LIFECON DELIVERABLE D 6.1

Validation of LIFECON LMS and recommendations for further development

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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 management system, concrete structures

Abstract

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 in the Technical Handbook, D1.1, 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 a network.

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 been fully implemented into the LMS. Nevertheless, beside results that have been directly implemented into the LMS, the project has generated a high amount of general knowledge that will be beneficial 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.

List of terms, definitions and symbols

MMS	Maintenance Management System is an IT-tool developed in two earlier EU-projects, WoodAssess and MMWood. This generic tool provides a database structure where all data can be stored and handled.
IFC	Industry Foundation Classes are data elements that represent parts of buildings, or elements of the process, and contain the relevant information about those parts.

List of Contents

1 Introduction

1.1 Objectives of the LIFECON Project

The general objective of the LIFECON project is to contribute to the development of facility management towards a system, which is able to guarantee a sustainable and serviceable operation of concrete infrastructures, meeting the generic requirements of sustainability: human requirements (usability, safety, health, comfort), lifetime economy, lifetime cultural acceptance and lifetime ecology. This is possible by changing the traditional reactive management approach into a open, predictive, integrated and life cycle based approach.

To meet this objective, methodologies and methods of optimisation and decision making are integrated with life cycle based stochastic or deterministic generalised limit state analysis and risk analyses at different levels of the structural hierarchy. This takes into account the integrated optimisation and control of mechanical (static, dynamic and fatigue) performance, degradation, usability and obsolescence in relation to the generic requirements of sustainability. The existing knowledge on materials, structures and environmental loads is gathered together. An essential part of the system methodology consists of statistically based models of degradation and service life. A detailed classification of environmental loads on regional, local and object level, sometimes even on component or surface level is needed. The degradation models are also aimed to be connected to an advanced condition assessment protocol so that they can be repeatedly updated by new condition assessment data.

1.2 Novelties and structure of LIFECON LMS

The novelty of Lifecon LMS encompass a delivery of an open and generic European model of an integrated and predictive Life cycle Maintenance and management planning System (LMS). This will facilitate the change of the facility maintenance and management from a reactive approach into a predictive approach. The novelties of this system are:

- Integration; which means that all requirement classes (human requirements: usability, safety, health and comfort, economy, ecology and cultural acceptance) are included in the MR&R (Maintenance, Repair and Rehabilitation) planning, design and execution processes. Modular product systematics, methods of system technology, reliability theory and mathematical modelling have been applied.
- Predictivity, which means that the functional and performance quality of the facilities is predicted for a planning and design period of the facility with integrated performance analysis, including:

– predictive analysis and control of usability and obsolescence
– predictive performance and service life modelling
– residual service life prediction of structures
– quantitative classification of degradation loads.

- Openness, which means

– freedom to apply the generic LMS into specific applications, using selected modules of the LMS for each application, and freedom to select between methods given in Lifecon reports or outside these. The openness is valid for both the LMS description and the IT application.

Lifecon system consists of the following modules, which altogether are building the system:

- System and process description in a generic handbook [D1.1]
- Demonstrative IT prototype [D1.2, D1.3]
- Reliability Based Systematics [D2.1]
- Methods for Optimisation and Decision Making [D2.3]
- Condition Assessment Protocol model [D3.1]
- Degradation Models and methodology for Service Life Prediction [D3.2, D2.1 and D2.2, D4.1, D4.2, D4.3]
- MR&R (Maintenance, Repair, Rehabilitation) planning methodology [D5.1, D5.2, D5.3]
- European Validation and Case Studies [D6.1]

These modules interact in the Lifecon LMS system and process. In this open system the modules can be applied to varying degree and combinations for different cases of application. This flexibility is the most important power of a generic and open system.

1.3 Objectives of the validation process

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. In practise this means to:

- confirm that the LIFECON LMS is well grounded and the procedures contained within it are defensible.
- verify that the LIFECON LMS complies with relevant EU Directives, norms, standards etc.
- verify that the LIFECON LMS Instruction Manual is consistent with operation of IT tool.
- assess whether the prototype LIFECON LMS meets the aims stated in the original project proposal.
- assess the ease of use of the LMS

The validation report is divided into five parts (chapters):

– Validation of systematics in the LMS. This means mainly a control of the Technical Handbook and how the results from the different work packages has been incorporated in the Technical Handbook.
– Real structures were used as case studies in order to validate procedures in practise.
– The opinion of practitioners were obtained via questionnaires covering effort, usability and understanding of the LMS.
– Key results and novelty findings from the individual work packages. This includes results that contributes to the European knowledge base, but not necessarily has been used in the LMS.
– Future work in order to get a full working prototype and possible further developments of the LMS.

2 Validation of LIFECON Systematics

2.1 LIFECON procedures

This section of the validation report describes outcomes of reviews and check procedures undertaken to verify consistency of the various inter-related generic LIFECON LMS procedures between originators of the various components of the system. This review has been undertaken through a) a systematic tracking of data flow through the LIFECON LMS conducted by WP6 by eliciting specifications for input and output data types and hierarchical level from module originators in respect of their own modules b) a review of data flow as described in the draft 4 and the 'final' version of the Generic Handbook Deliverable D1.1, and subsequent communications with WP co-ordinators.

Validation had been planned to use the IT prototype, but this had not been developed to an adequate level at the time the validation was undertaken. It has also not proved possible to validate the claim in the project proposal that LIFECON would produce a 40% saving in repair and maintenance costs.

2.1.1 Maintenance and repairs - general

Maintenance and repair activities on concrete structures may be classified in two types, namely routine or operational maintenance, and major maintenance or repairs. The former type of activity is carried out on an almost continuous basis, generally by operatives who are not professionally qualified, and comprises activities such as ensuring that surface drainage and guttering is functioning correctly, and effecting repairs on an almost daily schedule. Such repair and maintenance activities act on ancillary rather than structural components. LIFECON is, on the other hand, concerned with structural components with intervals between maintenance/ repair actions measured in years if not in decades, and will be the responsibility of professionally qualified personnel.

The fact that the LIFECON does not treat routine maintenance must not be allowed to hide the importance of this activity, which remains essential for a structure to be able to fulfill its intended service life with any degree of economy. Indeed there is no prospect of LIFECON delivering any improvements in lifetime economy without effective routine maintenance, and this should be stressed throughout the deliverables.

It is desirable that MR&R actions for structures should be according to the principles of repair described in ENV 1504-9 for consistency with the developing Standard.

2.1.2 Differences in hierarchical level

As part of the validation process WP6 requested all module originators provide a specifications for input and output data types and their corresponding hierarchical level within the object system description. Differences in opinion were evident from the responses received. The Generic Handbook Deliverable D1.1 addresses these differences simply by stating that an averaging process will be used to transfer data from a lower hierarchical level to a higher. While the validation group have no reason to believe that this process will not function adequately, it felt it would be useful that this be checked before implementation.

2.1.3 Environmental loads and representation of degradation

The Generic Handbook Deliverable D1.1 makes little direct reference to environmental modelling as described in the deliverables from WP4; the influence of environment appears to be assimilated into degradation matrix coefficients along with models for degradation processes. WP6 has undertaken analysis of degradation observations from 2 sets of bridge structures, objects within each set being broadly similar in form and being subjected to the same regional climates. Observations from the structures were back-analysed in order to derive degradation matrix coefficients, following the process outlined in D1.1, ch. 4. The analysis shows a considerable scatter in the value of coefficients. The cause of the variations cannot be ascertained, although it appears to be larger than could be accounted for through variations in concrete material properties. This suggests that the cause of the variations may lie in environmental influences.

Derivation of coefficients in Markovian matrices through back-calibration in this way is a somewhat empirical process, and hence it becomes difficult to separate effects of environmental loads and materials resistances, and of the various parameters influencing each aspect.

LIFECON deliverables describe two approaches to degradation modelling, namely physico-chemical Service Life models as described in Deliverable 3.2 and Markovian chain processes as described in Deliverable 1.1. The deliverable makes clear that these two approaches may be used in tandem and complement each other. It is evident that the Markovian approach has major benefits when dealing with a population of objects, as it readily deals with measures of differing types, and can draw on performance data from other objects in the population. It also provides a basis for representing repair actions through action effect matrices. The physico-chemical models currently available are largely confined to the initiation phase of corrosion degradation. A Markovian approach based on back calibration of observations may thus be the only practical approach during the propagation phase of corrosion. Depending on the nature of the service life models considered, (deterministic or probabilistic) extensive sampling and testing, may be required, with significant cost implications. Practitioner views (see chapter 4) suggest such extensive sampling is generally unfeasible. Nonethless, there may well be some particularly sensitive or safety critical structures where detailed service life modelling using physico-chemical models might be more beneficial.

2.1.4 Combined actions of different degradation mechanisms

Section 4.4/3.4 ‘Condition rating system’ of the Generic Handbook D1.1 presents condition classifications for a range of degradation mechanisms. The classifications are presented as a proportion of the condition to the relevant limit state. WP6 understands that each degradation mechanism is treated independently in LIFECON. This would seem to create potential problems in some areas. Firstly, the degradation mechanisms are not independent. Taking first the example of chloride penetration, the limit state is set at the chloride concentration for initiation of corrosion at the depth of the reinforcement. The value set for the limit state might thus be 0.4% chlorides by weight of cement at cover depth. However, if the carbonation front has reached the reinforcement, the chloride concentration for initiation of corrosion is markedly reduced, and the two mechanisms in fact interact rather strongly. D1.1 also illustrates integration of active and passive phases of corrosion degradation, Section 5.3.3/4.3. It should be appreciated that matrix coefficients for the active corrosion phase of degradation may be markedly different depending on the mechanism of depassivation. It is suggested that this be made clear.

Limit states for initiation of corrosion are set according to the chloride concentration at the depth of the reinforcement or penetration of the carbonation front of concrete in relation to cover depth. This means that matrix coefficients will be cover dependent. Thus in order to exploit generic data for network predictions some conversion of coefficients will be required for individual structures if the ‘as built’ cover differs, even for otherwise identical structures and environmental exposures. It is suggested that some safeguards to avoid errors by those with imperfect understanding of the foundations of the system will be necessary.

Improved integration of some aspects of the system would seem to be desirable; for example, it is unclear why separate decision trees are used for surface repair and for structural repair.

2.1.5 Updating of degradation models

WP6 agree fully with the statement [3.5.4] that updating of degradation models is not a routine job, and must be undertaken by a suitably competent and qualified person. We would wish in particular to draw attention to the difficulty in updating predictions for a subsequent phase of the degradation process from observations during an earlier phase. This is particularly so for corrosion where initiation and propagation phases are controlled by different phenomena.

2.1.6 Development of LCAP

There appears to be disagreement between WP5, the originators of the RAMS system for appraisal of repair options, and WP1, responsible for the generic system, on the feasibility of introducing RAMS at the time the system is set up for an object. WP5 envisages RAMS should be applied at the time of detailed repair planning, i.e. it is not viable to predict a repair technique that might be deployed several decades in the future. From the datapath figure drawn up within WP1, RAMS is deployed to generate the decision tree, an activity which has to be undertaken when the LCAP is first set up (or at least when the object is first brought into the LMS).

In the opinion of WP5 it is not particularly useful, or even viable, to decide many years in advance on the best way to repair something. By the time one gets around to repairing, the "predicted" technique may no longer be viable, or available, or even allowed. Examples of the last from the past abound - cf. aluminate cement, lead based paints, restrictions on use of epoxy and polyurethane, acryl amide injection materials, to mention a few. So, how does LIFECON respond when an action point is reached on the decision tree but the intended action is no longer available.

It would be easier to predictively allow for the cost of repairing something in the future, since the cost of repairing concrete per unit area or volume is unlikely to change dramatically. For example, steel sheathing of pillars for seismic strengthening costs roughly the same as Kevlar or carbon fibre wraps. A more difficult thing to predict is cost escalations due to increasing stringency of regulations. Present examples are the classification of concrete painted with lead paint or rendered with PAB containing materials as dangerous waste requiring special treatment. This was no problem 20 years ago. Noise, dust, pollution, use of chemicals, EMI, worker hygiene, radon dissemination, etc. are all going to be the subject of tougher and tougher regulations. We may even soon see heavy "environmental" taxes on some common building materials - with perhaps a cement tax being the first serious one. These cost uncertainties are likely to heavily outweigh other inaccuracies in cost prediction.

Other aspects of the decision making process on repair actions also appear to be taken at the point of setup of the object within the LMS when the decision tree is produced, and these will also be subject to change over the service life of a structure.

Clearly LIFECON has to start with some initial information on attributes of repair techniques for it to have the predictive capability required, and hence some attempt at RAMS etc. is required when the object is first entered to the system. Although updating of degradation models, costs and decision trees is mentioned in D1.1, but the need for updating of RAMS does seem to present particular difficulties, in that each structure must be treated individually. But this raises a question of the maintenance needs of the system - how often will it be necessary to revisit the decision tree and re-evaluate the many factors which contribute to its set-up, particularly if this cannot be done automatically? A continual revision of decision trees would require significant resources, particularly in relation to RAMS where each structure must be treated individually, and raises potential ‘instability’ issues in operation of the LMS.

It is conceivable that changes in RAMS scores or other aspects of the data on which LCAPs are derived could invalidate the original decision tree. If frequent updating is not carried out, this could mean that when the structure reached the condition originally set to trigger a specific maintenance action that it had passed the point for deployment of that action on the updated LCAP. Would repairs to the object simply slip to a later intervention point with a different repair technique, in which case any repair action is deferred? A consequence of so doing would be to release money back into the annual budget for use elsewhere. But a process of continually updating LCAPs and revising the budget could then bring other projects into the frame for repair during the next period, and if their decision trees also change when a detailed re-appraisal is carried out the potential for an unstable analytical (network) procedure is generated with objects entering and being removed from the workplan. It would seem necessary that a safeguard be introduced to the system to ensure such instability problems do not arise.

Hence, the LMS must maintain a clear distiction between the automatic decision tree runs and the manual design which is performed in the final phase in the object level process.

In summary of this section, it is our view that while LIFECON includes all the necessary modules, and that the linkages between these component modules are identified, and that the need for updating is stated, that the system does not fully describe the necessary flow of information. It is necessary, we believe, that further attention be given to the sequence in which these links are organised, the frequency of updating data within each module, and the potential for solution instability in a full network level system.

2.1.7 Summary

In summary of this section, it is our view that while LIFECON includes all the necessary modules, and that the linkages between these component modules are identified, that this does not fully describe the necessary flow of information. It is necessary, we believe, that further attention be given to the sequence in which these links are organised, the frequency of updating data within each module, the transfer between hierarchical level and the potential for solution instability in a full network level system. While none of these are seen as critical defects it is desirable that they be addressed before further development of the IT prototype is undertaken.

It is noted that the contents of the component modules are at varying stages of refinement. It is worth pointing out that the project was not intended to produce a definitive system and that the system that has been produced is designed to permit upgrading of component parts of the system such as models for various degradation processes, evaluation techniques etc., as these will be the subject of continuing development.

2.2 Gains from LIFECON

The project proposal envisaged significant savings in repair costs through deployment of a LIFECON LMS. These savings could arise from two inter-related but distinct areas of benefit, namely a) better management of a network and b) from deployment of more efficient repair strategies. It is evident that the object level system will benefit primarily from the second source, while the network level might benefit from both. It has not, within the timescale of the project, been possible to either quantify the savings that may result from LIFECON or even to estimate the relative magnitude of savings from each source. Some knowledge of the potential savings from each would evidently be of value in identification of the likely market for a product. While we do not consider ourselves fully competent to judge, it seems that a system might well be of greatest value to the owner/operator of a medium sized network, for individual objects the approximations inherent in the Markovian approach may not fully exploit benefits from deployment of more efficient repair strategies. Owners of large networks will have to live with a substantial maintenance budget and the selection of specific structures for repair actions might be carried out on a short time horizon. Owners of a medium sized network are the ones with the more difficult task of controlling a repair budget where maintenance expenditure may be subjected to peaks and troughs. Some appreciation of such factors would again be of value in identification of the likely market.

2.3 Exploitation of benefits from LIFECON LMS

LIFECON seeks to demonstrate improvements in the overall condition of the asset stock through tracking the average condition of the system. It has not yet been possible to trial the system in order to identify the most cost effective strategy to achieve this. Even once the system is set up, a considerable amount of 'what if' studies will be necessary to identify the best strategy for funding and prioritisation of repairs. For example, should priority go to repair of structures in the worst condition, to maintaining those structures in good condition while allowing those in poorer condition to deteriorate until replacement, or to same grading of the 'importance' of individual structures, as described in D3.1? It is not clear whether LIFECON has developed a clear strategy in this respect, or whether development of a strategy is to follow implementation of an IT tool to assist in performance of the necessary calculations and evaluations.

3 Case studies

As part of the validation procedure for the LIFECON Life cycle Management System (LMS) a number of structures were selected to be used as case studies in the validation process. These case studies were to be selected to provide a range of common reinforced structural types and cover the range of conditions to which and in which a structure would typically be found in the duration of its lifetime. The structures to be considered were limited to bridges, buildings, wharves and tunnels.

3.1 Selected Structures for case studies

To fulfil the required criteria all partners were asked to provide nominated structures that could be used in case studies. In order to better quantify the structural types, exposure conditions and structural condition each partner was required to complete a condition matrix for each structure nominated. In addition the partners were asked to indicate the range of information that would be available and the reliability of the information actually being available as and when required. Of total 21 nominated structures 9 were selected to be apropriate structures for case studies. The selected structures represent north and central Europe and are located in five countries, Sweden, Norway, Finland, Germany and UK. The nine case study structures selected fulfil the majority of the criteria set out in the initial conditions for the selection of the case studies. This is illustrated in table 1.

Table 1. Selected Structures for case studies

Structure Type	Age Years	Degradation Mechanism	Condition	Location	Environment	Exposure Condition	Socio/ Ecological Impact	Range of Data	Availability of Data
Wharf OS	0-20 OS, OJ	Chloride OS, HH, HS, CW, BB, OJ, FS	No visible corrosion HH	Northern European OS, HS, CC, CW, BB, OJ, FS, PS	Maritime OS, CW, HS	Severe OS, CW, PS, HS, FS, OJ, BB	Low HH	Visual	* CW
Building CC, CW	20-45 HH, FS, CW, CC, PS	Carbonation OJ, CC	Rust staining OJ, FS	Central European HH	Urban CC, FS, PS	Moderate HH	Moderate BB, OJ, CC	Routine CC, CW, PS	** CC, OJ, PS
Bridge HH, BB, OJ, FS	45+ BB, HS	Freeze/thaw OJ	Fine Cracking OJ	Southern European	Non-Urban HH, OJ, BB	Light CC	Severe CW, FS, PS, OS, HS	Comprehensive OS, HH, BB, OJ, FS, HS	*** OS, HH, BB, FS, HS
Tunnel PS		ASR	Cracking CW, FS						
Lighthouse HS			Delamination Spalling OS, CW, BB,CC						
			Repair BB, CC						
			New Build						
			Subsidence PS						

Ormsund (OS) Congress Centre (CC) Backbron (BB) Faeltskaersleden (FS)

Hofham (HH) CW Structure (CW) Ojoinen (OJ) Parliament Station (PS)

Hamborsund(HS)

3.2 Validations conducted through case studies

During the LIFECON project different case studies have been applied on different selected structures to ensure that procedures within the LMS achieve its aim and objectives. One case study includes a Markovian chain approach, a probabalistic method of assessing the residual service life. Some other case studies have been carried out to validate the methods for how to characterise and classify the environmental loading onto structures. It includes validation of the availability of environmental data as well as validation and evaluation of different standards that are intended for the classification and characterisation of the environment. Finally one case study concern validation of the IT-tool, and the efforts that are needed to meet different user-needs, system requirements and standard.

The case study structures have been used in two ways. Firstly, they were used to enable owners/operators to trial collection and IT input of information and data on test structures. Secondly, they have been used to investigate and validate the feasibility of the proposed LIFECON procedures using real data. In addition, the various decision aids for ranking of alternatives have been trialed by WP1 and results are reported in deliverable D2.3.

It should be noted that the case studies were carried out wth early (i.e. not final) versions of deliverables from WPs 3-5. The outcomes from the case studies was given to originating WPs as feedback, and final versions of deliverables have in most cases been adjusted to address issues identified through the case studies.

3.3 Markovian chain approach

The possibilities of the Markovian chain approach are theoretically discussed in the Generic Technical Handbook (chapter 5). The main practical problem is to determine the degradation matrices so that they conform to the observed degradation and to imitate the action effects of various MR&R actions so that they conform to the real observed effects.

In addition to the approaches presented in the Generic Technical Handbook, the validation team has applied the Markovian chain principle on a set of 12 bridges. This application can be seen as an additional network case study. The bridges were selected from a database governed by the Swedish Road Administration. The bridges are of the same type and built during approximately the same time period but located in two typically different location types, near coastal and inland respectively. The reason for this sub-grouping is that the environmental loading and degradation increase is expected to be quite different. Furthermore, each bridge have been repeatedly inspected and documented since it was build.

The edgebeam inspection data were assessed and put into a Markovian chain spread sheet. The spreadsheet contained a general degradation matrice and two different action matrices. By altering the degradation matrice coefficients, individually for each bridge, and using an appropriate action matrice, when the recordings says there have been a repair action, the possibility to adjust Markov chains to inspection data were tested. The result shows that it is possible to get a fair conformity between the predicted degradation rating and the inspection data. There is also a clear distinction between the coastal and inland sub-groups, probably caused by different environmental loading on a regional level. However, within each sub-group there are individual structures that show a somewhat deviating behaviour.

A conclusion of this validation approach 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. On the other hand, each object must be treated individual due to local differences in maintenance, environmental loading etc.

3.4 Classification and characterisation of environmental loading

All management systems that include a prediction module, such as LIFECON LMS, need reliable environmental load data. The relevant systematic and requirements for quantitative classification of environmental loading onto structures, as well as sources of environmental exposure data are given in LIFECON deliverable D4.2. The deliverable contains instructions/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 a full LMS.

3.4.1 Methods

Two different strategies have been chosen. Firstly, a more practical approach of validation is where the EN 206-1 standard and the standard prEN 13013 have been tested out on the selected structures. Validation of proposals for environmental characterisation and classifications has also been carried out. Such studies have been undertaken in five countries: Norway, Sweden, Germany, Finland and United Kingdom. A summary of the national reports is given in D4.3. The complete national reports, including references, are presented in D4.3 Annex.

Secondly, a more theoretical classification based upon parametric sensitivity analysis of the complex Duracrete damage functions under various set conditions is carried out. In this way the determining factors are singled out and classified. This is performed in D3.2. Beside the methodology outlined in D4.2, other approaches are demonstrated in the individual national reports presented in D4.3 Annex. It includes a discussion on how the result of a statistical analysis could be expressed in form of moments (mean value, standard deviation) or parameters of a chosen distribution type, principals of producing weather models from statistical raw data and description of how to simulate environmental load by use of Computational Fluid Dynamics (CFD).

3.4.2 Results and conclusions

According to the case studies almost all needed data were available and rather easy to recieve. 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 recieve. 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.

The case studies shows that the standard EN 206-1 is appropriate to use for classifying and mapping the deteriorating environment in regard to concrete structures. In order to develop EN 206-1 further into a more quantitative system the EN 206-1 system has been tested out and compared to different degradation mechanisms and functions. The connection between the classified environment and the corresponding degradation functions needs to be clarified. Nevertheless, this approach is feasible but needs to be developed.

One crucial factor in a full-probabilistic model on carbonation of concrete is the weather exponent w. The exponent is dependent on Time of Wetness (ToW) and the probability of splash event due to driving rain, which are defined and explained in LIFECON deliverable D3.2. However, the definition of driving rain within the definition of probability of splash event is not the same as defined in prEN 13013-3. The use of prEN 13013-3 with regard to the degradation models in LMS (weather exponent) is then questioned. In the strive of using existing standards as far as possible a suggestion is to develop and adapt the definition of probability of splash event so that application of the standard prEN 13013-3 is possible. When applying the standard on a real case, one remark is that the different surrounding and building factors could be complicated or even impossible to decide for bridges, especially the wall factor (W). The standard is developed specific for geometries like houses, which makes it difficult to apply the standard on other geometries as e.g. bridges. The calculation of the wall spell index requires a lot of meteorological data and tools to handle the data properly, which could be costly and time consuming. That might not be a problem for large and middle size companies but for small size companies with fewer resources.

3.5 Application of MMS on a case study structure

A Life cycle Management System (LMS) has to correspond to user needs, national and international standards and to co-operate with other systems. To fulfil those requirements the system has to be “open” and integrative and it must cope with adaptations and adjustments. This case study concern validation of the IT-tool, and the efforts that are needed to meet different user needs, system requirements and standard. When LMS not yet exist as an operational IT-tool the already existing Maintenance Management System (MMS) has been used for administrative, technical and condition data input of the bridge at Faeltskaersleden. MMS will also be the kernel in the developed LMS. It is important to mention that MMS has been adapted to correspond to both LMS and a user requirements, in this case in the form of SAFEBRO, a maintenance management system used by the Swedish National Road Administration.

3.5.1 Results, comments and conclusions

Only two modules in MMS have been adapted and tested out, the Inventory Recording module and the Condition Survey module. The result of the validation of the two modules in MMS shows that it is possible to adapt and adjust the system with respect to different user, system and standard requirements. However, a comprehensive inventory of user needs, system requirements and applicable valid standards is needed. It has to include investigation of general user needs as well as the required level of detail of data. Though many of the requirements and needs are listed in the CAP some additional needs and requirement may have to be identified, e.g. administrative data and data for interconnection of LMS with other facility management system.

4 Opinion of practitioners

The validation of the LIFECON Management System (LMS) was split into seven stages, as detailed below. This report describes the results of the validation and verification of stage 1-4. Because of the lack of a fully developed IT-tool prototype the last stages were out of this validation. The validation and verification of stages 1-4 included obtaining the opinions of the practitioners with regard to technical accuracy, reliability, economy, comprehensiveness and clarity of the developed tools.

Stage	Operation
1	IT software (MMS)
2	Environmental Loading/Modelling
3	Condition Assessment Protocol
4	Repair Assessment
5	Predictive Models
6	Decision Making Tool
7	Systematics

The validation was conducted within a logical framework commensurate with the order in which each stage was to be used within the LMS. These opinions were sought using a range of activities as site visits, questionnaires, workshops and informal discussions. The validation was conducted on a set of nine case study objects which were chosen to represent a range of reinforced concrete structures under a range of conditions, see table 1. The validation considered the LMS from a number of standpoints as input to LMS, operation of LMS, outcomes from LMS and future use of LIFECON. The standpoints were considered using a range of categories of respondents as operators of the application, intermediate users of the application like providers of information, end-users of the application and individuals or groups affected indirectly from the application but who cannot be classed as either operators, end-users or intermediate users.

4.1 Methodology

The IT software (MMS), Environmental Loading/Modelling, Condition Assessment Protocol, Repair Assessment were assessed by the use of questionnaires issued to members of the user group (i.e. operators, intermediate users and end-users), site visits and informal discussions. These produced a qualitative response, reflecting the opinions of the members of both the user group and the appraisal group, the latter represented by companies, individuals or organisations affected by the impact of the application.

The questionnaires were divided into two sections. These corresponded to questions relating to the application of the system, user acceptance and physical functioning, termed “system” questions and questions relating to the effort required to implement the system, input and expertise required, termed “effort” questions. The questionnaires consisted of a number of statements relating to the relevant section. The response took the form of an integer value in accordance with the scale below.

1 Strong Agreement

2 Agreement
3 Neutral/uncertain impact
4 Disagreement
5 Strong Disagreement

The assessment was undertaken with reference to the relevant deliverables produced by each Workpackage within LIFECON and the available IT software. A workshop on the available IT software (MMS) was held at BMG in Gavle, March 2003, to demonstrate the use of the initial IT software and to obtain feedback on the IT system. This workshop was available to all LIFECON partners. It must be noted that MMS contains only the input and coding modules which will be used in LMS.

4.2 Analysis

Considerable scatter is observed on the replies to the questionnaires. This is illustrated in table 2. The range of the responses to each of the questions and number of questions having that range are shown.

Table 2, Range of responses to questionnaires.

Range of response	1	2	3	4	5
Section 1 (5 replies)					
System		1	1	2	
Effort		3	2		
Section 2 (4 replies)					
System		3	1	2	
Effort		1	3		
Section 3 (3 replies)					
System		4	3	2	
Effort		3			
Section 4 (0 replies)					
System					
Effort					

The wide range of responses to the system questions indicates that the system needs clarification and to be simpler to follow. Partners are unclear on aspects of the operation of the system.

Comments indicate the system, while designed to be generic, is bridge orientated and application to other structures leads to uncertainties. Some aspects of the system also need modifying for application to bridges. Following analysis and conclusions was drawn out from the results.

- There is greater consensus on the effort required, as seen by the small range of the responses. All partners are in agreement that greater time/detail and expertise are required than what is used at present. Partners do, however, generally agree with the level of detail that is required for the LMS.

- Partners are neutral or in agreement that the terminology can be understood, neutral on the terminology in the handbook and in agreement with the terminology in deliverables 4.2 and 3.1. However, there is disagreement that there is consistency between the deliverables, in particular with regard to the division of the objects for the environmental loading categories.
- There was disagreement that the Code System for the structural layout, section 5.1.3 in the Handbook, was simple to follow. Comments indicated that this is with particular reference to levels 5 and 6, environmental classification and repair classification. This is further illustrated by disagreement on the ease of division of components for environmental categories. Once the division has been made there is agreement with the selection of the classes for each component.
- Considerable scatter is observed on the replies to the questionnaires for the "system" questions. The mean value of these responses indicated that the group considered the LMS needed clarification and to be simpler to follow. The wide range may reflect factors such as a bridge orientated nature for the code system, pre-existing knowledge or assumptions made by members of the group.
- There was a large scatter on the availability of the environmental data. According to the results it seems to be that environmental data is more readily available in some countries than others.
- No partner agreed with the need to re-assign categories after following the input of detailed environmental data.
- Partners did not agree that Figure 1.1 in the CAP was simple to follow but were in agreement with the selection of the visual inspection criteria but not with the deterministic and probabilistic criteria. However, partners were neutral on the availability of inspection techniques.

4.3 Comments and conclusions

Following comments and conclusions were drawn out from the results and analysis of the opinions of practitioners. Most of the comments were addressed to clarification or simplification of parts of the system.

The comments indicated that it would be appreciated if the code system for the structural layout, in particular level 5 and 6, could undergo some clarifications or simplifications. They also indicated that clarification and simplification of the basic model of framework for the condition assessment would be appreciated, in particularly with relevance to the selection of the inspection type. The relation between the Condition Assessment Protocol and the division of the objects for environmental loading categories seems to be clarified. The differentiation between deterministic and probabilistic and the selection of inspection techniques were difficult to understand and apply, which indicates that some kind of clarification is needed.

Overall the limited number of replies would indicate that greater clarity, consistency and simplification is required to make a simple to follow generic system. Particular areas that need to be resolved are the assignment of levels 5 and 6 in the hierarchical code system and the selection of deterministic and probabalistic inspection categories.

5 Key results and novelties

To fulfil the objectives and scopes of the LIFECON project, the individual work packages have produced a number of results. These results have then been implemented into the overall LIFECON LMS frame. In most cases it has been necessary to develop new knowledge or at least new applications of earlier existing methodologies, models and methods. Beside the use in LIFECON LMS, these results contribute to the overall European knowledge base and may be used outside LIFECON, for example in standardisation work.

The work package leaders have summarised key results and novelties from each individual work package. These points reflect naturally the core contributions from the work packages into LIFECON and to general knowledge.

5.1 Summary of key results and novelties

5.1.1 Methodologies for life cycle management

- Automatic transformation of degradation models to Markov Chain transition probability models.
- Combination of Markov Chain based performance analysis with Life Cycle Cost (LCC) analysis and Life Cyle Ecology (LCE) analysis.
- Combination of the decision tree technique into the Markov Chain based LCC analysis.
- Combination of the Markov Chain based LCC analysis into the processes of the network level LMS and the object level LMS.

5.1.2 Methodologies for decision making and reliability analysis

- A comprehensive list of terms and definitions for life cycle management.
- A definition of lifetime quality, and list of generic lifetime quality requirements, which are based on general requirements of sustainability.
- A comprehensive and systematic reliability methodology for lifetime quality in relation to the generic mechanical, durability and obsolescence (usability) limit states.
- Methodologies and methods for Multi Criteria Optimisation and Decision Making.

5.1.3 Degradation models

- Existing service life models have been adapted to be applicable at various levels of precision using available inspection data for parameter updating following the idea of Bayesian reliability theory.
- The models have been used to derive a classification for environmental input parameters on a European scale.
- The methodology of using full-probabilistic models for the calibration of the Markov Chain approach as needed for life-cycle-analysis was developed.

5.1.4 Condition assessment

- Probabilistic Service Life Models & Reliability Theory have been integrated into the condition assessment process.
- Precision of predictions as a basis for decisions on maintenance, repair and rehabilitation (MR&R) actions is improved.
- A cumulative rating system fitting into the concept of predictions with the Markov Chain approach was developed, which connects the condition state of a concrete component to the corresponding inspection techniques and feasible MR&R options.

5.1.5 Environmental characterisation

- Relevant systematics and requirements for quantitative classification of environmental loading onto structures.
- Sources of environmental exposure data, and methods for their assessment and modelling on various geographical scales on a European level.

5.1.6 Maintenance, repair and rehabilitation planning

- New and pertinent RAMS definitions.
- Highlighting of the way in which RAMS characteristics depend on the structure in question.
- Transition of qualitative RAMS aspects to quantitative numbers using QFD, taking into account general lifetime quality requirements of human conditions, economy, ecology and culture.
- Development of methodology for the calculation of LCE.

5.1.7 Concluding remarks

The comprehensive lists of key results and novelties shows the wide range of research areas that the LIFECON LMS project covers. Since the identified key results and novelties origin from the work package leaders themselves, there is a risk of getting a non-objective view. However, the work package leaders are highly respected in their respective areas, which should reduce the non-objective risk to a minimum.

It appears to the validation team that all of the key results and novelties have not been fully implemented into the LMS. For example, results from WP4 dealing with environmental loading onto structures seem to be quite briefly dealt with. This is an area that needs greater attention in order to make full use of the systems potential. Nevertheless, beside results that have been directly implemented into the LMS, the project has generated a high amount of general knowledge that will be beneficial to other projects and in other contexts on a European level.

6 Future development of the Life Cycle Management System, LMS

The LIFECON LMS appears after the conclusion of the project predominantly as a generic structure on which an operable IT/GIS-system for Life Cycle Management of Concrete Infrastructures can be programmed and adapted to meet the specific needs of different clients.

Generic is to be interpreted so that either the LMS as a whole with all inherent modules and assets is programmed to establish a customised client version of LMS, or single modules of LMS are adapted to be incorporated with an existing facility management system in use by a client.

The main assets of LMS lie with the predictivity of key characteristics of a built structure, the accountability of the probabilistic nature of material properties, environmental and performance characteristics, the incorporated methods for decision making and analyses, and the capacity of life cycle management at both an object and a network level.

The LIFECON LMS is developed with specific regard to concrete infrastructures, but the generic systematic 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. As regards both materials and environmental data availability is not considered to be the main challenge but rather the issue of data format.

LMS builds on development and adaptation of present best knowledge as to the methodologies being used.

6.1 Summary of and conclusions from the LIFECON partners plans for further use and development of LMS

The members of the LIFECON partnership, consisting of R&D entities (universities, institutes), different categories of owners of concrete infrastructures, contractors, and consultants, have presented their plans for the future use and development of the LIFECON results. These plans reflect naturally the core (business) activities of each partner. The following account in brief categories for the near future plans of the LIFECON partners

6.1.1 The generic systematic of LMS

- Using the LMS systematics in developing customised predictive IT-based facility management systems for specific clients.
- Adaptation and inclusion of the LMS systematics into existing facility management systems.
- Making use of the LMS systematics in planning and procurement of maintenance, repair, rehabilitation and upgrading (MR&R) work.
- Using the LMS systematics in consultancy work to determine the requirements and solutions for new structures.
- Making use of the LMS systematics in structuring and programming academic PhD research as well as basic education.
- Making use of the LMS systematics in focusing and programming directed consortia R&D projects.

6.1.2 The LMS IT-prototype

- To govern the development of customised IT-system for specific clients.
- To fit in adapted single modules of the LMS IT-prototype into existing facility management systems.

6.1.3 Methodologies for decision making and reliability analysis

- Making use of the methodologies in consultancy work on new as well as old structures to determine life performance and maintenance resource needs.
- Integration of the decision making and reliability analyses methods into customised facility management systems.
- Making use of the Markov chain method for modelling the life performance of networks of structures and linking object and network level performance data and analyses, and also on the object level to account for distributions and the probabilistic character of degradation.

6.1.4 Degradation models and methods for environmental characterisation

- To further develop and integrate the LMS systematic for environmental characterisation in projects aiming at implementation of an IT-system. This issue is also in focus of a ongoing PhD work.
- To further develop and integrate the LMS systematic for prediction of residual service life in projects aiming at implementation of an IT-system.

6.1.5 Condition assessment

- Making use of the LMS condition assessment protocol to govern the condition assessment of concrete structures, either in direct consultancy work, or as an integrated part of implementing a complete facility management system.

6.1.6 Maintenance, repair and rehabilitation planning methodology

- The LIFECON RAMS system is being integrated in existing facility management systems.
- The LIFECON RAMS system is being further developed in ongoing PhD work.
- The LCC and LCE (Life Cycle Ecology) methods are being implemented as part of the tool portfolio in planning of MR&R action profiles for network of structures.

6.1.7 Concluding remarks

Members of the LIFECON Partnership have to varying degree on project basis already started the further and future developments of LMS, primarily executed as implementation projects in co-operation with partners on the market. These projects focus both LMS on an overarching level, and specific modules of LMS.

On a long-term perspective the knowledge base of LMS is anticipated to further develop and strengthen through ongoing academic merit R&D. At present three known PhD works are addressing different aspects of LMS; a first thesis to be presented during 2004.

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, which is the focus of the LIFECON project.

In the following these R&D issues are accounted for under broad headings.

6.2 Future development needs at the LMS module level

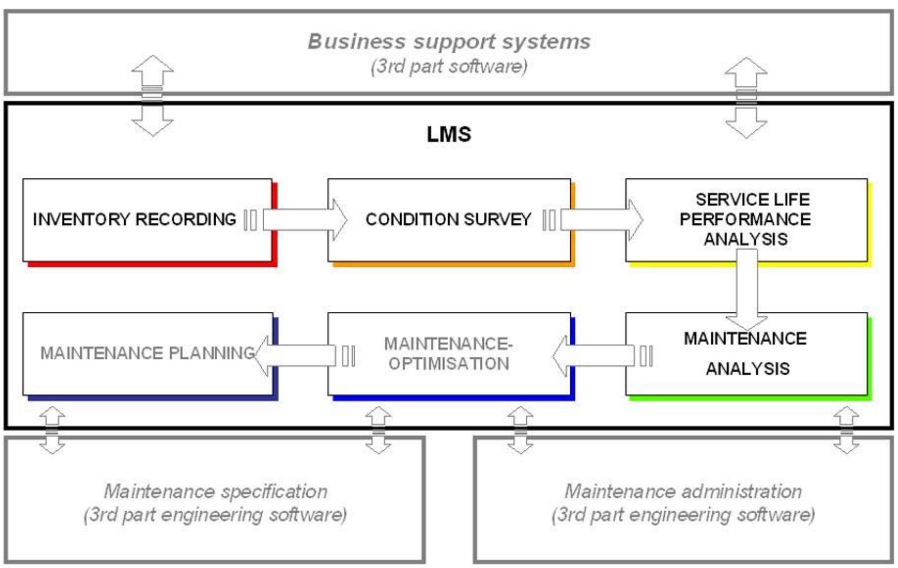

Figure 1: The figure depicts the LIFECON LMS build up with different modules

6.2.1 The Inventory Recording Module

The structure of the Inventory Recording Module is based on a Modular Systematic describing a constructed asset at six different levels. The contents of each level is governed by the requirements and needs put forward by the user, the system itself and applicable standards. The contents may be of an informative character, but also convey information making it possible to interconnect LMS with other facility management systems and more specific engineering systems applied in design (e.g. CAD), analysis and planning of new and existing structures. The development and exploitation of digital product models and the IFC standard will have a large impact on this module, see also under “Future development …” in this chapter. These are issues that have to be developed and detailed in each LMS implementation project

6.2.2 The Condition Survey Module

An essential part of the Condition Assessment Module is the CAP (Condition Assessment Protocol). CAP needs in every implementation project to be adapted to specific user requirements, applicable standards and codes, for example as to the Condition Classes to be used. This also means that the Damage Atlas should be adapted with account of the condition classes used and to contribute to a harmonised condition assessment between different surveyors.

6.2.3 The Service Life Performance Analysis Module

A reliable Service Life Prediction of any kind needs being based on a best possible assessment and characterisation of the environmental loading on the constructed asset in question. A conclusion by the validators (chapter 2.1.3) is "It would appear that LIFECON needs to develop further an understanding of the significance of variations in local exposure and to determine ways of incorporating its effects into the representation of degradation in the LMS". This statement is based on the observation "The Generic Handbook Deliverable D1.1 makes little reference to environmental modelling as described in the deliverables from WP4; the influence of environment appears to be assimilated into degradation matrix coefficients".

While this observation should not be interpreted as stating that the degradation environment characterisation has been neglected, it points rather at the importance of the further development of these issues in any programming of the LMS structure and any implementation project. It has not been possible within the resources of the LIFECON project to fully test out and make use of the systematics and modelling possibilities accounted for in the deliverables of WP4.

However, the WP4 deliverables provide relevant systematics and requirements for quantitative classification of environmental loading onto structures, overview of existing classification systems, overview of sources of environmental exposure data, and methods for their assessment and modelling on various geographical scales in Europe with examples, and present the conclusions:

- For most European countries environmental data and models are available from meteorological offices and the environmental research area, and these data and the work performed are directly applicable for LIFECON.
- The present LMS prediction module, contain such modelling of environmental exposure loads and service life functions for a range of the supplementary materials in concrete structures, such as for example galvanised (and coated) steel.
- Some of the main parameters for concrete degradation (Temperature, ToW, RH and Chloride) have been classified based on Probalistic Service Life Models. These parameters should be modelled, classified and mapped on the national and European level, thus forming a good platform for validating and further developing the EN 206-1 towards quantitative environmental classes.

6.2.4 The Maintenance Optimisation Module

Maintenance optimisation has not been covered as a specific R&D topic or IT-development in LIFECON since these issues are generically treated in several R&D project worldwide. However, the LIFECON LMS enables analyses of service life strategies for single parts of structures or whole structures and these assets are to be further adapted in each implementation of LMS.

6.2.5 The Maintenance Planning Module

As pointed out in Chapter 2 Validation of LIFECON Systematics, the LMS as for now does not treat the routine or operational maintenance needed to manage a constructed asset. While this, in specific cases, may be handled through a facility management system or other business support system to which the LMS is connected and adapted, it is an important general signal that the issue of routine maintenance is considered in every implementation project. The LIFECON LMS is developed with a fully standard programmable interface that enables operative connection to other systems that handle routine maitenance.

In Chapter 2 it is also stated that MR&R actions for structures should be in accordance to the principles of repair described in ENV 1504-9 for consistency with the developing standard.

6.3 Future development of the present LMS as an entity -new R&D directions for LMS

6.3.1 LMS as a tool for Service Life Planning and Client Quality Assurance

It was stated in the introduction of this chapter that the generic LMS systematic is applicable and adaptable to any constructed asset, e.g. predictive maintenance management systems building on essentially the same systematics is being implemented for housing. This observation and an awareness of strategic needs in the building and construction sector trigs the validators to briefly signal a possible development path for LMS.

LMS may, par preference, be further developed to a complete IT-based tool for service life planning of buildings and other constructed assets, in operation from the point of departure when a client orders a building and hence starts the design process. Such a LMS version would support a necessary quality assurance in the design process, while offering the life cycle management assets to the building manager when the building is taken into operation. The development should preferably be linked to the ongoing development of information systems within the building industry, and hence be based on technologies supporting interoperability in the value chain. This development exploits digital product models and the use of the IFC standard and ISO/PAS 12006-3:2001 Building construction - Organisation of information about construction works - Part 3: Framework for object-oriented information exchange.

6.3.2 LMS to estimate Ecological Costs, LCC savings and Social Benefits

LMS includes adapted LCA and LCC tools. Given that e.g. the necessary boundary conditions on an EU or member state level is stated as regards ecological goals, it would be possible to further develop and adapt a LMS version for estimations of ecological costs, savings in LCC (Whole Life Costing; British) and hence social benefits. A further and future developement of this kind calls for close interaction with authorities on an EU or member state level.