# Life Cycle Management System

# LIFECON LMS

## Technical Summary


## Asko Sarja

### VTT Building and Transport


**Shared-cost RTD project**

| | |
|---|---|
| Project acronym: | **LIFECON** |
| Project full title: | **Life Cycle Management of Concrete Infrastructures for Improved Sustainability** |
| Project Duration: | 01.01.2001 - 31.12.2003 |
| Co-ordinator: | Technical Research Centre of Finland (VTT)<br>VTT Building Technology<br>Professor, Dr. Asko Sarja |


Date of issue of the report: 05.04.2004

Project funded by the European Community under the Competitive and Sustainable Growth Programme (1998-2002)

# Project Information

**CONTRACT N°:** G1RD-CT-2000-00378

**ACRONYM:** **LIFECON**

**PROJECT TITLE:** Life Cycle Management of Concrete Infrastructures for Improved Sustainability

**PROJECT CO-ORDINATOR:** Technical Research Centre of Finland (VTT), VTT Building Technology
Professor, Dr. Asko Sarja

**PARTNERS:**

The Finnish Road Administration, Finland

CT LAASTIT Oy Ab, Finland;

Optiroc Oy Ab, Finland

Technische Universität München, Germany

OBERMAYER PLANEN+BERATEN, Germany

Norwegian University of Science and Technology, Norway

Interconsult Group ASA,
(Since 01. 01.2003: Interconsult Norgit AS), Norway

Norwegian Building Research Institute, Norway

Kystdirektoratet, Norway

Millab Consult A.S., Norway

Centre for Built Environment, Sweden

Gävle Kommun, Sweden

Ljustech Konsults AB, Sweden

L.Öhmans Bygg AB, Sweden

British Energy Generation Ltd, UK

Heriot-Watt University, UK

Centre Scientifique et Technique du Batiment CSTB, France.

**PROJECT DURATION:** FROM 01.01.2001 TO 31.12.2003

Project funded by the European Community under the Competitive and Sustainable Growth Programme (1998-2002)

## 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<br>• Part 1: Markov chain based LCC analysis<br>• Part 2: Reference structure models for prediction of degradation |
| D2.3 | Methods for optimisation and decision making in lifetime management of structures<br>• Part I: Multi attribute decision aid methodologies (MADA)<br>• Part II: Quality function deployment (QFD)<br>• 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 |

# List of Contents

# 1 Introduction

This report presents the technical summary of Lifecon LMS (Life Cycle Management System created in LIFECON project).

Lifecon LMS addresses the rapidly increasing need of maintenance, repair and modernisation of eldering European civil infrastructures, such as bridges, harbours, tunnels, power plants and off-shore structures, as well as building stock. The deteriorating civil engineering structures and buildings make a great impact on resources, environment, human safety and health. The influence of business buildings on productivity of work of organisations, and on safety and health of people is important. Infrastructures (in LIFECON: including buildings, excluding roads and railways) represent about 70 % of national property in European countries. Operation (excluding traffic), maintenance, repair, modernisation and renewal of the infrastructure is consuming about 35 % of all energy, and producing about 30 % of all environmental burdens and wastes. At the time being the maintenance and repair are reactive, and the need of maintenance and repair is mostly realised at a very advanced stage of deterioration, causing huge investments in repair measures, or even the need of demolition.

Current goal and trend in all areas of mechanical industry as well as in building and civil engineering is the socially, economically, ecologically and culturally sustainable development. A technical approach for this objective is called Lifetime Engineering (also called Life Cycle Engineering). This can be defined as follows:

**Lifetime Engineering** is a theory and praxis for solving the dilemma that currently exists between infrastructures as a very long-term product and the prevailing short-term approach to design, management and maintenance planning.

Lifetime engineering includes:

- Lifetime investment planning and decision-making
- Integrated lifetime design
- Integrated lifetime construction
- Integrated lifetime management and maintenance planning
- Modernisation, reuse, recycling and disposal

The integrated lifetime engineering methodology concerns the development and use of technical performance parameters to optimise and guarantee the lifetime quality of the structures in relation to the requirements arising from human conditions, economy, cultural and ecological considerations. The lifetime quality means the capability of an object or the whole network of objects to fulfil the requirements of users, owners and society over its entire life, which means in practice the planning period (usually from 50 to 100 years).

**Integrated lifetime design** includes a framework, a description of the design process and its phases, special lifetime design methods with regard to different aspects: human conditions, economy, cultural compatibility and ecology. These aspects will be treated with parameters of technical performance and economy, in harmony with cultural and social requirements, and with relevant calculation models and methods.

**Integrated lifetime management and maintenance planning** includes continuous condition assessment, predictive modelling of performance, durability and reliability of the facility, maintenance and repair planning and decision-making procedure regarding alternative maintenance and repair actions.

The **Lifecon LMS** belongs to the group of integrated lifetime management and maintenance planning. It is practically oriented and respects the principles applied by most European public authorities as well as by private owners or owner organisations.

The main innovative aspect of Lifecon LMS is a delivery of **an open and generic European model of an integrated and predictive Life Cycle Maintenance and Management Planning System (LMS)** that

- facilitates the change of the facility maintenance and management from a reactive approach into a predictive approach
- works on life cycle principle
- includes following aspects of sustainable and conscious development: human requirements (usability, safety, health and comfort), life cycle economy, life cycle ecology and cultural requirements.

**Novelties in Lifecon LMS are**:

*1. Predictivity*, which means that the functional and performance quality of the infrastructure facilities will be predicted for a planning and design period of the facility with integrated performance analysis, including:

- predictive performance and service life modelling
- modular product systematics
- methods of system technology, reliability theory and mathematical modelling
- residual service life prediction of structures
- quantitative classification of degradation loads

*2. Integration***,** which means that all requirement classes of sustainable and conscious development (human social, economic, ecological and cultural) are included in MR&R planning, design and execution processes.

*3. Openness*, which means freedom to apply the generic Lifecon LMS into specific applications, using selected modules of the LMS for each application, and freedom to select between methods presented in LIFECON deliverables or outside of these. The openness is valid for both the LMS description and the IT application.

Lifecon LMS is aiming to fill the gap between generic requirements of sustainable building, and European and global norms, standards and practice.

**The main target group of Lifecon LMS** are owners of buildings and infrastructures, who will gain an open model for management system and methods which can be applied for individual requirements. The LIFECON systematics will also allow the suppliers and manufacturers to compare, select and develop their maintenance and repair methods and materials to fulfil the multiple requirements in varying conditions. This will improve the competitiveness of European SME's on this sector. For consultants the advanced IT applications of Lifecon LMS will provide new business possibilities in Europe and globally.

# 2 System Structure

Lifecon LMS is a system approach, where generalised reliability principles, different facility management process phases, predictive durability calculation models, usability and obsolescence analyses, as well as multi criteria decision making and optimisation methods are applied and integrated into a system description.

Open systems always have a modular structure; consisting of modules and components. In LIFECON the modular principle has several meanings:

- Real modular structure of objects: structural system, structural modules, components, details and materials (see Appendix 1: Terms and Definitions). These are described and applied in Lifecon deliverable D3.1.
- Modular structure of the Lifecon LMS structure, consisting of thematic modules, and model and method components. This is described and applied in Lifecon deliverable D2.1.
- Modular structure of Lifecon LMS management process. This is described and applied in Lifecon deliverable D1.1.

Lifecon LMS has a modular structure, consisting of following thematic modules, which are also presented in Figure 1, together with the relevant interaction between the modules.

- System and Process Description: "Generic Technical Handbook" [Lifecon D1.1]
- IT TOOLS [Lifecon D1.2, D1.3 and D1.4]
- Reliability Based Methodology [Lifecon D2.1]
- Methods for Optimisation and Decision Making [Lifecon D2.3]
- Condition Assessment Protocol [Lifecon D3.1]
- Degradation Models [Lifecon D3.2, D2.1 and D2.2]
- Planning of MR&R Projects [Lifecon D5.1, D5.2 and D5.3]

These modules of Lifecon LMS system support the following activities in the LIFECON management system and process modules:

- Assistance in inspection and condition assessment of structures
- Determination of the network level condition statistics of a building stock
- Assessment of MR&R needs
- LC analysis and optimisation for determination of optimal MR&R methods and life cycle action profiles (LCAP's) for structures
- Definition of the optimal timing for MR&R actions
- Evaluation of MR&R costs
- Combination of MR&R actions into projects
- Sorting and prioritising of projects
- Allocating funds for MR&R activity
- Performing budget check
- Preparation of annual project and resources plans
- Updating degradation and cost models using inspection and feed back data

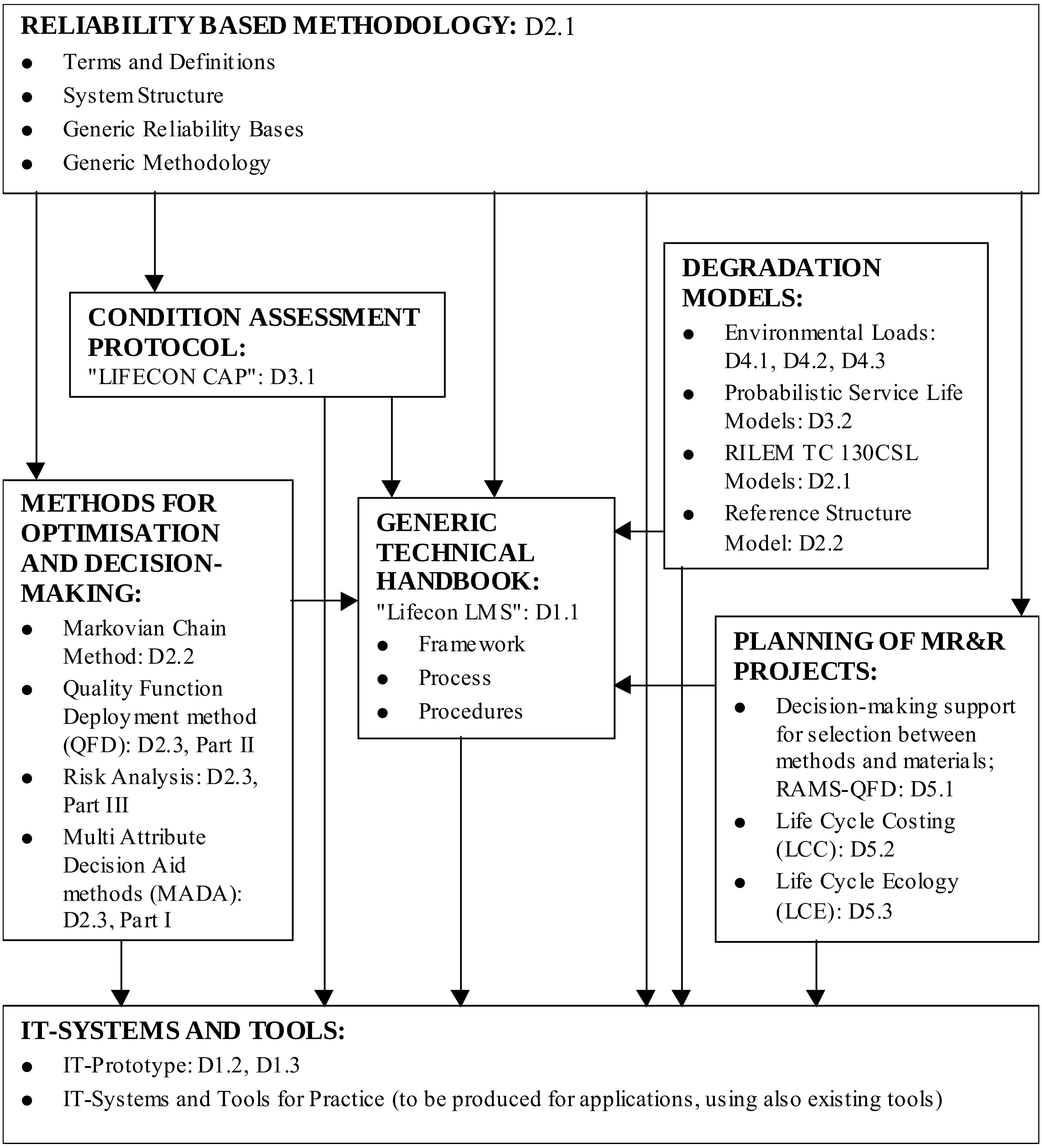


*Figure 1. Thematic modules and their main interaction in Lifecon LMS (the numbers in the boxes refer to the Lifecon deliverables)*

As can be seen in Figure 1, some modules include alternative methods and models. This property is aimed at helping the users to select best-suited methods or models for each specific application.

Lifecon LMS includes a generic system, methodology and methods for management of all kind of structures. The only exception is that durability management: condition assessment protocol and degradation models, are focused on concrete structures only. When applying Lifecon LMS into other materials, these have to be replaced with other kind of condition assessment protocols and degradation models.

# 3 Generic Methodology [D2.1]

## 3.1 Generic Requirements

The lifetime quality means the capability of the structures to fulfil the multiple requirements of the users, owners and society in an optimised way during the entire design or planning period (usually 50 to 100 years). The multiple generic requirements are presented in Table 1.

*Table 1. Generic classified requirements of structures and buildings.*

| | |
|---|---|
| 1. Human requirements<br>• functionality in use<br>• safety<br>• health<br>• comfort | 2. Economic requirements<br>• investment economy<br>• construction economy<br>• lifetime economy in:<br>- operation<br>- maintenance<br>- repair<br>- rehabilitation<br>- renewal<br>- demolition<br>- recovery and reuse<br>- recycling of materials<br>- disposal |
| 3. Cultural requirements<br>• building traditions<br>• life style<br>• business culture<br>• aesthetics<br>• architectural styles and trends<br>• imago | 4. Ecological requirements<br>• raw materials economy<br>• energy economy<br>• environmental burdens economy<br>• waste economy<br>• biodiversity |

## 3.2 Optimisation and Decision-Making Methodology

The objective of the integrated and predictive lifetime management is to achieve optimised and controlled lifetime quality of buildings and civil infrastructures in relation to the generic requirements. This objective can be achieved with a performance-based methodology, applying generic limit state approach. This means that the generic requirements have to be modelled with technical and economic numerical parameters into quantitative models and procedures, and with semi-numerical or non-numerical ranking lists, classifications and descriptions into qualitative procedures. This procedure can be described with a scheme which is presented in Figure 2. The generic requirements are listed in Table 1.

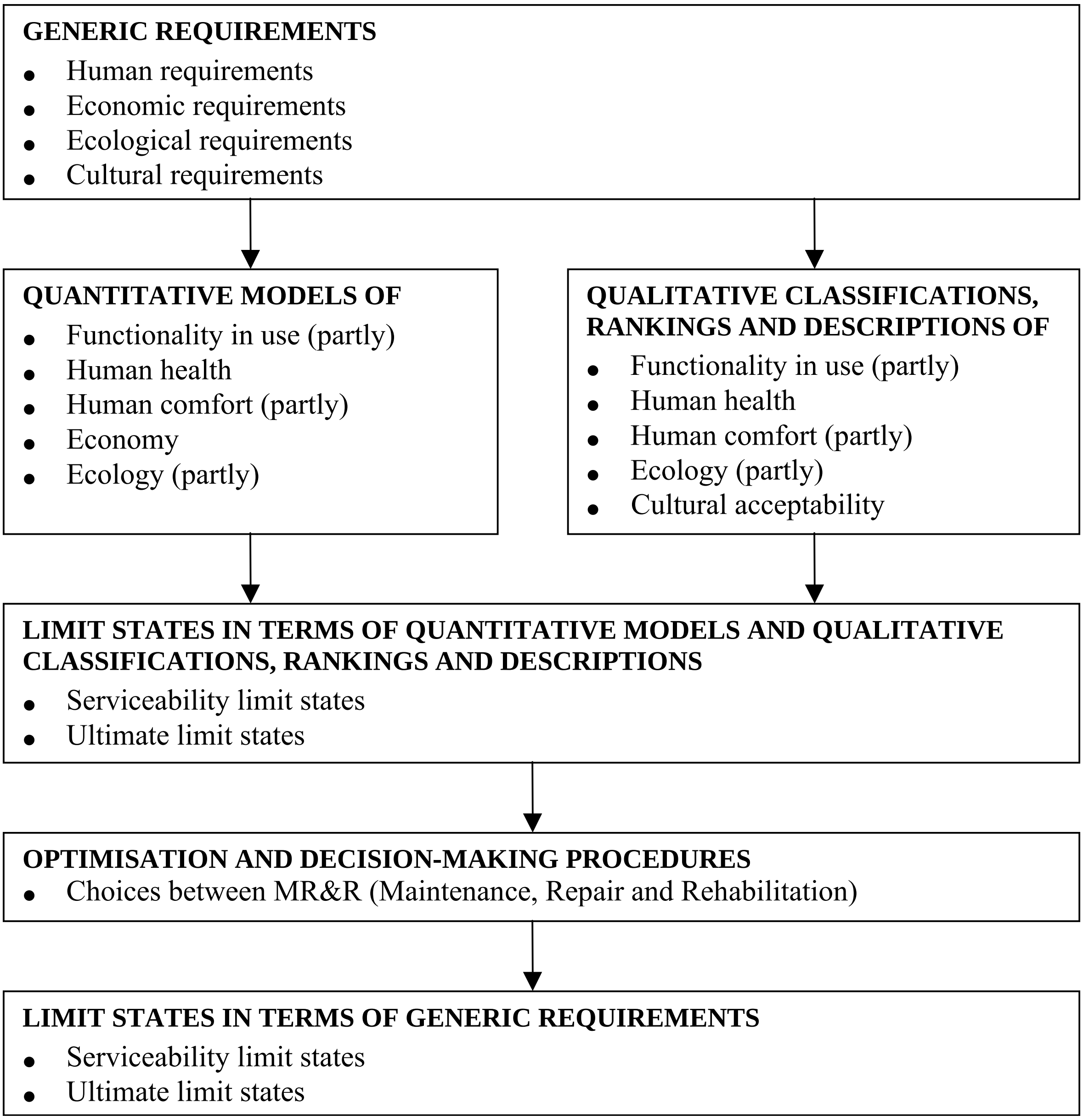


*Figure 2. Scheme of the generic procedure of reliability management in Lifecon LMS.*

The lifetime performance modelling and the limit state approach are building an essential core of the lifetime management and MR&R planning. Performance based modelling includes the following classes:

1. Modelling of the behaviour under mechanical (static, dynamic and fatigue) loads
2. Modelling of the behaviour under physical, chemical and biological loads
3. Modelling of the usability and functional behaviour

The mechanical modelling has been traditionally developed on the limit state principles already starting in 1930's, and introduced into common practice in 1970's. The newest specific standard for reliability of structures is Eurocode EN1990:2000. The mechanical behaviour (safety and serviceability), beside the other categories mentioned above, have to be checked in several phases of the management process. This is important especially in condition assessment and in MR&R planning. It is sometimes possible to combine the mechanical calculations with degradation and service life calculations, but often its is better to keep these separated. Because the models and calculation methods of mechanical behaviour are very traditional and included in normative documents of limit state design, this issue is not treated in this context, which is focused on durability limit state design and obsolescence limit state design.

Modelling for physical, chemical and biological loads includes a large variety of thermal behaviour, behaviour under fire conditions, moisture behaviour and behaviour under biological impacts, and biological phenomena (e.g. mould and decay). These are connected with several phenomena and properties of structures in use, and in this context this section is distributed into different procedures of the reliability assessment. Traditional analysis of thermal, fire and moisture behaviour are excluded in this report.

Modelling of usability and functionality in life cycle management system means the management of obsolescence. Obsolescence means the inability to satisfy changing functional (human), economic, cultural or ecological requirements. Obsolescence can affect the entire building or civil infrastructural asset, or just some of its modules or components. Obsolescence is the cause of demolition of buildings or infrastructures in about 50% of all demolition cases. In the case of modules or component renewals the share of obsolescence is still higher. Therefore this issue is very central in developing modern LMS.

Main issue of healthiness during the MR&R actions is to avoid unhealthy materials [Lifecon D5.1]. During the use of assets (especially in closed spaces like buildings or tunnels) the goal is to avoid moisture in structures and on finishing surfaces, because it can cause mould, and to check that no materials used cause emissions or radiation which are dangerous for health and comfort of the users. In some areas radiation from the ground must also be eliminated through insulation and ventilation of the foundations. Thus the main tools for health management are: selection of materials (especially finishing materials), eliminating risks of moisture in structures (through waterproofing, drying during construction and ventilation), and elimination of possible radioactive ground radiation with airproofing and ventilation of ground structure. Health requirements can follow the guidelines of national and international codes, standards and guides. The modelling of the health issues thus focuses on calculating comparable indicators on the health properties mentioned above, and on comparing these between alternatives in the optimisation and decision-making procedures. These can usually be calculated numerically, and they are thus mainly quantitative variables and indicators, which can be compared in the optimisation and decision-making procedures.

Comfort properties are related to the functionality and performance of the asset, having for example the following properties:

- acoustic comfort, including noise level during MR&R works or in the use of closed spaces like tunnels and buildings
- insulation of airborne sound between spaces
- comfortable internal climate of closed spaces like tunnels and buildings
- aesthetic comfort externally and in functions of use in all kinds of assets
- vibrations of structures

These are calculated with special rules and calculation methods, which are also traditional and therefore will not be treated in this report. Mainly quantitative (exact numerical or classified) values can be used for these properties.

Ecology can be linked to the environmental expenditures: consumption of energy, consumption of raw materials, production of environmental burdens into air, soil and water, and loss of biodiversity. Most of these can be calculated numerically, and thus are quantitative variables and indicators. These can be also compared quantitatively in the optimisation and decision-making procedures. In buildings, energy consumption mostly dictates environmental properties. For this reason the thermal insulation of the envelope is important. Finally the reuse and recycling of the components and materials after the demolition belong to the ecological indicators. Engineering structures such as bridges, dams, towers, cooling towers etc. are often very massive and their material consumption is an important factor. Their environmental efficiency depends on the selection of environmental-friendly local raw materials, high durability and easy maintainability of the structures during use, recycling of construction wastes and finally recycling of the components and materials after demolition. Some parts of engineering structures, such as waterproofing membranes and railings, have a short or moderate service life and consequently easy re-assembly and recycling are the most important issues in order to minimise the annual material consumption property. During MR&R works it is important to apply effective recycling of production wastes. This leads to calculations of waste amounts as quantitative variables of this component of ecology. Some ecological properties, like loss of biodiversity, are difficult to calculate numerically, and often they can be only qualitatively described. This qualitative description can then be used in comparing alternatives during optimisation and decision-making procedures.

The functionality of civil infrastructures means the capability to serve for the main targets of an asset, e. g. in case of tunnels and bridges the capability to transmit traffic. This can be modelled numerically using suited geometric dimensions and load bearing capacity etc. as variables and indicators. The functionality of buildings is very much related to the flexibility for changes of spaces, and often also on the loading capacity of floors. Also the changeability of building service systems is important. Internal walls have a moderate requirement of service life and a quite high need to accommodate changes. These are dictating the capability of a building to enable changes in the functions during the lifetime management. For this reason internal walls must have good changeability and recycleability. An additional property is good and flexible compatibility with the building services system, because the services system is the most often changed part of the building.

For avoiding the repeating of traditional and well known issues, the generalised and reliability based life cycle management approach can be focused and formulated into following three categories:

1. Static and dynamic (mechanical) modelling and design
2. Degradation based durability and service life modelling and design
3. Obsolescence based performance and service life modelling and design

In Lifecon LMS system the transformation of generic requirements into functional and performance property definitions, and further into technical specifications and performance models will be realised with the following methods:

1. Requirements Analysis and Performance Specifications: Quality Function Deployment Method QFD: [Lifecon D2.3]
2. Environmental Degradation Loads: [Lifecon D4.1, D4.2, D4.3]
3. Service Life Estimation:
    - Probabilistic Service Life Models: [Lifecon 3.2]
    - RILEM TC 130 CSL Models: [Lifecon D2.1]
    - Reference Structure Method: [Lifecon D2.2]

4. Condition Assessment Protocol: [Lifecon D3.1] and Condition Matrix: Markovian Chain Method: [Lifecon D2.2].
5. Total and Systematic Reliability Based Methodology: [Lifecon D2.1]
6. Risk Analysis: [Lifecon D2.3]
7. MR&R (Maintenance, Repair and Rehabilitation) Planning: [Lifecon D5.1, D5.2,D5.3]

### 3.3 Reliability Based Systematics

Taking into consideration all classes of limit states: mechanical (static and dynamic), durability and obsolescence limit states, we have to define these limit states first in generic terms, see Table 2. Using the generic definitions we are able to describe more detailed definitions and criteria of limit states in each specific case separately.

*Table 2. Generic mechanical, degradation and obsolescence limit states of concrete structures.*

| Classes of the limit states | Limit states | | |
|---|---|---|---|
| | Mechanical (static and dynamic) limit states | Degradation limit states | Obsolescence limit states |
| A. Serviceability limit states | 1. Deflection limit state<br>2. Cracking limit state | 3. Surface faults causing aesthetic harm (colour faults, pollution, splitting, minor spalling)<br>4. Surface faults causing reduced service life (cracking, major spalling, major splitting)<br>5. Carbonation of the concrete cover (grade 1: one third of the cover carbonated, grade 2: half of the cover carbonated, grade3: entire cover carbonated) | 6. Reduced usability and functionality, but still usable<br>7. The safety level does not allow the requested increased loads<br>8. Reduced healthy, but still usable<br>9. Reduced comfort, but still usable |
| B. Ultimate limit states | 1. Insufficient safety against failure under loading | 2. Insufficient safety due to indirect effects of degradation:<br>• heavy spalling<br>• heavy cracking causing insufficient anchorage of reinforcement<br>• corrosion of the reinforcement causing insufficient safety. | 3. Serious obsolescence causing total loss of usability through:<br>• loss of functionality in use (use of building, traffic transmittance of a road or bridge etc.)<br>• safety of use<br>• health<br>• comfort<br>• economy in use<br>• MR&R costs<br>• ecology<br>• cultural acceptance |

The generic durability limit states and their application in specific cases can be described with numerical models and treated with numerical methodology, which are quite analogous to the models and methodologies of the mechanical (static and dynamic) limit states design. The durability design procedure is as follows:

1. specifying the target service life and design service life
2. analysing environmental loads onto structures
3. identifying durability factors and degradation mechanisms
4. selecting a durability calculation model for each degradation mechanism
5. calculating durability parameters using available calculation models
6. possible updating the calculations of the ordinary mechanical design (e.g. own weight of structures)
7. transferring the durability parameters into the final design

The limit states of obsolescence are quite different from the others, and often they cannot be described in quantitative means. Often we have to apply qualitative descriptions, criteria and methods. Even with these quite inexact means we can however reach a level of rational selection and decisions between the alternatives. The principles of obsolescence analysis follow the risk analysis and control procedure, Quality Function Deployment (QFD) method and Multiple Attribute Decision Aid (MADA), or their combinations [Lifecon D2.3].

# 4 Methods for Optimisation and Decision-Making [Lifecon D2.3]

## 4.1 The Aim of the Methods

The aim of the methods for optimisation and decision-making is to rank the alternative MR&R strategies, technologies and materials in order of preference, which is measured by means of the generic requirements: human requirements, lifetime economy, lifetime ecology and cultural criteria. These optimisations and decisions are made at different levels of management:

- Network level
- Object level
- Module, Component, Detail and Material levels

Following three different methods for requirements analysis, optimisation and decision-making are presented:

- Multi Attribute Decision Aid (MADA)
- Quality Function Deployment (QFD) method
- Risk Analysis

## 4.2 Multi Attribute Decision Aid (MADA)

MADA is a methodology that is able to rank the alternatives in order of preference (in Lifecon LMS preference is measured by means of human requirements, lifetime economy, lifetime ecology and cultural criteria).

The decision maker can decide at different phases of maintenance planning:

- Network level: Among all the objects of the stock, which one(s) is (are) identified as having priority for intervention?
- Object level: Which part(s) of the object is (are) identified as having priority (e.g. during condition assessment)?
- Module, Component, Detail and Material levels: what are the best solutions to keep or upgrade the level of requirements in performance?

As an example, once identified the need of intervention on an object (by means of the condition assessment of the stock of objects), various actions (strategies for object management) are possible:

- No action
- Maintenance solutions
- Repair solutions
- Restoration solutions
- Rehabilitation solutions
- Modernisation solutions
- Demolition and new construction

Framework for identifying and explaining the six-step-procedure of MADA in Lifecon LMS is presented in Figure 3.

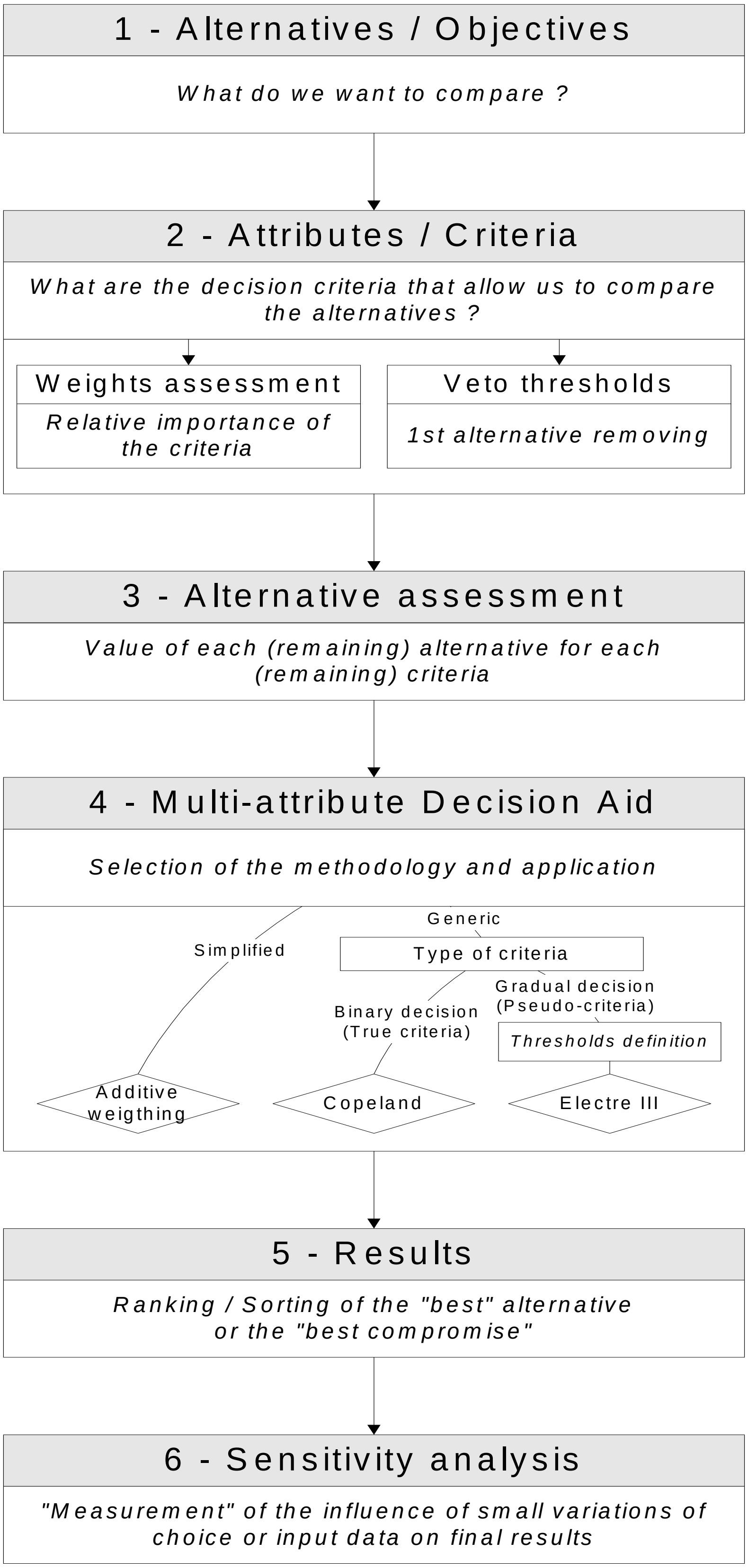


*Figure 3. MADA Flow-chart.*

## 4.3 Quality Function Deployment (QFD)

In short, the QFD method means building of a matrix between Requirements (=Whats) and Performance Properties or Technical Specifications (=Hows). Usually the Performance Properties are serving only as a link between Requirements and Technical Specifications, which is the reason why the Performance Properties are often not treated with QFD method. Additionally weighting factors of Requirements and Technical Specifications as well as correlations between Requirements and Technical Specifications are identified and determined numerically. In practical planning and design the application shall be limited into few key Requirements and key Specifications in order to maintain good control of variables and in order not to spend too much efforts for secondary factors.

QFD can be used for interpreting any Requirements into Specifications, which can be either Performance Properties or Technical Specifications. Thus QFD can serve as an optimising or selective linking tool between Requirements, Performance Properties and Technical Specifications. It can be used both at product development, at design of individual civil infrastructures or buildings, and at maintenance and repair planning. Fundamental objectives of QFD are:

- Identification of functional Requirements of owner, user and society
- Interpreting and aggregating functional Requirements first into Performance Properties and then into Technical Specifications of the structures
- Optimising the Technical Specifications and/or Performance Properties in comparison to Requirements
- Selection between different design and repair alternatives

The alternatives and possibilities for application in QFD methodology are the same as described above for MADA. QFD is most suited for the numerical analysis of requirements and their weights, which always is the first phase of QFD. QFD is always applied in numerical analysis, but it can be combined with non-numerical evaluations and rankings between alternatives, like repair strategies, actions and technologies and materials.

## 4.4 Risk Analysis

The main objectives of Lifecon risk assessment and control are:

- to make facility owner aware of the risks *in Lifecon extent* (the four generic requirement classes)
- to form a solid framework and base for risk-based decision-making
- to give guidelines how to use the Lifecon risk approach in decision-making process

In short the Lifecon risk assessment and control procedure can be described with the following four steps:

1. Identification of adverse incidents
2. Analysis of the identified adverse incidents
    - deductively (downwards), in order to find causes (e.g. using fault tree analysis)
    - inductively (upwards), in order to find consequences (e.g. using event tree analysis)
3. Quantitative risk analysis
4. Risk based decision-making (and continuous updating of risk database)

The steps 1, 2 and 4 are always performed if risk analysis is used, forming qualitative risk analysis. The step 3 is only performed if qualitative risk analysis is not enough for decision-making *and* if quantification is possible.

A very important feature in the procedure is the continuance. Management of concrete infrastructures is a continuous process and new experience gained every day. The same applies to risk management. The steps described above form Lifecon risk management loop that is continuously maintained and updated, with strict documentation.

In Lifecon the consequences are divided in four main categories, which are

- human conditions (usability, safety, health, comfort)
- culture (local building traditions, local ways of living, local working environments, aesthetics, architectural styles and trends, imago)
- economy (construction costs, MR&R)
- ecology.

The four main categories are further divided into sub-categories, to make the inductive part (event tree analysis) of the risk analysis easier to handle.

If the qualitative risk analysis is not enough, a quantitative risk analysis can be performed (if there is enough source data for the analysis). The quantitative risk analysis utilises the same fault and event tree skeletons that were created in the step number two. In this quantitative phase, estimations about probabilities of basic events are added to the fault tree part of the analysis. Likewise, in the event tree part of the analysis, estimations about the probabilities of the subsequent events are added to the event tree skeleton. Because risk is defined as the product of probability and consequence, mere estimation and calculation of probabilities is not enough in calculating risk. Also the consequences (defined in event tree analysis) must be estimated numerically. After having those numbers, the risk can be easily calculated.

When the identified adverse incidents have been analysed and risks estimated (qualitatively or quantitatively, according to need), risk evaluation can be performed. In this phase judgements are made about the significance and acceptability of the risks, and finally, decisions are made on how to deal with the risks.

It is recommended to use fault tree and event tree analyses in evaluation of risk, but other very applicable methods exist too. The logics is always the same, regardless of the chosen risk analysis method. The following three questions must be answered:

- What can go wrong?
- How likely is it?
- What are the consequences?

Apart from the logics of risk analysis procedure, another fact is common to all risk analysis methods: strong expertise is needed and the results depend highly on how rigorously the analyses are performed. No shortcuts should be taken if real benefits are wanted. It should be remembered that a huge part of the accidents, failures and unintended events happen due to negligence, not ignorance. All risk analysis methods (when pertinently carried out) include brainstorming and prioritisation processes performed by a multi-discipline team consisting of members from different stakeholder groups. These people who give "raw material" (data, opinions, estimations etc.) for risk analyses, must be experts with solid experience in their business. These are for example maintenance engineers, facility owners, statisticians, inspectors, material suppliers, etc.

# 5 Management Process

## 5.1 MR&R Strategy, Optimisation and Decision-Making [Lifecon D1.1]

Typical needs and requirements of governmental organisations for a computer aided management system are the following. For the administration of the organisation:

- Need for economic justification of decisions
- Objective basis for decisions, based on engineering, economic and ecological grounds
- Strategic guidelines for preservation of assets
- Determination of medium and long-term objectives, and need for definition of appropriate maintenance strategies to achieve this
- Optimising MR&R strategies based on engineering and economic grounds
- Need for selection of justificable maintenance decisions within budget constraints
- Need for showing value for money in infrastructure provision and maintenance
- Need for integration of allocation of funds
- Evaluation of whole life costing, including user costs

For the maintenance engineers and repair designers the needs are:

- Well organised condition assessment and inventory for the structures
- Optimisation of MR&R actions for specific components, modules and objects
- Guaranteed safety
- Safeguarded investments
- Correct timing of MR&R actions
- Evaluation of MR&R costs
- Combination of optimised actions into MR&R projects
- Prioritisation of projects
- Producing annual repair and reconstruction programmes
- Budget control

The ultimate objective of a management process is to make the necessary decisions between the inspection of structures and the execution MR&R projects. In other words a life cycle (LC) management process should be able to answer the strategic questions: which structures should be repaired? which MR&R methods should be used? when to do the MR&R actions? how to combine the actions into projects? All these questions should be answered taking into account technical demands, functional performance, safety, economy, ecology and other necessary viewpoints. The MR&R projects are then executed according to the system assisted decisions.

Lifecon LMS is a predictive and integrated life cycle management system. The system makes it possible to organise and implement all the activities related to planning, constructing, maintaining, repairing, rehabilitating and replacing structures in an optimised way taking into account safety, serviceability, economy, ecology and other aspects of life cycle planning.

The following activities are included in the LIFECON management process:

1. Assistance in inspection and condition assessment of structures,
2. Determination of the network level condition statistics of a building stock,
3. Assessment of MR&R needs,
4. LC analysis and optimisation for determination of optimal MR&R methods and life cycle action profiles (LCAP's) for structures

5. Definition of the optimal timing for MR&R actions
6. Evaluation of MR&R costs,
7. Combination of MR&R actions into projects
8. Sorting and prioritising of projects,
9. Allocating funds for MR&R activity
10. Performing budget check,
11. Preparation of annual project and resources plans
12. Updating degradation and cost models using inspection and feed back data

The decision making process is performed at three levels of structural hierarchy (Figure 4):

1. Component/module
2. Object
3. Network level.

The component/module level addresses structural components such as beams and columns and their combinations, i.e. modules. The object level refers to complete structures or buildings such as bridges and nuclear power plant units. The network level addresses networks of objects such as stocks of bridges or buildings.

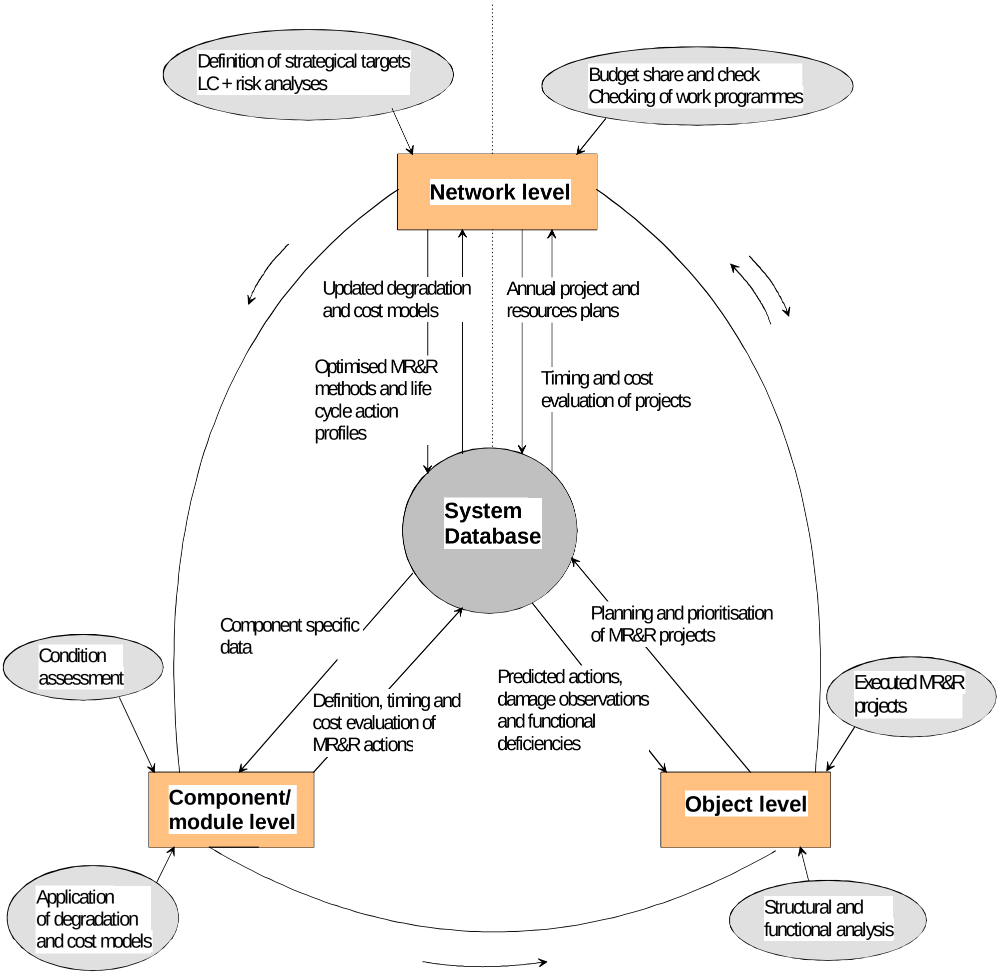


*Figure 4. Three levels of decision making in Lifecon LMS.*

The object level process is designed for companies and organisations which own only a limited amount of concrete infrastructures. It is a practically oriented process which helps the maintainers to plan and execute the MR&R projects based on the inspection and condition assessment data. It provides maintainers with proposals for MR&R actions with optimised timing, composition of actions (project planning) and annual project programmes of infrastructure networks.

The network level process is designed for national road administrations and other organisations which are responsible for the upkeep of a large network of concrete infrastructures. The network level process can be applied administration level operative planning and decision-making. It makes it possible for the administration of an organisation to evaluate the necessary funding for MR&R activity and optional maintenance strategies.

The network + object level process is an integrated network and object level process. By a special interface the optimised work programmes produced of the object level can be compared and harmonised with the network level optimum before returning back to the object level and implementation. The integrated network and object level process (complete version) is presented in Figure 5. In the figure the network level process and the object level process is separated with thick dotted lines.

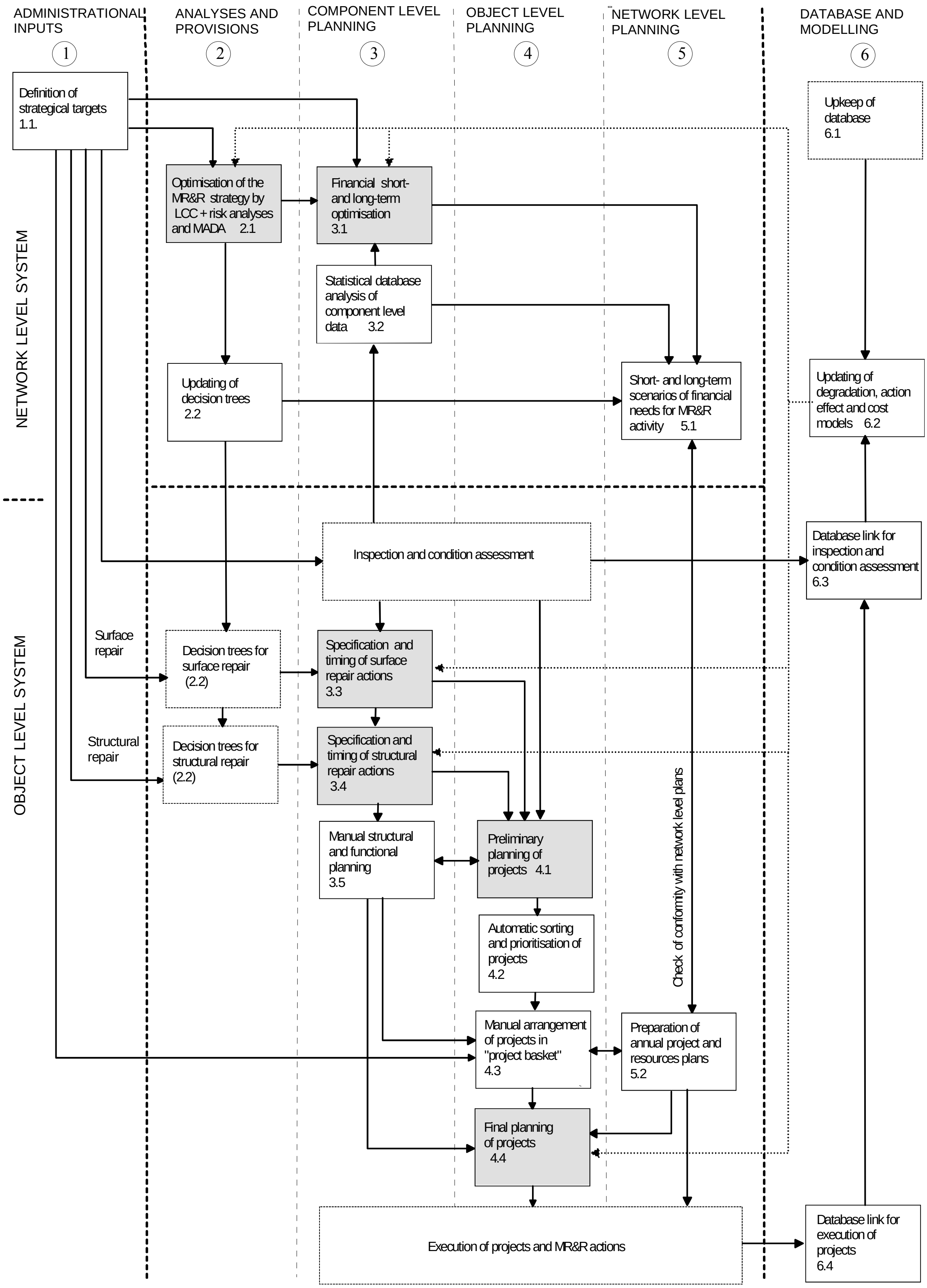


*Figure 5. Flow diagram of the integrated network and object level Lifecon LMS process. The numbering of the modules and a full description of each module is presented in Lifecon deliverable D1.1.*

## 5.2 Condition Assessment Protocol (CAP) [Lifecon D3.1]

The repeated assessment of the structure condition is a decision process, which serves to identify necessary actions which lead to the most effective fulfilment of all defined requirements. One option is to "buy" additional information by inspection to obtain more reliable information on the current condition. This knowledge can be used to update models with the intention of improving the precision of future predictions. In summary the following aims were pursued:

- Integration of existing probabilistic service life models and reliability theory in the framework for condition assessment of concrete structures
- Provision of an organized system for collecting, rating and storing of data
- Ensure that information is only collected if necessary and information is suitable for the defined purpose
- The approach has to be applicable to users managing small to very large assessment projects, with or without a) large sampling effort and b) experience on and capacities for reliability analysis.

The main idea is to start with a low inspection volume and with basic investigation methods which will be increased or become more sophisticated if intermediate results suggest so. The scheme of this ideology can be found in Figure 6, where the basic framework of condition assessment is presented. The flowcharts concerning planning of condition assessment, visual inspection as well as general inspection are presented in detail in Lifecon deliverable D3.1.

Eventhough Lifecon LMS focuses on the management of concrete structures, such objects are never built solely of concrete. The CAP is meant for the assessment of concrete, protective measures for concrete and imbedded re-bars and pre-stressing steel. Those materials (e.g. sealers) whose failure due to deterioration leads to concrete deterioration are included. Other materials are out of the scope. The developed framework can nevertheless be adopted to every type of material.

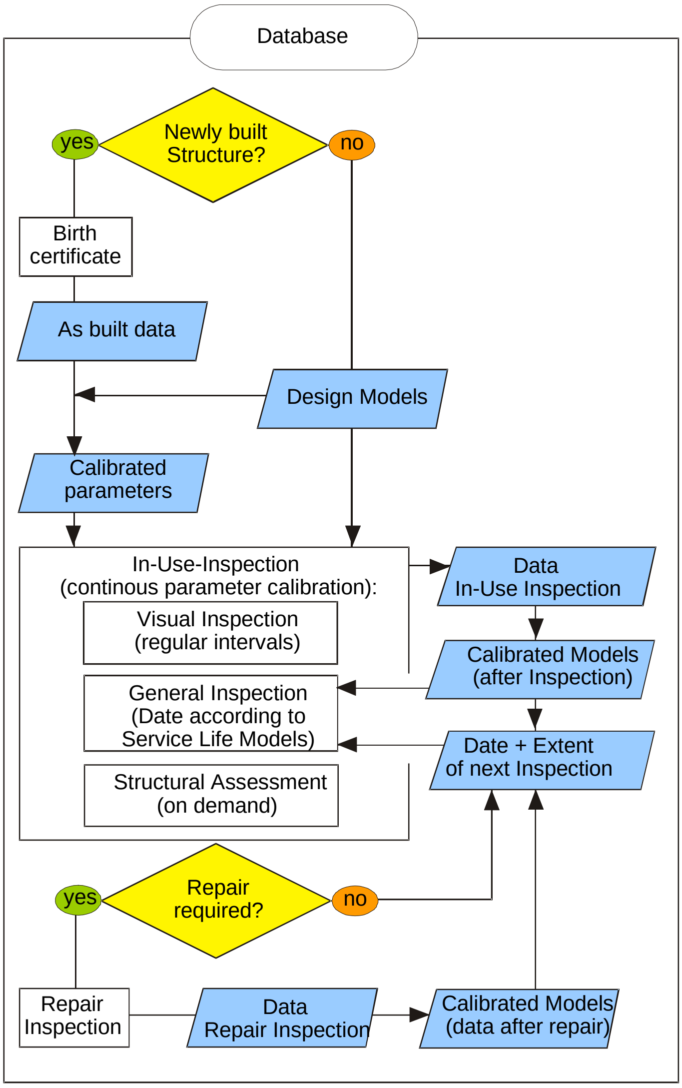


*Figure 6. Basic framework for the condition assessment.*

## 5.3 Service Life Prediction

### *5.3.1 Alternative models*

Three types of degradation models are described in detail, including some examples of application. These models are:

- Statistical degradation models
- RILEM TC130 CSL models
- Reference Structure model

Characteristic properties of these models are as follows:

- Statistical degradation models are based on physical and chemical laws of thermodynamics, and thus have a strong theoretical base. They include parameters, which have to be determined with specific laboratory or field tests. Therefore some equipment and personnel requirements exist for the users. The application of statistical "Duracrete" method raises need for a statistically sufficient number of tests. Statistical reliability method can be directly applied with these models.

- RILEM TC 130 CLS models are based on parameters, which are available from the mix design of concrete. The asset of these models is the availability of the values from the documentation of the concrete mix design and of the structural design.
- Reference structure model is based on statistical treatment of the degradation process and condition of real reference structures, which are in similar conditions and own similar durability properties with the actual objects. This method is suited in the case of a large network of objects, for example bridges. It can be combined with Markovian Chain method in the classification and statistical control of the condition of structures.

Because of the openness principle of Lifecon LMS, each user can select the best suited models for their use. It is sure, that there exist also a lot of other suited models, and new models are under development. They can be used in Lifecon LMS after careful validation of the suitability and reliability. Special attention has to be paid to the compatibility of entire chain of the procedure of reliability calculations.

### *5.3.2 Statistical degradation models [Lifecon D3.2]*

Statistical degradation models include the mathematical modelling of corrosion induction due to carbonation and chloride ingress, corrosion propagation, frost (internal damage and surface scaling) and alkali-aggregate reaction. Models are presented on a semi-probabilistic and a full-probabilistic level. Semi-probabilistic models only include parameters obtainable throughout structure investigations, without making use of default material and environmental data. Full-probabilistic models are applicable for service life design purposes and for existing objects, including the effect of environmental parameters. For each full-probabilistic model a parameter study was performed in order to classify environmental data.

The application of the models for real structures is outlined. The objects of the case studies have been assessed in order to obtain input data for calculations on residual service life. Each degradation mechanism will be treated separately hereby demonstrating:

- possible methods to assess concrete structures
- the sources for necessary input data
- approach used in durability design
- application of models for existing structures
- the precision of the applied models
- necessary assumptions due to lack of available data
- possible method to update data gained from investigations throughout condition assessment
- default values for input data
- output of the calculations

The use of full-probabilistic models for the calibration of the Markov Chain approach is described.

### *5.3.3 RILEM TC 130 CSL models [Lifecon D2.1]*

RILEM TC 130 CSL degradation models include a set of selected calculation models consisting of parameters, which are known from mix design and other material properties and ordinary tests. Therefore these models are usually easy to apply also in cases when no advanced laboratories and equipment are available. The following degradation processes are included in the RILEM TC 130 CSL models:

- Corrosion due to chloride penetration
- Corrosion due to carbonation
- Mechanical abrasion
- Salt weathering
- Surface deterioration
- Frost attack

Degradation affect either the concrete or the steel or both. Usually degradation takes place on the surface zone of concrete or steel, gradually destroying the material. The main structural effects of degradation in concrete and steel are the following:

- Loss of concrete leading to reduced cross-sectional area of the concrete.
- Corrosion of reinforcement leading to reduced cross-sectional area of steel bars. Corrosion may occur
  a) at cracks
  b) at all steel surfaces, assuming that the corrosion products are able to leach out through the pores of the concrete (general corrosion in wet conditions).
- Splitting and spalling of the concrete cover due to general corrosion of reinforcement, leading to a reduced cross-sectional area of the concrete, to a reduced bond between concrete and reinforcement and to visual unfitness.

### *5.3.4 Reference structure models [Lifecon D2.2]*

Reference structure degradation prediction is aimed for the use in cases, when the network of objects (e.g. bridges) is so large in number that a sample of them can be selected for a follow-up testing, and these experiences can be used for describing the degradation process of the entire population. The reference structure models are of two types: 1) surface damage and 2) crack damage models. Degradation factors such as frost damage, corrosion of reinforcement, carbonation and chloride penetration may have combined effects that may be of great importance to the service life of a structure. By traditional prediction methods of service life these combined effects are usually ignored. However in computer simulation they can be considered without great theoretical problems. The progress of the depth of carbonation or the depth of critical chloride content is promoted by both the frost-salt scaling of a concrete surface and the internal frost damage of concrete. The internal frost damage is evaluated using the theory of critical degree of saturation. The internal damage is evaluated as the reduction of the dynamic E-modulus of concrete.

The condition state (or damage index) of a structure is evaluated using the scale 0, 1, 2, 3, 4. This scale is also used throughout the bridge management system.

The degradation models for both surface damage and crack damage have been programmed on Excel worksheets. The surface damage models describe normal degradation processes on the surfaces of reinforced concrete structures combining the effects of frost-salt attack, internal frost damage attack, carbonation, chloride ingress and corrosion of reinforcement. The crack damage models emulate the processes of depassivation and corrosion at a crack of a concrete structure.

All management systems that include a prediction module, such as Lifecon LMS, need reliable environmental load data. In Lifecon deliverable D4.2 the relevant systematic and requirements for quantitative classification of environmental loading onto structures, as well as sources of environmental exposure data are given. Lifecon D4.2, chapter 6 contains instructions and guidelines for how to characterise the environmental loads on concrete structures on object and network level.

However, these guidelines have to be validated (and possibly adjusted) before they finally can be used in the LMS. In this report the results from the practical validation are summarised. The EN 206-1 system and the standard prEN 13013 have been tested out on the chosen objects and compared with detailed environmental characterisation of the same objects using the available data and methods for environmental characterisation. Such studies have been undertaken in five countries (Norway, Sweden, Germany, Finland and United Kingdom) to develop the needed national annexes for a proper implementation of EN206-1 across Europe.

Strategies and methodologies for developing the quantitative environmental classification system for concrete are given. Those are, firstly, comparative case studies using the new European standard -“EN 206-1 Concrete” and detailed environmental characterisation of the same objects, and secondly, a more theoretical classification based upon parametric sensitivity analysis of the complex Duracrete damage functions under various set conditions. In this way the determining factors are singled out and classified. Such classification systematic is needed to enable sound prediction of service lives and maintenance intervals both on object and network level. This in turn is a necessary prerequisite for change of current reactive practise into a pro-active life-cycle based maintenance management.

## 5.4 Environmental Degradation Loads

### *5.4.1 Environmental load parameters [Lifecon D4.1]*

The first and general approach to generate data on the degradation agents affecting concrete infrastructures ought to be through utilisation of the climate and weather data normally measured at meteorological sites. This data has to be processed, adapted and modelled to fit into the degradation models. A summary of the needed environmental data is presented in *Table 3*.

*Table 3. Environmental data for degradation modelling.*

| Deterioration mechanism | RH | Temp. | $CO_2$ | Precipi-tation | Wind | Radia-tion | Chloride Conc. | Freeze -thaw cycles | $[SO_2]$ | $[O_3]$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Reinforced concrete | | | | | | | | | | |
| Carbonation induced corrosion | X | (X) | X | X | X | | | | | |
| Chloride induced corrosion | X | X | | X | | | X | | | |
| Propagation of corrosion | X | X | | X | | | X | | | |
| Alkali-aggregate reaction | No model | | | | | | | | | |
| Frost attack internal/scaling | (X) | X | | X | (X) | (X) | (X) | X | | |
| Supplementary materials (Dose-response functions) | | | | | | | | | | |
| Galvanised steel/zink coating | X | X | | X | | | X | | X | |
| Coil coated steel | X | X | | X | | | | | X | |
| Sealants/bitumen | No function | | | | | | | | | |
| Polymers | No function | | | | | | | | | |
| Aluminium | | | | X | | | X | | X | X |

*5.4.2 Quantitative classification of environmental loads [Lifecon D4.2]*

***Object level***

The different components are exposed in different ways and different amounts, due to orientation, sheltering, sun/shadow, distance from "source" for exposure, and more, and all this have to be taken into account.

A step-wise characterisation of the environmental parameters onto the surface of the structure is as follows:

1. Choose object
2. Divide the structure/construction into components with different expected Categories of Location (due to orientation, sheltering...). Use either the EOTA system [D4.2 Annexes] or the height classification system [Table 5 in D4.2].
3. Attain EN206-1 exposure classes to the various components/parts of the construction

4. Adjust for the effect of sheltering, etc. on driving rain and deposition on other agents to the structure by calculation of CR, CT, O and W [Chapter 5.6.1 in D4.2].
5. Find climatic information from nearby meteorological stations. Necessary information:
   a. Temperature. Preferably, if available, time series for a long period (>10 years). Main information is average temperature for summer and winter conditions, max/min and average monthly temperature. Surface temperature can be calculated from the following equation:

$$T_{s,eq} = T_{air} + \frac{1}{\alpha_{cv} + \alpha_r} \cdot \left( I_{solar} \cdot a + g \cdot h_e + \alpha_r \cdot \left( \overline{T}_r - T_{air} \right) \right)$$

   b. Moisture. Preferably, if available, time series for a long period (>10 years). Main information is average annual precipitation and monthly number of days with rain > 0.1mm and rain >2.5mm. Monthly or seasonal relative humidity.
   c. Wind. Preferably, if available, time series for a long period (>10 years). Main information is wind rose showing frequencies of wind speed and direction.
6. Check correlation or relevance for meteorological data for the object.
   a. From some (2-4) nearby stations – any significant difference in meteorological data?
   b. Distance from meteorological station.
   c. Height above sea level. Normally the average temperature decreases 0.6-0.7º C per 100 m.
   d. Sunny/shadowed areas (for instance of valleys). A difference of 0.5-1º C in air temperature may be expected.
   e. Topography – differences in wind speed and direction.
7. Calculation of spell index and wall spell index and driving rain [D4.2 annexes].

For the various EN206-1 classified parts of the structure:

8. Characterisation of RH
9. Characterisation of moisture: Total time with moisture comes from: time with rain + condensation + high RH
10. Characterisation of temperature profiles on construction
11. Characterisation of chloride, either from sea-salt from Cole models/mapping authorities for land transported sea-salt, ref example from Germany, or from deicing salts-formula Cr = 1000(-9.56+0.52SF +0.38SL+0.14FD-0.20ID)/w (Average amount of de-icing salt for each application incident [g/m²]).
12. Characterisation of pollutants like $SO_2$, $O_3$, $H^+$ and $CO_2$. Contact national (and local) ICP Modelling and Mapping groups concerning already mapped information. Contact points for all European countries are given on web-page http://www.rivm.nl/cce/. Find available environmental data from national or local authorities.

***Network level - regional level***

On regional level the mapping and classification is related to the objects location. Necessary input is meteorological and other environmental information. These guidelines will await the proper characterisation on object level and choice of appropriate parameters for network level.

### *5.4.3 GIS-based quantification of environmental load parameters [Lifecon D4.3]*

All countries have extensive meteorological networks that can provide the necessary meteorological data on all levels, either as point measurements or as models on network level for the area in question. Meteorological data can be shown as maps showing the common meteorological parameters (i.e. average temperature and precipitation), or specifically derived parameters may be generated from the time series of the basic parameter.

The measuring, testing and evaluation of air quality are assuming growing importance in developed countries as elements of a comprehensive clean air policy and geared to sustainable development. A huge bulk of data is therefore generated on the various geographical levels.

In 1995 EEA (European Environment Agency) summarised the state of the air pollution-monitoring situation in Europe. The report provides detailed country-wise tables on networks, sites, compounds, reporting etc., summarised into country reports, and again summarised into summary tables covering all the 29 countries from which data were available.

The costs for climatic and pollution data varies between the different countries. In most cases it is quite expensive to get these data, especially if they have to be adjusted in some extent.

The guideline given in Lifecon D4.2 is possible to adopt, which have been shown by the Norwegian and the Swedish contributions. However, the work effort is quite large, which possibly will be a problem in the future.

The standard prEN 13013 (driving rain) is possible to use in most cases, but some difficulties arise when assessing other constructions than buildings.

# 6 MR&R Planning

## 6.1 RAMS Analysis Supported with QFD Method [Lifecon D5.1]

The purpose is to offer an assisting decision making tool, which takes into account LIFECON generic requirements, when considering best choices between different repair methods, systems and materials. The combination of RAMS-analysis (Reliability, Availability, Maintainability, Safety) and QFD (Quality Function Deployment) method consists in principle of 3 phases, as presented in *Figure 7*.

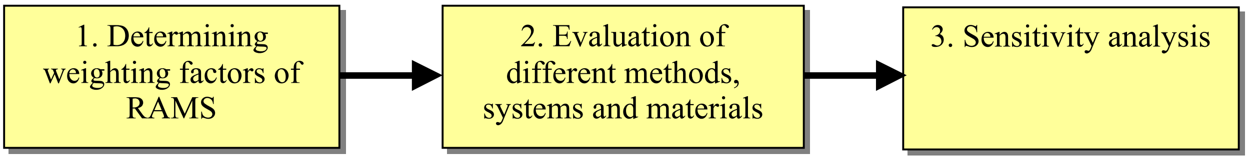


*Figure 7. The phases of combined RAMS and QFD mehods in the optimising MR&R planning.*

In maintenance and repair planning QFD is serving as a quantitative method and RAMS as a qualitative method. The merging of the two methods (phase 2) is presented in Figure 8.

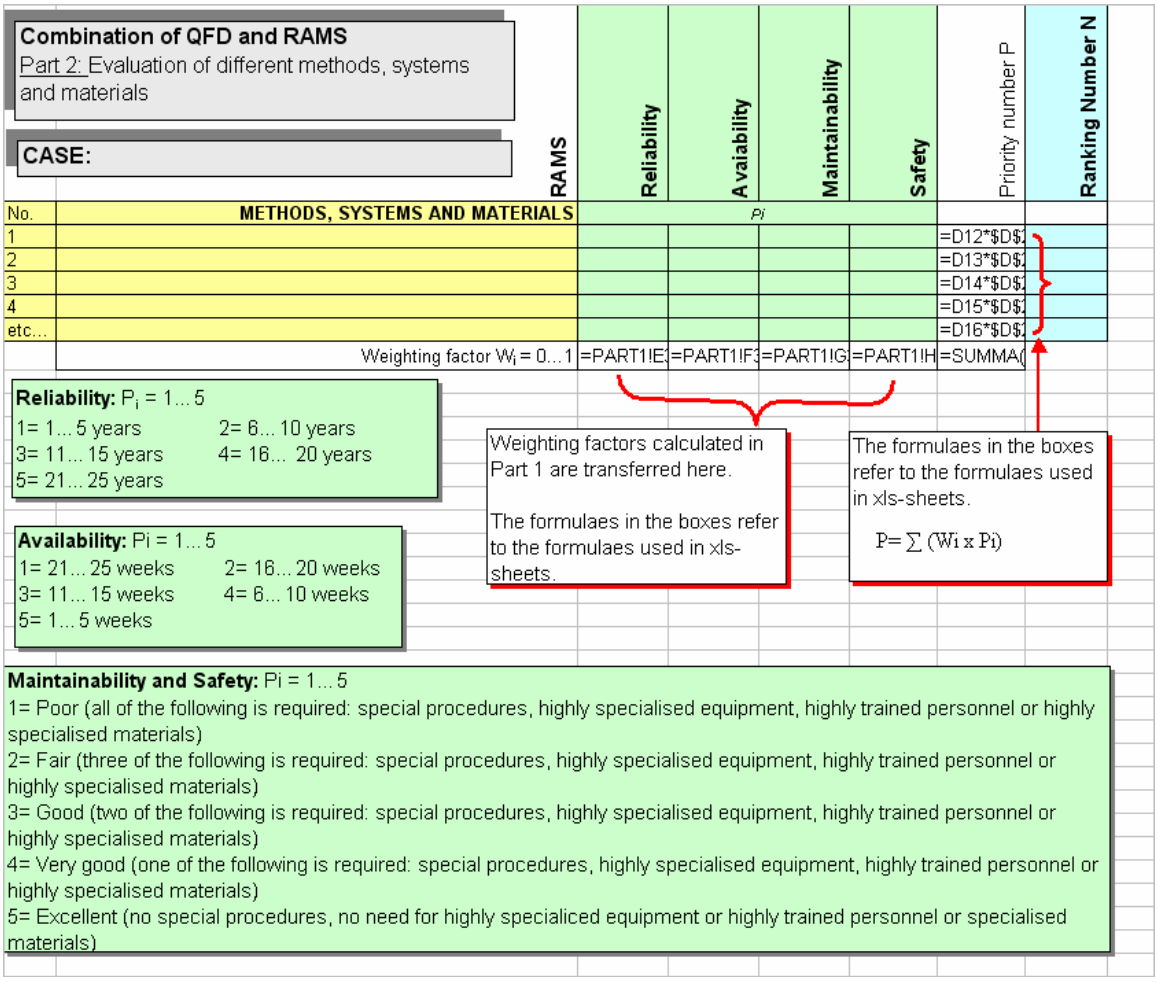


*Figure 8. Combination of QFD and RAMS, phase 2.*

QFD can be used for interpreting any requirements into specifications, which can be either performance properties or technical specifications. In this connection QFD serves as an optimising and selective linking tool between alternative repair methods and products and their performance properties (RAMS).

Fundamental objectives in the combination of QFD and RAMS are:

- Identification of the functional requirements of the owners, the users and the society (generic Lifecon requirements)
- Interpreting and aggregating generic Lifecon requirements first into Performance Properties (RAMS) and then into alternative repair methods and products of structures
- Optimising the alternative repair methods or products in relation to Performance Properties (RAMS)
- Selection from different design and repair alternatives

Full description of the merging of QFD and RAMS, as well as application of the combination to four different cases (bridge, wharf, building, tunnel) is presented in Lifecon deliverable D5.1.

### 6.2 Life Cycle Costing (LCC) of MR&R [Lifecon D5.2]

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. That is why it is recommendable to build a Cost Breakdown Structure (CBS) for the different MR&R methods, using commensurate subtitles and units to compare the costs of the different methods. An example of a Cost Breakdown Structure is presented in Figure 9.

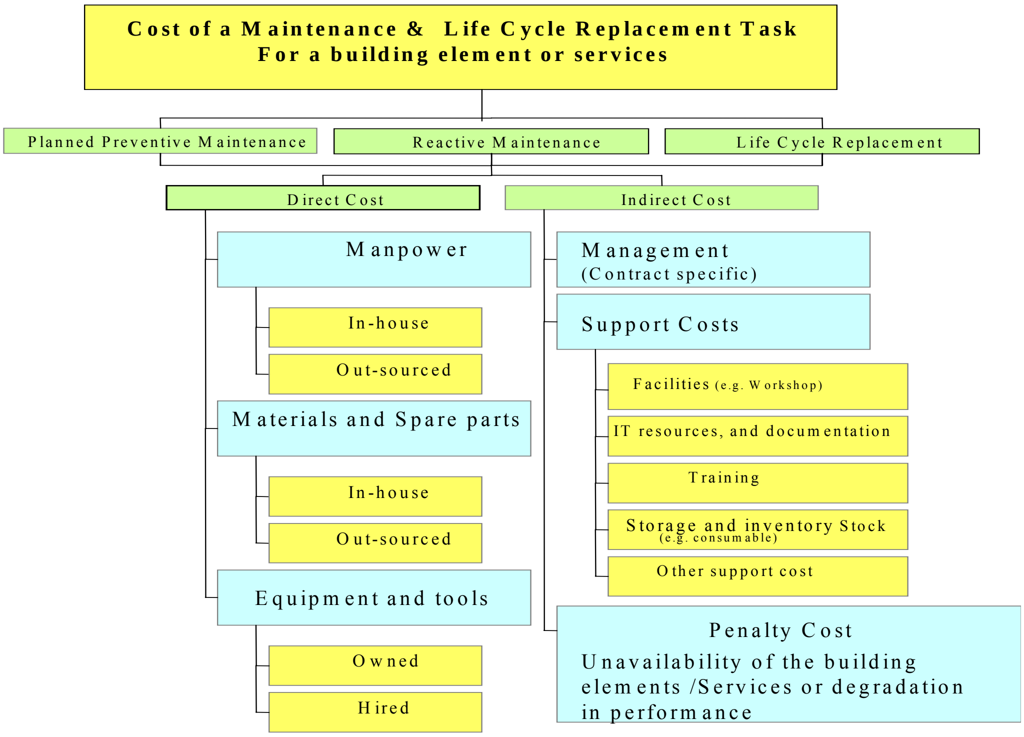


*Figure 9. Cost Breakdown Structure.*

Life cycle cost 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 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.

Lifecon D5.2 gives 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 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)

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.

### 6.3 Life Cycle Ecology (LCE) of MR&R [Lifecon D5.3]

The generic life cycle ecology (LCE) includes the following components [Lifecon D2.1].

- raw materials economy
- energy economy
- environmental burdens economy
- waste economy
- biodiversity

These components are weighted differently in different areas and places of the world, because the critical components are varying. Therefore we have to treat LCE on different levels:

- global level (e.g. the green house gas production and energy consumption)
- regional level (e.g. water consumption and biodiversity)

- local level (e.g. wastes, biodiversity, raw materials)

LCE should ideally include assessment of environmental impacts caused by all human activities throughout the whole life cycle of a structure. This is, however, a very difficult process since the relationship between the external environment and the category endpoint can be very complex. Normally, the Life Cycle Ecology (LCE), will stop at the step before category endpoint, showing only the impact categories, which is fairly easy to do, and then interpret the results from the various category indicators. The methodological framework for the assessment of environmental impacts from rehabilitation and maintenance of concrete structures is based on the ISO-standards 14040 - 14043.

From the condition survey of a concrete structure, the method of maintenance and type of maintenance are first selected. The selections depend on type and extent of damage and type of external environmental conditions as well as type of equipment and materials to be used for the repair.

The next step in the process is to determine the functional unit. The functional unit is the reference unit used in a life cycle study. All emission, energy and flow of materials occurring during the repair process are related to this unit. The functional unit shall be measurable and will depend on the goal and scope of the analysis. The goal of the Life Cycle Ecology (LCE) shall unambiguously state the intended application and indicate to whom the results will be communicated. Thus, the functional unit for a paint system may be defined as the unit surface ($m^2$) protected for a specified time period.

The maintenance/life cycle inventory (LCI) phase will consist of:

1. Quantifying the amount of all raw materials, chemicals and equipment, which are necessary to fulfil the maintenance function. This quantification gives the reference flow, for which all inputs and outputs are referred to and are closely connected to the functional unit.
2. Providing environmental data of consumed raw materials, chemicals and equipment from the suppliers (specific data) or from databases (generic data) or from a life cycle inventory (LCI) carried out at supplier level. All materials used are recommended to have an environmental declaration with scope “Cradle to port”. The environmental declaration shall include use of resources such as energy (renewable, non renewable), materials (renewable, non renewable), water and waste as well as emissions to air and water.
3. Quantifying and classifying the waste from the process as recycling, disposal or hazardous waste.

The framework for application of the LCE into MR&R projects is presented in Figure 10.

In order to demonstrate how the methodological framework for the assessment of environmental impacts can be applied to various types of repair and maintenance systems for concrete structures, two examples of commonly used systems have been selected for analysis. The one system is a patch repair with shotcreting, where the damage has been caused by a chlorideinduced corrosion of embedded steel. The other system is a preventive measure based on a hydrophobic surface treatment, which is commonly used as a general protection of the concrete surface both against moisture and chloride penetration. The examples are presented in Lifecon deliverable D5.3.

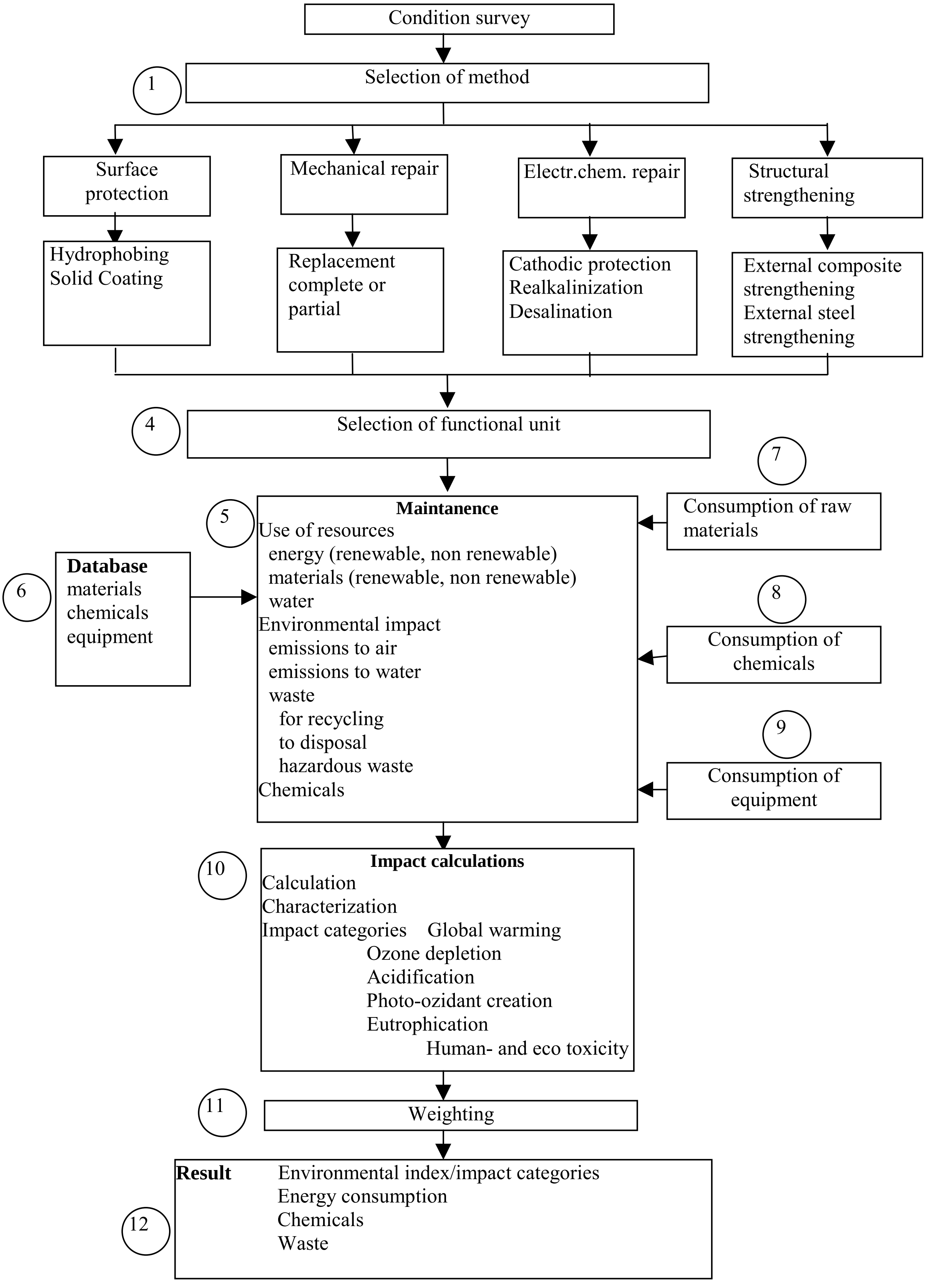


*Figure 10. Methodological framework for assessment of environmental impacts from rehabilitation and maintenance of concrete structures.*

# 7 IT- Prototype [Lifecon D1.2, D1.3]

A demonstrative prototype includes the main modules of generic user requirements, and some modules of the object structuring and MR&R algorithms. The prototype is aimed at demonstration of the Lifecon LMS, and as a core for development of more focused software tools.

The user documentation will give a brief overview on how to use the system. It will not go into detail on the Lifecon LMS methods or how to apply them in the Lifecon LMS IT system. *Figure 11* shows the workflow and dataflow for the IT prototype and the interactions between the main components.

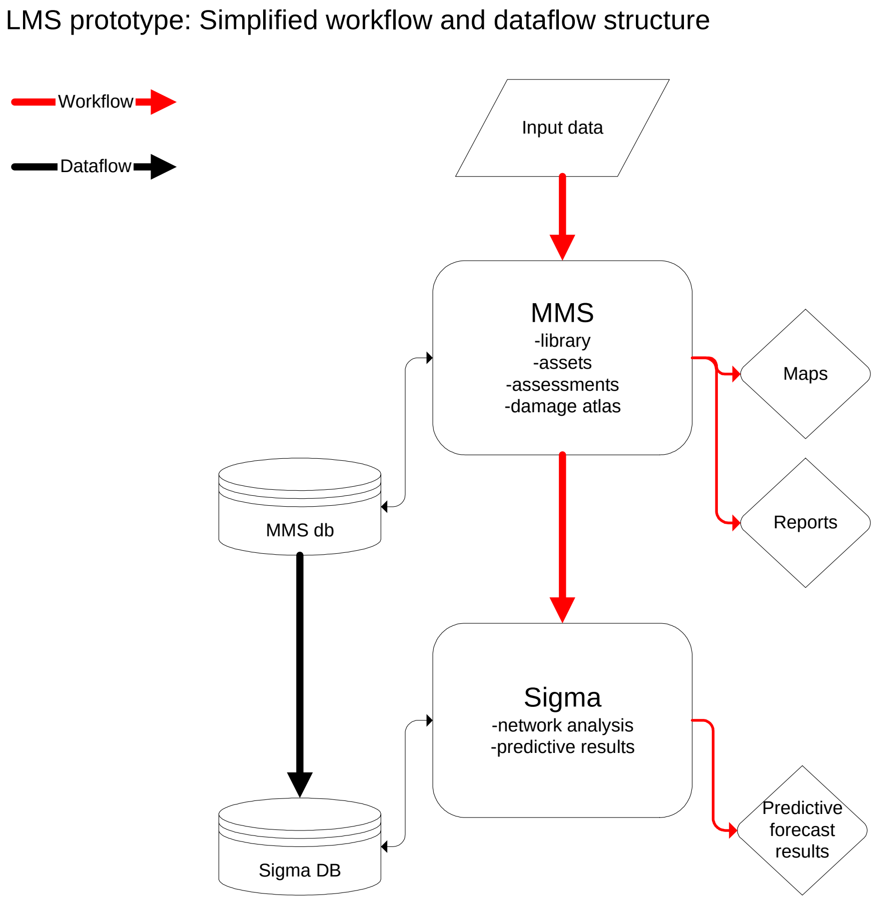


*Figure 11. Lifecon LMS: Simplified workflow and dataflow structure*

The Lifecon IT system consists of three modules:

1. The Norgit Cafe Application Platform This platform is based on standard, third party and Norgit developed Windows components and add ins with rich functionality. Included in Norgit Cafe is a Data Explorer, a License manager, a Lookup manager, a Photo manager, a Document manager, a Drawing manager, a Graph manager, a Report Generator, a 3D visualizer and a Data Access Class Layer. The Norgit Cafe is extensible with additional modules and functionality by providing a set of standard Windows "com" interfaces for this purpose. The Visual Basic, Visual C++ and the Java programming languages can be used for this purpose. The Norgit Cafe Application Platform with its add ins and

components are the building blocks for the Maintenance Management System (MMS). MMS Assets and Condition Assessment are built on top of the Norgit Cafe Data Explorer GUI addin. The Assets and Condition Assessment add ins are integrated with Norgit Cafe standard functionality: Photos, maps, documents and drawings. The Kompas system is based on the Norgit Cafe Component Data Access Class Layer.

2. Maintenance Management IT system prototype (MMS). Two modules/addins named Assets and Condition Assessment is made for the Maintenance Management System prototype. Condition Assessment contains Inspection Plans and Inspection Programs. Most of the content in Assets and Condition Assessment may have photos, maps, documents and drawings assigned.
3. The Material Upgrade/Degrade Kompas system model for Maintenance Analysis and Planning. This model requires Maintenance Groups and Degrade matrixes as input. The percent amount of upgrade/degrade from year to year for each maintenance group is user defined. The results are Life Cycle Condition profiles for each Maintenance group and also values and Life Cycle Costs for each Maintenance group is calculated.

# 8 European Validation and Case Studies [Lifecon D6.1]

The overall objective of the validation process was to assess, tune and validate guidelines and procedures produced within the LIFECON project on a European level. This has been accomplished by a theoretical scrutiny of the generic systematics, the Technical Handbook, and the practical application of proposed procedures on selected case structures. The case studies include validation of the methods for how to characterise and classify the environmental loading onto structures, availability of environmental data and evaluation of different standards.

While LIFECON systematics includes all the necessary modules, and the linkages between these component modules are identified, this does not fully describe the necessary flow of information. It is necessary that further attention be given to the sequence in which these links are organised, to the frequency of updating data within each module, to the transfer between hierarchical level and to the potential for solution instability in a full network level system. It is also evident that the object level system will benefit primarily from deployment of more efficient repair strategies, while the network level might benefit also from a better management of available financial, knowledge and material resources for optimal management of an entire network of assets.

According to the case studies almost all needed data were available and rather easy to receive. In some cases the data had to be transformed into other formats. However, according to the opinions of practitioners not all agree that the environmental data were easy to receive. It seems to be highly influenced by country of origin and skill/interest of the operator. From this the conclusion is that a system like LMS has to cope with different levels of detail. Another conclusion of the case studies is that the Markovian chain principle is fully possible to adapt to old constructions that have recorded condition assessment data. It is also possible to get a good overview at a network level.

It appears that all of the key results and novelties have not yet been fully implemented into the LMS process description. Nevertheless, beside results that have been directly implemented into the LMS process decsription, the project has generated a high amount of general knowledge that will be beneficial to practical applications of generic Lifecon LMS, to other projects and in other contexts on a European level.

The Lifecon LMS is developed with specific regard to concrete infrastructures, but the generic systematics is applicable to any constructed asset. The full accountability of the LMS prospects is mainly restricted by the input data on materials and products and environmental characteristics, and by the governing requirements set by a client. However, there are general development needs of LMS, connected both to the level of LMS as an entity and to the specific modules, that deserve further R&D attention in order to make full use of the systems potential. LMS is furthermore well suited to be developed and adapted to completely new application areas outside the area of concrete infrastructures.

# Appendix 1: Terms And Definitions

| TERM | DEFINITION |
|---|---|
| ***Life cycle and life time*** | |
| **Life cycle** | The consecutive and inter-linked stages of a facility or structure, from the extraction or exploitation of natural resources to the final disposal of all materials as irretrievable wastes or dissipated energy. |
| **Lifetime** | The time period from start of the use of a facility or structure until a defined point in time. |
| **Design period** | A specified period of the life time, which is used in calculations as a specific time period. |
| **Design life,** *or* **Design working life** (EN 1990-2002) | Assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary |
| ***Serviceability and service life*** | |
| **Serviceability** | Capacity of a structure to perform the service functions for which it is designed and used. |
| **Service life** (ENV1504-9:1996) | The period in which the intended performance is achieved. |
| • target life | Required service life imposed by general rules, the client or the owner of the structure or its parts. |
| • characteristic life | A time period, which the service life exceeds with a specified probability, usually with 95 % probability. |
| • design life (*or:* design working life) (EN 1990-2002) | Assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary. Design life is calculated dividing the characteristic life with lifetime safety factor. Calculated design life has to exceed the target life. |
| • reference service life | Service life forecast for a structure under strictly specified environmental loads and conditions for use as a basis for estimating service life. |
| **Residual service life** | Time between moment of consideration and the forecast end of service life. |
| **Service life design** | Preparation of the brief and design for the structure and its parts to achieve the desired design life e.g., in order to control the usability of structures and facilitate maintenance and refurbishment. |
| **Reference period** (EN 1990-2002) | Chosen period of time that is used as a basis for assessing statisticallly variable actions, and possibly for accidential actions. |
| ***Reliability and performance*** | |
| **Reliability** (EN 1990-2002) | Ability of a structure or structural member to fulfil the specified requirements, including the design working life, for which it has been designed. Reliability is usually expressed in probabilistic terms.<br>NOTE: Reliability covers safety, serviceability and durability of a structure. |
| **Reliability differentiation** (EN 1990-2002) | Measures intended for socio-economic optimisation of the resources to be used to build construction works, taking into account all the expected consequences of failures and the cost of the construction works. |

| TERM | DEFINITION |
|---|---|
| **Performance** | Measure to which the structure responses to a certain function. |
| **Performance requirement or performance criterion** | Qualitative and quantities levels of performance required for a critical property of structure. |
| **Life time quality** | The capability of the facility to fulfil all requirements of the owner, user and society over the specified design life (target life). |
| **Failure** | Loss of the ability of a structure or its parts to perform a specified function. |
| • durability failure | Exceeding the maximum degradation or falling below the minimum performance parameter. |
| **Failure probability** | The statistical probability of failure occurring. |
| **Risk** | Multiplication of the probability of an event; e. g. failure or damage, with its conseguences (e. g. cost, exposure to personal or environmental hazard, fatalities). |
| **Obsolescence** | Loss of ability of an item to perform satisfactorily due to changes in human (functionality, safety, health, convenience), economic, cultural or ecological requirements. |
| **Limit state** (EN 1990-2002) | States beyond which the structure no longer fulfils the relevant design criteria. |
| • serviceability limit state | State which corresponds to conditions beyond specified service requirement(s) for a structure or structural member are no longer met. |
| • irreversible serviceability limit states | Serviceability limit states where some consequences of actions exceeding the specified service requirements will remain when the actions are removed |
| • reversible serviceability limit states | Serviceability limit states where no consequences of actions exceeding the specified service requirements will remain when the actions are removed |
| • ultimate limit state | State associated with collapse or with other similar forms of structural failure. |
| **Serviceability criterion** (EN 1990-2002) | Design criterion for a serviceability limit state. |
| **Lifetime safety factor** | Coefficient by which the characteristic life is divided to obtain the design life. |
| **Factor method** | Modification of reference service life by factors to take into account of the specific in use conditions. |
| **Attribute** | A property of an object or its part, which will be used in optimisation and selective decision making between alternatives. |
| • multiple attributes | A set of attributes, which will be used in optimisation and selective decision making between alternatives. |
| ***Durability*** | |
| **Durability** | The capability of a structure to maintain minimum performance under the influence of actual environmental degradation loads. |
| **Durability limit state** | Minimum acceptable state of performance or maximum acceptable state of degradation. |

| TERM | DEFINITION |
|---|---|
| **Durability model** | Mathematical model for calculating degradation, performance or service life of a structure. |
| **Performance model** | Mathematical model for showing performance with time. |
| **Condition** | Level of critical properties of structure or its parts, determining its ability to perform. |
| **Condition model** | Mathematical model for placing an object, module, component or subcomponent on a specific condition class. |
| **Deterioration** | The process of becoming impaired in quality or value. |
| **Degradation** | Gradual decrease in performance of a material or structure. |
| **Environ-mental load** | Impact of environment onto structure, including weathering (temperature, temperature changes, moisture, moisture changes, solar effects etc.), chemical and biological factors. |
| **Degradation load** | Any of the groups of environmental loads, and mechanical loads. |
| **Degradation mechanism** | The sequence of chemical, physical or mechanical changes that lead to detrimental changes in one or more properties of building materials or structures when exposed to degradation loads. |
| **Degradation model** | Mathematical model showing degradation with time. |
| ***Management and maintenance*** | |
| **Maintenance** (EN 1990-2002) | Set of activities performed during the working life of the structure in order to enable it to fulfil the requirements for reliability<br>NOTE: Activities to restore the structure after an accidental or seismic event are normally outside the scope of maintenance. |
| **Repair** (EN 1990-2002) | Activities performed to preserve or restore the function of a structure that fall outside the definition of maintenance. |
| **Restoration** | Actions to bring a structure to its original appearance or state. |
| **Rehabilitation** | Modification and improvements to an existing structure to bring it up to an acceptable condition. |
| **Renewal** | Demolition and rebuilding of an existing object. |
| **M&R** | Maintenance, repair, restoration, refurbishment and renewal, or some of them. |
| **Project** | Planning and execution of repair, restoration, rehabilitation or dismantling of a facility or some parts of it. |
| **Life cycle cost** | Total cost of an asset throughout its life, including the costs of planning, design, acquisition, operations, maintenance and disposal, less any residual value. |
| **Environmental Burden** | Any change to the environment which permanently or temporarily, results in loss of natural resources or deterioration in the air, water or soil, or loss of biodiversity. |
| **Environmental Impact** | The consequences for human health, for the well-being of flora and fauna or for the future availability of natural resources. Attributable to the input and output streams of a system. |
| **Integrated lifetime design of materials and structures** | Producing descriptions for structures and their materials, fulfilling the specified requirements of human requirements (functionality, safety, health, convenience), monetary economy, ecology (economy of the nature),and culture , all over the life cycle of the structures. Integrated structural design is the synthesis of mechanical design, durability design, physical design and environmental design. |

| TERM | DEFINITION |
|---|---|
| **Environmental structural design** | The part of the integrated structural design that considers environmental aspects during the design process. |
| **Integrated lifetime management** | Planning and control procedures in order to optimise the human, economic, ecological and cultural conditions over the life cycle of a facility. |
| | ***Actions onto structures*** |
| **Representative value of an action ($F_{rep}$)** (EN 1990-2002) | Value used for the verification of a limit state. A representative value may be the characteristic value $F_k$ or an accompanying value $\psi F_k$. |
| **Design value of an action *($F_d$)*** (EN 1990-2002) | Value obtained by multiplying the representative value by the partial safety factor $\gamma_f$. |
| | ***Material and product properties*** |
| **Characteristic value ($X_k$ or Rk)** (EN 1990-2002) | Value of a material or product property having a prescribed probability of not being attained in a hypothetical unlimited test series. This value generally corresponds to a specific fractile of the assumed statistical distribution of the particular property of the material or product. A nominal value is used as the characteristic value in some circumstances. |
| **Design value of a material or product property ($X_k$ or $R_k$)** (EN 1990-2002) | Value obtained by dividing characteristic value by a partial factor $\gamma_m$ or γx, or, in special circumstances, by direct determination. |
| **Nominal value of a material or product property ($X_k$ or $R_k$)** (EN 1990-2002) | Value normally used as a characteristic value and established from an appropriate document such as a European Standard or Prestandard. |
| | ***Hierarchical system*** |
| **System** | An integrated entity which functions in a defined way and whose components have defined relationships and rules between them. |
| **Hierarchical system** | A system consisting of some value scale, value system or hierarchy. |
| **Modulated system** | A system whose parts (modules) are autonomous in terms of performance and internal structure. |
| **Structural system** | A system of structural components which fulfil a specified function. |
| **Network** | Stock of objects (facilities), (e. g. bridges, tunnels, power plants, power plants, buildings) under management and maintenance of an owner. |
| **Object** | A basic unit of the Network serving a specific function. |
| **Module** *or* **assembly** | A part of an object, or a set of components which is designed and manufactured to serve a specific function or functions as apart of the system, and whose functional and performance and geometric relations to the structural system are specified. |

| TERM | DEFINITION |
|---|---|
| **Structural component** | A basic unit of the structural system, which is designed and manufactured to serve a specific function or functions a s part of a module, and whose functional and performance and geometric relations to the structural system are specified. |
| **Subcomponent** | Manufactured product forming a part of a component. |
| **Detail** | A specific small size part of a component or of a joint between components. |
| **Material** | Substance that can be used form products. |
| ***Stakeholders*** | |
| **Stakeholders** | Owners, users, designers, contractors, industry sectors. public interest organizations, regional interests. and/or goveminent agencies connected to the structure during the life cycle. |
| **Owner** | Person or organisation for which structure is constructed and/or the person or organisation that has the responsibility for maintenance and upkeep of structural, mechanical and electrical systems of the building. |
| **Designer** | Person or organisation that prepares a design or arranges for any person under his control to prepare the design. |
| **Contractor** | Person or organisation that undertakes to, or does, carry out or manage construction work. The contractor bids a contract for a new building with information from **manufacturers**/suppliers. The contractor's representative on the building site is the **site supervisor.** |
| **Manager** | At take over the building is administrated by a **property manager** who engages **maintainers** to be responsible for proper maintenance inspections or to carry out the necessary maintenance. |
| **Supplier** | Person or organisation that supplies structures, parts of structures or services for construction or maintenance of structures. |
| **Inspector** | Suitably qualified and experienced person who carries out inspections on structures or their components in compliance with relevant procedures. |
| **Assessor** | Suitably qualified and experienced person who uses results of inspections to assess the condition of a structure or its components i.e. its ability to perform its service requirements, to predict the residual service life of a structure or its components, to measure or deduce other relevant parameters relating to the service of a structure or its components, and to define the appropriate maintenance, refurbishment or repair regime for a structure or its components. |
| **User** | Person, organisation or animal which occupies a facility. |
| **Dismantler** | Any person who carries out dismantling work. |
| ***Methods*** | |
| **Allocation** | The division of specified recourses (financial and physical) into objects, projects and other actions on the Network level. |
| **Briefing** | Statement of the requirements of a facility. |
| **Service life planning** | Preparation of the brief and design for a facility and its parts in order to optimise the required properties of the facility for owner and facilitate maintenance and refurbishment. |
| **Condition assessment** | Methodology and methods for quantitative measurements and visual inspection of the properties of an object and its parts, and conclusions drawn from the results regarding to the condition of the object. |

| TERM | DEFINITION |
|---|---|
| **Optimisation** | Selection between alternative properties of an object or its parts, or of an action in order to reach best solution or result. |
| • Short term optimisation | Optimisation in a short time period (usually one or couple of years). |
| • Long term optimisation | Optimisation in a long term period (usually several years or even dozens of years). |
| **Decision-making** | Methodology for rational choices between alternatives, basing on defined requirements and criteria. |