor called time. It is very demanding task to predict future, and that is exactly what one should do when making LCC calculations, because the study period can be 100 years or more. "Guessing" of discount rates, general development of prices (raw material, manpower, expertise, etc), rate of development of new materials or MR&R methods, possible prohibitions of some methods, etc. produces a lot of uncertainty to the LCC calculations.

The prediction of future degradation is complex and may be subject to considerable uncertainty. The producers of the repair materials may promise their materials to last even for 100 years, but the success of a repair is not function of durability of repair material only. Local climate, condition of substrate, local loads, accuracy of condition survey, quality of workmanship, etc. have impact on the success of the repair work. The quality of executed repair work in turn has a direct impact on the time that will pass before next intervention is needed, which logically has an impact on the overall LCC. In /11/ are given some examples of times elapsed between interventions, but they are by no means mandatory nor universal. The elapsed time between consecutive interventions differs markedly for the various maintenance or repair methods.

Predicting the length of the maintenance free period is also problematic, because for many MR&R methods, e.g. different types of coatings, different anode systems (ICCP, Impressed Current Cathodic Protection), etc. maintenance free periods between 15... 25 years have been promised. Some of those methods are not that old, or documentation from the MR&R actions executed is scarce and not thorough. So, valid statistics from real life are almost completely absent. The times (maintenance free periods) given by manufacturers of repair materials or suppliers of protection systems may hold in ideal conditions, but in real life the conditions are never ideal.

3.5 Sources of information and presentation of cost estimates

The sources of information for making cost or time estimates are numerous, below are listed few examples:

- statistics and databases
- experience from executed MR&R actions and works
- laboratory tests and simulations (time to next MR&R action or repair)
- material producers (cost of material, time to next MR&R action or repair...)
- contractors (cost of manpower, cost of equipment, time to next MR&R action or repair...)
- consultants (cost of condition survey and repair planning, time to next MR&R action or repair...)
- societal sources (interest rates, inflation rates, discount rates...)
- authorities (changes in loads, traffic volumes, environmental loads, time to next MR&R action or repair...)

In giving cost estimates and summing them up by equation 1, two different methods are available, namely the deterministics or the probabilistics.

The difference is in the way of presenting estimates. In the deterministic way the estimates are given with single numbers, while in the probabilistic approach statistical distributions are used. When dealing with uncertainties, probabilistics and simulation offer better results /8/, /13/. However, the practical engineers are not yet too familiar with probabilistics, so the traditional deterministic way of handling costs may be easier to adopt. The combination of the two methods is also possible. For example, some costs can be known very exactly (current price of certain repair material), while other estimates can have a lot of variation and could be better expressed with distributions (e.g. maintenance free period between interventions).

3.6 Sensitivity analysis

Whatever the applied method in presenting estimates is, one very important thing must not be forgotten. That is the sensitivity analysis. When uncertainty is involved in modelling, a sensitivity analysis should be run. Sensitivity analysis was originally created to deal with the uncertainties in the input factors, but lately the ideas have been extended to incorporate model conceptual uncertainty, i.e. uncertainty in model structures, assumptions and specifications /9/.

Sensitivity analysis methods are many (and not treated here), but the main idea for all of them is to determine:

- if a model resembles the system or processes under study

- the factors that mostly contribute to the output variability and that require additional research to strengthen the knowledge base
- the model parameters (or parts of the model itself) that are insignificant, and that can be eliminated from the final model
- if there is some region in the space of input factors for which the model variation is maximum
- the optimal regions within the space of the factors for use in a subsequent calibration study
- if and which (group of) factors interact with each other.

In Lifecon, the sensitivity analysis of LCC model should reveal the cost factors whose small variations can change the ranking order of MR&R alternatives. After finding out those risky factors, effort can be directed more precisely to solve (or alleviate) the uncertainty problem. To find best sensitivity analysis methods for different LCC cases, end user is referred to the vast literature of the discipline, e.g. /9/.

4. References

[1] ASTM E 917-94 (Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems)

[2] Elinjaksokustannus (LCC)- ja -tuotto (LCP) laskenta - Laskentamallin kehittäminen, VTT Automaatio, Tampere 1999 (in Finnish)

[3] Durairaj, S.K., et al., Evaluation of Life Cycle Cost Analysis Methodologies., Corporate Environmental Strategy, Vol. 9, No. 1 (2002)

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[5] State of Alaska - Department of Education & Early Development, Life Cycle Cost Analysis Handbook 1999

[6] Barringer H. Paul, Life Cycle Cost and Good Practices, NPRA Maintenance Conference May 19-22, 1998, San Antonio Convention Center, San Antonio, Texas

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[8] Probabilistic Approach for Predicting Life Cycle Costs and Performance of Buildings and Civil Infrastructure, Lifetime Cluster - EuroLifeForm Report, October 2002

[9] Wiley, John & Sons Ltd, Sensitivity Analysis, Chichester, England, 2000.

Lifecon Reports:

[10] Generic Technical Handbook for a Predictive Life Cycle Management System of Concrete Structures (LMS). Lifecon Report D1.1 (draft 3)

[11] Qualitative and quantitative descriptions and classifications of RAMS (Reliability, Availability, Maintainability, Safety), characteristics for different categories of repair materials and systems subjected to classified environmental exposures. Lifecon Report D5.1 (draft 3)

[12] Quantitative and classified information on RAMS and LCE for different categories of repair materials and systems subjected to classified environmental exposures. Lifecon Report D5.2 (draft 1)

[13] Risk Assessment and Control in Lifecon LMS. Lifecon Report D2.4 (draft 1)

[14] Condition Assessment Protocol. Lifecon Report D3.1 (draft 1)

Appendices

Appendix A

In the two tables below is presented ENV 1504-9:1997 approach for principles and methods related to the repair of defects in reinforced concrete. The content of table 1 and table 2 is the same, only the format changes.

Table 1. Principles and methods related to the repair of defects in reinforced concrete.

Principle no. and definition	Methods based on the principle
1. Protection against ingress, of adverse agents	Surface impregnation; surface coating; locally bandaged cracks; filling cracks; transferring cracks into joints; erecting external panels; applying membranes.
2. Moisture control	Hydrophobic impregnation; surface coating; sheltering and overcladding; electrochemical treatment
3. Concrete restoration	Applying mortar by hand; recasting with concrete; spraying concrete or mortar; replacing elements, encasement.
4. Structural strengthening	Adding or replacing reinforcement; installing bonded rebars in holes; plate bonding; adding mortar or concrete; injecting cracks or voids; prestressing.
5. Physical resistance *(to physical and mechanical attack)*	Overlays or coatings; impregnation
6. *(Surface)* Resistance to chemicals	Overlays or coatings; impregnation
7. Preserving or restoring passivity	Increasing cover with mortar or concrete; replacing contaminated or carbonated concrete; electrochemical realkalisation; realkalisation by diffusion; electrochemical chloride extraction
8. Increasing *(electrical)* resistivity	Limiting moisture content by surface treatment, coatings or sheltering
9. Cathodic control	Limiting oxygen content by saturation or coatings.
10. Cathodic protection	Applying electrochemical potential using impressed current or sacrificial anodes
11. Control of anodic areas	Painting rebar with coatings containing pigments; painting rebar with barrier coatings; applying corrosion inhibitors

Table 2. Principles and methods related to the repair of defects in reinforced concrete.

Principle no. and definition		Surface protection to concrete						Cracks		Adding mortar or concrete			New reinforcement or prestressing								Electrochemical methods			
		Impregnation	Coating	Membrane	Overlays	Saturation	Overcladding	Filling	Surface sealing	Hand applied mortar	Recast concrete	Sprayed concrete or mortar	Add or replace rebar	Install bonded bars	Plate bonding	Prestressing	Replace elements	Rebar coating	Realkalisation by diffusion	Corrosion inhibitors	Realkalisation	Chloride extraction	Cathodic protection	Moisture control
1	Protection against ingress, of adverse agents	X	X	X	X		X	X	X															
2	Moisture control	X	X				X																	X
3	Concrete restoration									X	X	X					X							
4	Structural strengthening							X		X	X	X	X	X	X	X								
5	Physical resistance (to physical and mechanical attack)	X			X																			
6	(Surface) Resistance to chemicals	X			X																			
7	Preserving or restoring passivity									X	X	X							X		X	X		
8	Increasing (electrical) resistivity	X	X	X			X																	
9	Cathodic control		X	X		X																		
10	Cathodic protection																						X	
11	Control of anodic areas																	X		X				

The selection of maintenance or repair method will also be influenced by the condition of the structure when action is carried out.

Appendix B

On the following pages is presented the CBS (Cost Breakdown Structure) summary matrix of the LCC analysis of MR&R. In the matrix the six degradation mechanisms of Lifecon approach are listed together with their normal repair methods. The condition assessment /14/ of the structure gives the background information for the selection of repair methods. The CBS matrix is illustrative and open for modifications: the number of lines and columns as well as their headings can be changed, according to the end user's needs and preferences.

It should be noted that the matrix on the following pages is the outcome for comparison of one intervention at a certain time at a certain location. The number of headings has been curtailed for easier comparison of methods. The numbers to the matrix will be automatically produced from other sheets (not presented here). The other sheets contain basic input variables and calculation routines and there the CBS can go much deeper. The basic input variables are for example estimates of:

- time needed for certain repair phase
- transportation distance or unit costs
- manpower needed for certain repair phase etc.

The calculation routines convert the estimates to monetary value by:

- multiplying transport unit costs and the distance
- multiplying manpower unit costs and the time used
- multiplying repair material unit costs and the amount of material used etc.

Damages 1: Corrosion due to chloride penetration	Replacing contaminated concrete / Applying mortar by hand	Replacing contaminated concrete / Recasting with concrete	Replacing contaminated concrete / Spraying concrete or mortar	Protection against ingress / Surface coating with inorganic paints or barriers	Protection against ingress / Surface coating with organic paints or barriers	Protection against ingress / Filling cracks	Protection against ingress / Surface impregnation	Structural strengthening / Adding mortar or concrete, injecting	Cathodic protection	Electrochemical desalination	Other
Preparation (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
Execution of the work (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
Finishing (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
TOTAL COSTS (€)											
Time to next intervention (years)											

Damages 2: Corrosion due to carbonation	Replacing carbonated concrete / Applying mortar by hand	Replacing carbonated concrete / Recasting with concrete	Replacing carbonated concrete / Spraying concrete or mortar	Increasing resistivity / Surface coating with inorganic paints / CO_2-barriers	Increasing resistivity / Surface coating with organic paints / CO_2-barriers	Preserving passivity by increasing cover to reinforcement with additional cementitious	Electrochemical realkalisation	Cathodic protection	Other		
Preparation (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
Execution of the work (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
Finishing (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
TOTAL COSTS (€)											
Time to next intervention (years)											

Damages 3: Frost	Concrete restoration / Applying mortar by hand	Concrete restoration / Recasting with concrete	Concrete restoration / Spraying concrete or mortar	Protection against water ingress / Surface coating with inorganic materials	Protection against water ingress / Surface coating with organic materials	Protection against ingress / Filling cracks	Protection against ingress / Impregnation	Structural strengthening / Adding mortar or concrete, injecting	Increasing resistance to physical attack / Overlays or coatings	Other	
Preparation (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
Execution of the work (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
Finishing (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
TOTAL COSTS (€)											
Time to next intervention (years)											

Damages 4: Chemical loads / Sulphates	Concrete restoration / Applying mortar by hand	Concrete restoration / Recasting by concrete	Concrete restoration / Spraying concrete or mortar	Protection against ingress / Surface coating	Protection against ingress / Filling cracks	Structural strengthening / Adding mortar or concrete, injecting	Increasing resistance of the concrete surface to deteriorations by chemical attack / Coating	Other			
Preparation (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
Execution of the work (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
Finishing (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
TOTAL COSTS (€)											
Time to next intervention (years)											

Damages 5: Deterioration due to water; surface deterioration, mechanical abrasion etc.	Concrete restoration / Applying mortar by hand	Concrete restoration / Recasting with concrete	Concrete restoration / Spraying concrete or mortar	Protection against ingress / Surface coating	Protection against ingress / Filling cracks	Protection against ingress / impregnation	Structural strengthening / Adding mortar or concrete, injecting	Increasing resistance to physical attack / Overlays or coatings	Electrochemical desalination	Other	
Preparation (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
Execution of the work (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
Finishing(subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
TOTAL COSTS (€)											
Time to next intervention (years)											

Damages 6: AAR (Alkali-aggregate reaction)	Concrete restoration / Applying mortar by hand	Concrete restoration / Recasting by concrete	Concrete restoration / Spraying concrete or mortar	Stuctural strengthening / Adding mortar or concrete	Stuctural strengthening / Injecting or filling cracks	Other					
Preparation (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
Execution of the work (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
Finishing (subtotal, €)											
Manpower (own work)											
Manpower (contract work)											
Material/spare parts (own)											
Material/spare parts (purchased)											
Equipment/tools (transport.)											
Equipment/tools (machinery on site)											
Quality assurance/control											
Consequential costs											
TOTAL COSTS (€)											
Time to next intervention (years)											

Appendix C

To clarify the LCC calculation system, a fictitious case study is presented. The object is a hypothetical highway bridge with a problem of carbonation (area of 1000 m^2), no cracking of concrete or visible problems with reinforcement as yet. The concrete cover over the reinforcement being about 25 mm, the carbonation depth at the time of observation lies around 20 mm and progressing. The study period is 50 years forward from the present. The unit costs (€/m^2) of different repair actions are estimated and the calculations are simplified but the key issues remain evident.

As the tables in appendixes A and B show, there are many alternative techniques to treat the carbonation in concrete, some of them are light and usually not so expensive ways to maintain the structure, some methods are heavier and add significantly the service life of the construction. The variations in the initial costs are noticeable, the economy of the particular repair action can be seen over the longer period of time. Different techniques can be compared by using LCC, the system reliability is dependent on the preciseness of the initial information (facts and estimations). The condition state analysis /10/ gives information to the decision maker.

<u>Surface coatings with semiorganic/organic CO_2-barriers</u>: it has been assumed that the coating have a lifetime of about 10-15 years and therefore need to be applied several times over the study period (50 years). The CO_2-barrier does not completely stop the carbonisation but slows it down, so heavier repair can be expected within 25-30 years (mechanical repair / shotcrete / cathodic protection etc. or a combination), it is taken into account in the calculation (rough estimate). This method would need to be applied immediately to be of benefit.

<u>Repair with shotcrete:</u> shotcrete (sprayed concrete or mortar) consists of cement, aggregate and water, sometimes admixtures or fibers. It is applied through a nozzle of an effective pump. Because of the high velocity of the mass it forms a dense concrete layer which is well bonded to the old surface. The technique is used especially in case of structural strengthening or large concrete repair, it also repassivates effectively the underlying concrete surface. About 20 mm layer of shotcrete protects the concrete from carbonation for many decades, in this calculation over 30 years. Some aesthetic repairs will be performed in 50 years.

<u>Repair with CarboCath (cathodic protection):</u> the system consists of carbon fiber net (anode) and a connector with carbon and copper cables. The net is covered and the surface is finished with inorganic coating. The system protects reinforcement for many decades (the anode lasts >> 50 years) and needs little maintenance. The surface of the concrete needs a “facelift” after certain intervals (15-20 years). Installation of CP could be deferred for some time, as there is no benefit from installation before the initiation phase of deterioration is complete.

<u>Repair with electrochemical realkalisation:</u> the lost alkalinity of the concrete is returned by absorbing alkaline solution into the structure. The effect can be expected to last well over 15 years, theoretically for over 50 years. The protection can be further improved by coating (inorganic). It has been assumed that also in this case the structure needs some surface maintenance in 50 years and this has been taken into account. Re-alkalisation could be

deferred for some time (albeit slightly less than for CP), as there is no benefit from installation before the initiation phase of deterioration is complete.

The other maintenance actions like the renewal of the bridge deck membrane or metal components is not taken into account in this example nor are the other repair needs caused by other damage functions (chloride attack, frost etc.).

The repair actions usually disturb the normal use of the structure; the traffic may be stopped or some extra protective measures must be done. The evaluated monetary value of these extra measures can be taken into account e.g. in consequential costs of LCC calculation.

Table 3. Cost comparison of alternative repair methods

Damage: **Corrosion due to carbonation, area of 1000 m^2**	**1)** Surface coating with organic CO_2-barrier	**2)** Shotcrete + coating	**3)** Cathodic protection with CarboCath	**4)** Electrochemical realkalisation
UNIT COST (€ / m^2)(*	60	100	180	110
TOTAL INITIAL COSTS (€/1000 m^2)	60 000	100 000	180 000	110 000
Time to next intervention (years, estimated)	10-15	30-35	20-25	20-25

(*estimated, including material, work and equipment

The optimal time for MR&R actions can be estimated by using the tools within Lifecon LMS. The surface coating is done year 0 to slow down the carbonation as soon as possible. The other techniques allow the situation develop further until the front of carbonated concrete is closer to reinforcement. The electrochemical realkalisation is done in year 5 and the heavier techniques like shotcreting as well as cathodic protection in year 10 (see table 4).

Table 4. LCC of alternative repair methods with minimum time to the next intervention, discount rate of 5%, study period of 50 years. Formula (1) in page 5 has been used (cost in 1000 €).

Year	**Discount factor**	**Repair method 1**		**Repair method 2**		**Repair method 3**		**Repair method 4**	
		Real cost	**Discounted cost**	**Real cost**	**Discounted cost**	**Real cost**	**Discounted cost**	**Real cost**	**Discounted cost**
Year 0	1,000	60	60,00	0	0,00	0	0,00	0	0,00
Year 1	0,952	0	60,00	0	0,00	0	0,00	0	0,00
Year 2	0,907	0	60,00	0	0,00	0	0,00	0	0,00
Year 3	0,864	0	60,00	0	0,00	0	0,00	0	0,00
Year 4	0,823	0	60,00	0	0,00	0	0,00	0	0,00
Year 5	0,784	0	60,00	0	0,00	0	0,00	110(**	86,19
Year 6	0,746	0	60,00	0	0,00	0	0,00	0	86,19
Year 7	0,711	0	60,00	0	0,00	0	0,00	0	86,19
Year 8	0,677	0	60,00	0	0,00	0	0,00	0	86,19
Year 9	0,645	0	60,00	0	0,00	0	0,00	0	86,19
Year 10	0,614	50(*	90,70	100(**	61,39	180(**	110,50	0	86,19
Year 11	0,585	0	90,70	0	61,39	0	110,50	0	86,19
Year 12	0,557	0	90,70	0	61,39	0	110,50	0	86,19
Year 13	0,530	0	90,70	0	61,39	0	110,50	0	86,19
Year 14	0,505	0	90,70	0	61,39	0	110,50	0	86,19
Year 15	0,481	0	90,70	0	61,39	0	110,50	0	86,19
Year 16	0,458	0	90,70	0	61,39	0	110,50	0	86,19
Year 17	0,436	0	90,70	0	61,39	0	110,50	0	86,19
Year 18	0,416	0	90,70	0	61,39	0	110,50	0	86,19
Year 19	0,396	0	90,70	0	61,39	0	110,50	0	86,19
Year 20	0,377	50(*	109,54	0	61,39	0	110,50	50(*	105,03
Year 21	0,359	0	109,54	0	61,39	0	110,50	0	105,03
Year 22	0,342	0	109,54	0	61,39	0	110,50	0	105,03
Year 23	0,326	0	109,54	0	61,39	0	110,50	0	105,03
Year 24	0,310	0	109,54	0	61,39	0	110,50	0	105,03
Year 25	0,295	0	109,54	50(*	76,16	50(*	125,27	0	105,03
Year 26	0,281	0	109,54	0	76,16	0	125,27	0	105,03
Year 27	0,268	0	109,54	0	76,16	0	125,27	0	105,03
Year 28	0,255	0	109,54	0	76,16	0	125,27	0	105,03
Year 29	0,243	0	109,54	0	76,16	0	125,27	0	105,03
Year 30	0,231	120(**	137,31	0	76,16	0	125,27	0	105,03
Year 31	0,220	0	137,31	0	76,16	0	125,27	0	105,03
Year 32	0,210	0	137,31	0	76,16	0	125,27	0	105,03
Year 33	0,200	0	137,31	0	76,16	0	125,27	0	105,03
Year 34	0,190	0	137,31	0	76,16	0	125,27	0	105,03
Year 35	0,181	0	137,31	0	76,16	0	125,27	50(*	114,10
Year 36	0,173	0	137,31	0	76,16	0	125,27	0	114,10
Year 37	0,164	0	137,31	0	76,16	0	125,27	0	114,10
Year 38	0,157	0	137,31	0	76,16	0	125,27	0	114,10
Year 39	0,149	0	137,31	0	76,16	0	125,27	0	114,10
Year 40	0,142	0	137,31	0 100(**	90,36	50(*	132,37	0	114,10
Year 41	0,135	0	137,31	0	90,36	0	132,37	0	114,10
Year 42	0,129	0	137,31	0	90,36	0	132,37	0	114,10
Year 43	0,123	0	137,31	0	90,36	0	132,37	0	114,10
Year 44	0,117	0	137,31	0	90,36	0	132,37	0	114,10
Year 45	0,111	50(*	142,87	0	90,36	0	132,37	0	114,10
Year 46	0,106	0	142,87	0	90,36	0	132,37	0	114,10
Year 47	0,101	0	142,87	0	90,36	0	132,37	0	114,10
Year 48	0,096	0	142,87	0	90,36	0	132,37	0	114,10
Year 49	0,092	0	142,87	0	90,36	0	132,37	0	114,10
Year 50	0,087	0	142,87	0	90,36	0	132,37	0	114,10
Remaining value of repair (50 yrs)		-25	-2,18	-33	-2,88	-17	-1,48	0	0
Discounted cost (1000€)		**140,7**		**87,5**		**130,9**		**114,1**	

(= light MR&R action (e.g. aesthetic repair, coating)*

*(** = heavy MR&R action*

Table 5. The effect of the discount rate on the discounted cost level (cost in 1000 €).

Discount rate (%)	Repair method 1	Repair method 2	Repair method 3	Repair method 4
2	212	146	195	158
5	144	88	131	114
8	107	58	93	89

Table 6. Sensitivity analysis, ranking order

Discount rate (%)	Repair method 1	Repair method 2	Repair method 3	Repair method 4
2	4	1	3	2
5	4	1	3	2
8	4	1	3	2

In table 6 the various repair alternatives are ranked in order of increasing cost. The ranking order is not altered by the discount rate applied in calculations, and it can thus be concluded that the choice of repair method is insensitive to discount rate.

It must be appreciated that the above examples are purely illustrative and the figures may be ranked differently depending on the labour and material cost or the place or the country the object is situated. The evaluation of time to the next intervention of the repair material/system is one of the most difficult tasks, the calculation method is very sensitive to the costs which accumulate during the first decades. This may change the ranking order of the most economical LCC of different repair techniques. When optimising the time of certain MR&R actions, condition state and degree as well as speed of degradation should be taken into account.