LIFECON
LIFECYCLE
MR&R Maintenance Repair Rehabilitation

LIFECON DELIVERABLE D 2.1

RELIABILITY BASED METHODOLOGY FOR LIFETIME MANAGEMENT OF STRUCTURES

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VTT Building and Transport

Shared-cost RTD project

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Lifecon Deliverables

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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:

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Abstract

The objective of this deliverable is provide the terminology and systematic reliability based methodology for modelling, analysing and optimising the lifetime quality in the Lifecon LMS. This reliability approach is working as a link between life cycle management and generic sustainability requirements and European and global normative requirements.

The lifetime performance modelling and the reliability based limit state approach are building an essential core of the integrated life cycle design, lifetime management and MR&R (Maintenance, Repair, and Rehabilitation) planning. Performance based modelling includes the following classes:

1. Modelling of mechanical (static, dynamic and fatigue) behaviour
2. Modelling of physical, chemical and biological behaviour
    - Degradation based durability and service life modelling and design
    - Modelling of thermal behaviour and the behaviour under fire conditions
    - Modelling of moisture behaviour
    - Modelling of biological behaviour
3. Usability modelling and service life calculations with obsolescence analysis

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. Also the modelling of thermal, moisture and biological behaviour of materials and structures are already traditional. Therefore these are not treated in this report, which is focused on durability limit state design and usability, which is treated with obsolescence limit state design.

The lifetime quality means the capability of the structures to fulfil the multiple requirements of the users, owners and society (human and functional requirements in use, lifetime economy, lifetime ecology (economy of the nature) and cultural acceptance) in an optimised way during the entire design or planning period (usually 50 to 100 years).

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. Using the generic definitions we are able to describe more detailed definitions and criteria of limit states in each specific case separately.

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, dynamic and fatigue) limit states design. The durability based service life calculation 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

Obsolescence means the inability to satisfy changing functional (human), economic, cultural or ecological requirements. Obsolescence can affect to the entire building or civil infrastructural facility, or to 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. The limit states of obsolescence are quite different from the others, and often they can not be described in quantitative means. Obsolescence is a "real world problem", which is coming from everyday world of events and ideas, and may be perceived differently by different people. Often these can not be constructed by the investicators as the "laboratory problems" ((degradation or static and dynamic stability) can be. Often we have to apply qualitative descriptions, criteria and methods. Even with these quite approximative means we can however reach a level of rational selection and decisions between the alternatives. The obsolescence management can be carried out with following methods: Quality Function Deployment (QFD) method/sensitivity analysis, Multiple Attribute Decision Aid (sensitivity analysis), risk analysis/FTA (Fault Tree Analysis), or their combinations [Lifecon D2.3].

The principles of generalised reliability approach, which is presented in this deliverable, can be applied in different phases of the Lifecon LMS process [Lifecon D1.1], Condition Assessment Protocol [Lifecon D3.1] and MR&R planning [Lifecon D5.1].

List of Contents

List of terms and definitions

General terms

List of general terms for Lifecon LMS is presented in Appendix 1.

Specific terms and definitions on systems and systematics

TERM	DEFINITION
	Systems

System	An organised whole consisting of its parts, in which the relations between the parts are defined by rules. The parts can be concrete (e. g. components of a building system) or abstract (e. g. components of an information system) [14].
	- *Lifecon LMS includes following systems:*
	  - *asset systems*
	  - *management system, and*
	  - *management process*
	Asset system is concrete, while management system and management process are abstract.

- ***modulated system***	A *system* whose components are independ of each other in terms of internal structure [3,7]. A *modulated system* can form at different hierarchical levels sub-entities, which to a significant extent are independent. The relations between the sub-entities are defined by system rules [14]. - *This means a possibility to select between alternative components, which in Lifecon LMS mean planning models and methods, and MR&R technologies and products.*
- ***open system***	A *modulated system* whose components have compatible interfaces [3,7]. An *open system* consists of modular parts at different hierarchical levels [14].

- ***hierarchical system***	A system consisting of some value scale, value system or hierarchy [3,7].
	The parts can be located at different levels in the organised whole. The parts of an upper hierarchical level [14].
	- *Lifecon LMS includes following hierarchical systems:*
	  o *concrete system: network of objects, object, module, component, subcomponent, detail, material*
	  o *management system: system, thematic modules, model and method components*
	  o *management process: network level process (system), object level process (system), procedure modules, model and method components .*

Structure *(of a system)*	General term for a perceived orderly arrangement and the ordering relationships between elements in a *system* from certain viewpoints, and its description or definition. Examples: - a sentence in language has a structure, described by syntax, grammar, parsing, etc. - a mechanism has a physical structure with changing geometry, described by its parts, assembly instructions, degrees of freedom, etc [16]. *The structure of Lifecon LMS means the arrangement and the ordering relationships betweem the thematic modules of the Lifecon system (Figure 1. of D2.1).*

Process	An artificial process or procedure in which the states of information are transformed in a planned goal-oriented way under the influence of human beings and by the effects exerted by technical means. The obtained states of operands (users) should directly or indirectly serve the satisfaction of human needs. The necessary operations and their sequence is established from the selected technology, which is based on natural laws and phenomena [16]. • *In Lifecom LMS the process is serving the satisfaction of human needs related to sustainability, which are defined in the generic requirements. Indirectly these needs are then served on the techno-economic level of the methodology and methods of Lifecon system.*
Systematics	
Problem, Laboratory	A problem which the investigator defines, in terms of form, content and boundaries. He decides what to take into account and what to leave out; such problems contrast with *real-world problems.* [15]. • *In Lifecon system these kinds of problems are typically related to modelling and methods.*
Problem, Real World	A problem which arises in the everyday world of events and ideas, and may be perceived differently by different people. Such problems are not constructed by the investicators as are *laboratory problems* [15]. • *In Lifecon system these kinds of problems are typically related to some generic requirements, which have an obsolescence, ecological or human character (e. g. cultural requirements, health, comfort, biodiversity)*
Method	Methodical rules that determine possible procedures and actions which are intended to lead via planned path to the accomplishment of a desired aim. Types may be classified according to method of thinking (intuitive or discursive methods), or according to aim and application (methods of searching for solutions, methods of evaluation or calculation [16]. • *The classification of Lifecon methods can mainly be done according to aim and application.*
Methodology	System of *methods* that may be used by an individual to attain a desired objective. For example, the way in which a teaching/learning process within an educational system is embodied, in the form of a curriculum or syllabus, and associated lecture outlines, case studies, problems, projects, experiments, demonstrations, etc. [16].
Function	Capability of an asset to fulfil its effects and actions, or the benefits or utility of the asset. (this is slightly modified from source[16]).
Value	Performance of a *system* refers either to a single *property* or to more complex values, e. g. total value, technical value, usage value (usability) or benefit. The assessment of *value* can use qualitative (verbal describing) or quantitative (numerical) information. One of the purpeses of natural sciences is the conversion of qualitative to quantitative information and models (quantification) [16].
System Technology, or **System Engineering,** or System Methodology	*System*-based methodology for tackling *real world problems* [15].

Model	An intellectual construct, descriptive of an entity in which at least one observer has an interest. The observer may wish to relate his model and, if appropriate, its mechanisms, to observables in the world. When this is done it frequently leads to descriptions of the *real world,* as if it were identical with models of it.
Evaluation	Basic operation of assessing the quality of an object to be evaluated. This process consists of selecting evaluation criteria, determining appropriate *values* for *system,* and processing these to a combined value for the purpose of assisting a decision. Evaluation may be objective, emotional or intellectual, or a combination of these.
Property	Any attribute or characteristic of a *technical system:* performance, form, size, colour, stability, life, manufacturability, transportability, suitability for a purpose, structure, etc.. Their totality represents the *value* or quality of the system Properties may be variant or invariant in time, external or internal [16]. • *Lifecon LMS is especially focused on time depended properties.*

1 Introduction

The aim of this report is to present comprehensive description of systematics of Lifecon LMS (Life Cycle Management System). This systematics includes:

- **Terms and definitions** of lifetime management
- Summary of general principles of **lifetime engineering**
- **Procedure from generic requirements of sustainability** (human requirements, lifetime economy, lifetime ecology and cultural acceptance) **into lifetime management**
- **Integrated management of lifetime quality** with reliability and the limit state approach, including generalised limit state methodologies and methods for :
  - management of mechanical (static, dynamic and fatigue) safety and serviceability
  - condition management of assets with modelling of performance, service life and degradation
  - usability and functionality management under varying use and requirements with obsolescence analysis
- **Generic theory of systems** as an application into management system for structural system, LMS structure and LMS process
- **Linking the European and global normative regulations into the reliability approach of Lifecon LMS** at different phases, especially in safety, serviceability and usability checkings of condition assessment and MR&R planning.

Different parts of this systematics have been applied for use in several modules of Lifecon LMS; especially in generic handbook [Lifecon D1.1], condition assessment protocol [Lifecon D3.1], statistical durability models [Lifecon D2.1 and 3.2] and MR&R (Maintenance, Repair and Rehabilitation) planning [Lifecon D5.1].

Current goal and trend in all areas of mechanical industry as well as in building and civil engineering is the socially, economical, ecologically and culturally sustainable development. A technical approach for this objective is the 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 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** is the capability of the whole network or an object to fulfil the requirements of users, owners and society over its entire life, which means in the practice the planning period (usually 50 to 100 years).

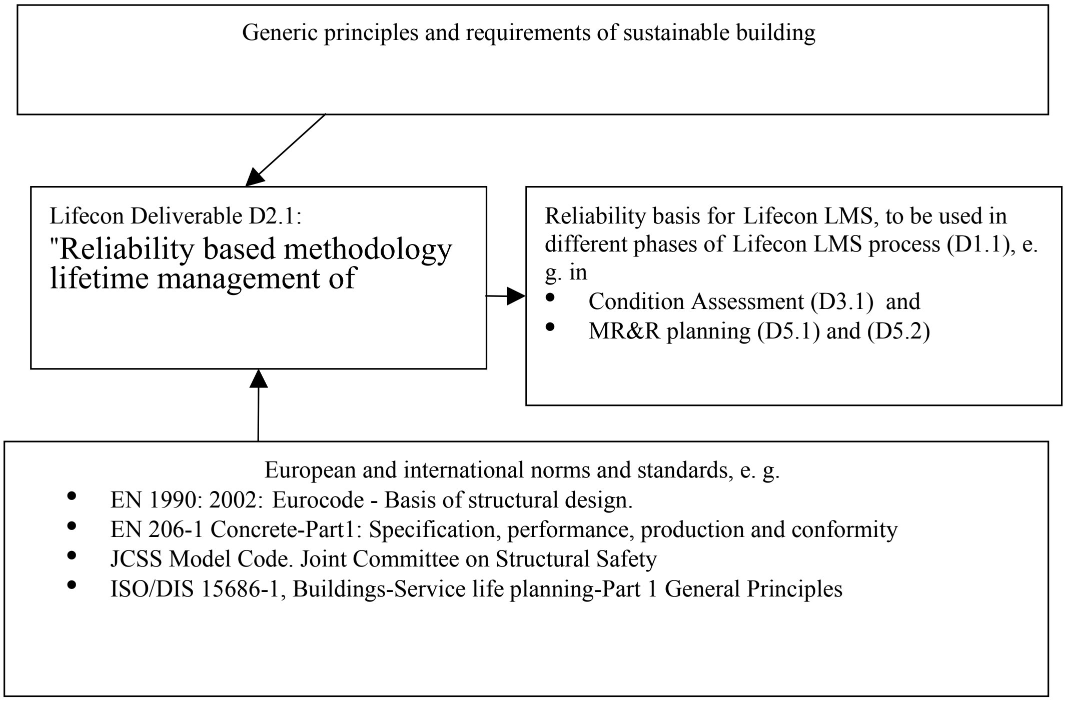
Integrated lifetime design includes a framework, a description of the design process and its phases, special lifetime design methods with regard to different aspects: human conditions, economy, cultural compatibility and ecology. These aspects will be treated with parameters of technical performance 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** (Lifetime Management System) 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 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 social, economic, ecological and cultural) are included in the MR&R (Maintenance, Repair and Rehabilitation) planning, design and execution processes
- **Predictivity**, which means that the functional and performance quality of the 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
- **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.

The objective of this deliverable is to provide an integrated, systematic and uniform reliability based methodology for modelling, analysing and optimising the lifetime quality in the Lifecon LMS under the constraints of normative reliability requirements. This reliability approach is working as a link between life cycle management and generic sustainability requirements and European and international normative requirements, as shown in the following schedule, which shows the flow of reliability approach between generic requirements of sustainable building, European and global norms and standards, Lifecon D2.1 and Reliability approaches of other modules of Lifecon LMS.



The generalised reliability based methodology guarantees conformity of Lifecon LMS with existing normative requirements together with an efficient integrated optimising of lifetime quality, which is based on generic requirements of sustainable building.

This deliverable is linked to several parts of Lifecon LMS, mainly those which are presented in Lifecon Deliverables: D1.1: "Generic technical handbook for a predictive life cycle management system of concrete structures (Lifecon LMS)", D3.1: "Prototype of condition assessment protocol" and D5.1:"Qualitative and quantitative description and classification of RAMS (Reliability, Availability, Maintainability, Safety) characteristics for different categories of repair materials and systems". The main links of this deliverable are presented in the schedule above.

2 System structure

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 will facilitate the change of the facility maintenance and **management for sustainability**, and from a reactive approach into a predictive approach. LMS is working for sustainability on life cycle principle, and includes following (integrated) requirements of sustainable building: human requirements, lifetime economy, lifetime ecology and cultural values. The content and use of these requirements will be explained more in detail later.

Lifecon LMS includes a generic system, methodology and methods for management of all kinds of assets. Only the durability management: condition assessment protocol and service life models, are focused on concrete structures. This is why Lifecon LMS can be applied to all kinds of assests by replacing the condition assessment protocol and service life models with other descriptions and models.

The system makes it possible to organise and implement all the activities related to maintaining, repairing, rehabilitating and replacing assets in an optimised way, taking into account all generic requirements of sustainable building:. life cycle human requirements (usability, performance, health, safety and comfort), life cycle economy, life cycle ecology, and cultural acceptance.

Lifecon LMS (Lifetime Management System) is an open system, which means:

- openness for applications in different environmental and cultural conditions of Europe
- openness for applications for different types of assets: bridges, tunnels, harbours, buildings etc.
- openness for applications into networks (set of objects under management) of very different numbers of objects (bridge, harbour, tunnel, building etc): from several thousands of objects into individual object
- openness for different weightings of generic requirements, technical criteria and properties

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 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.
- 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 (Fig 1):

- System and Process Description: "Generic 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:

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

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 of models for each specific application.

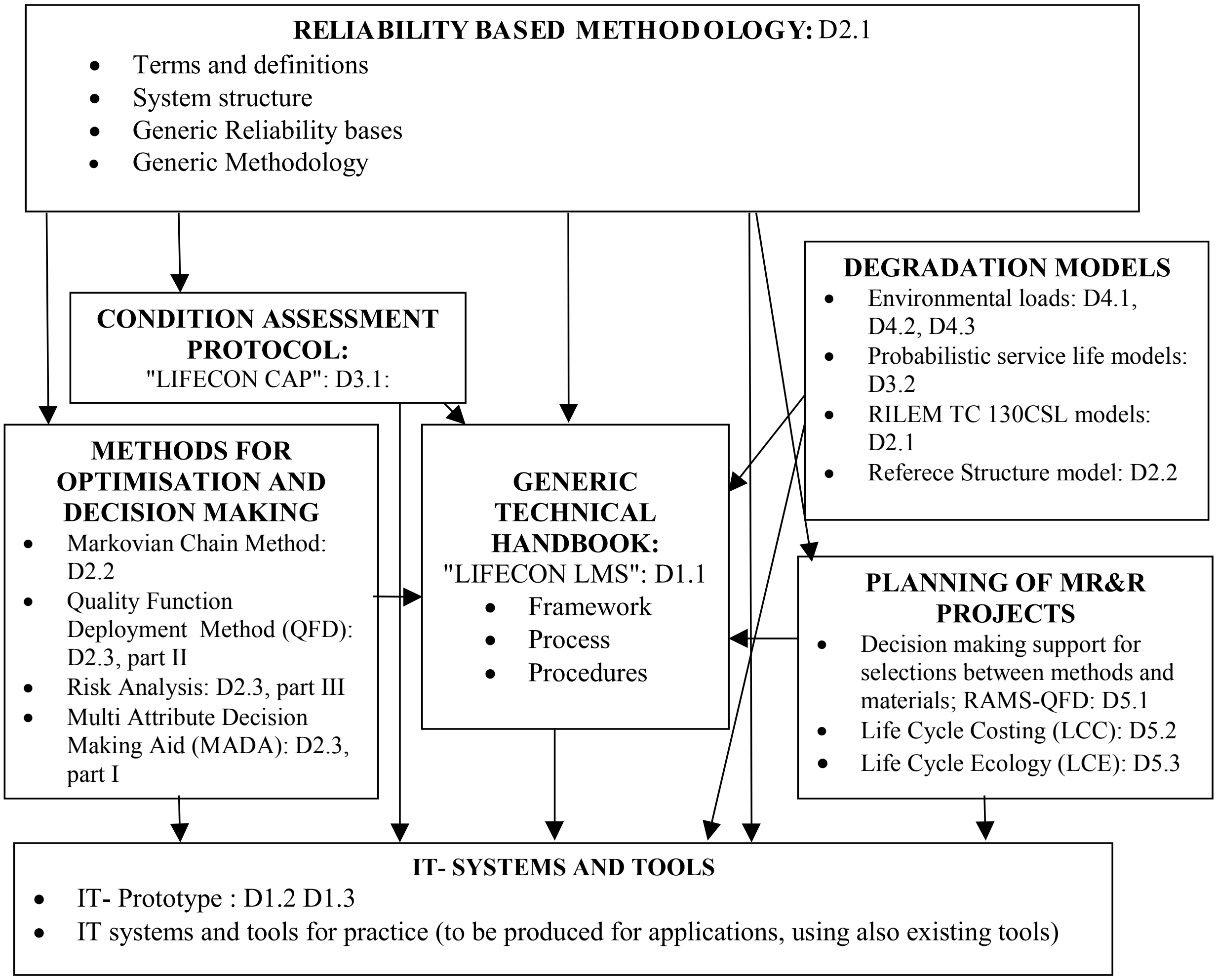


Fig 1. Thematic modules of the LIFECON LMS. and their main interaction (the numbers in the boxes refer to the Lifecon deliverables).

3 Generic Methodology

3.1 Optimisation and decision making

The **objective** of the integrated and predictive lifetime management is to achieve optimised and controlled **lifetime quality** of buildings or civil infrastructures in relation to the generic requirements. The lifetime quality means the **capability of an asset to fulfil the requirements of users, owners and society on an optimised way during the entire design life of the asset.** 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 methodology can be described in a schedule, which is presented in figure 2 [1]. The generic requirements are listed in table 1.

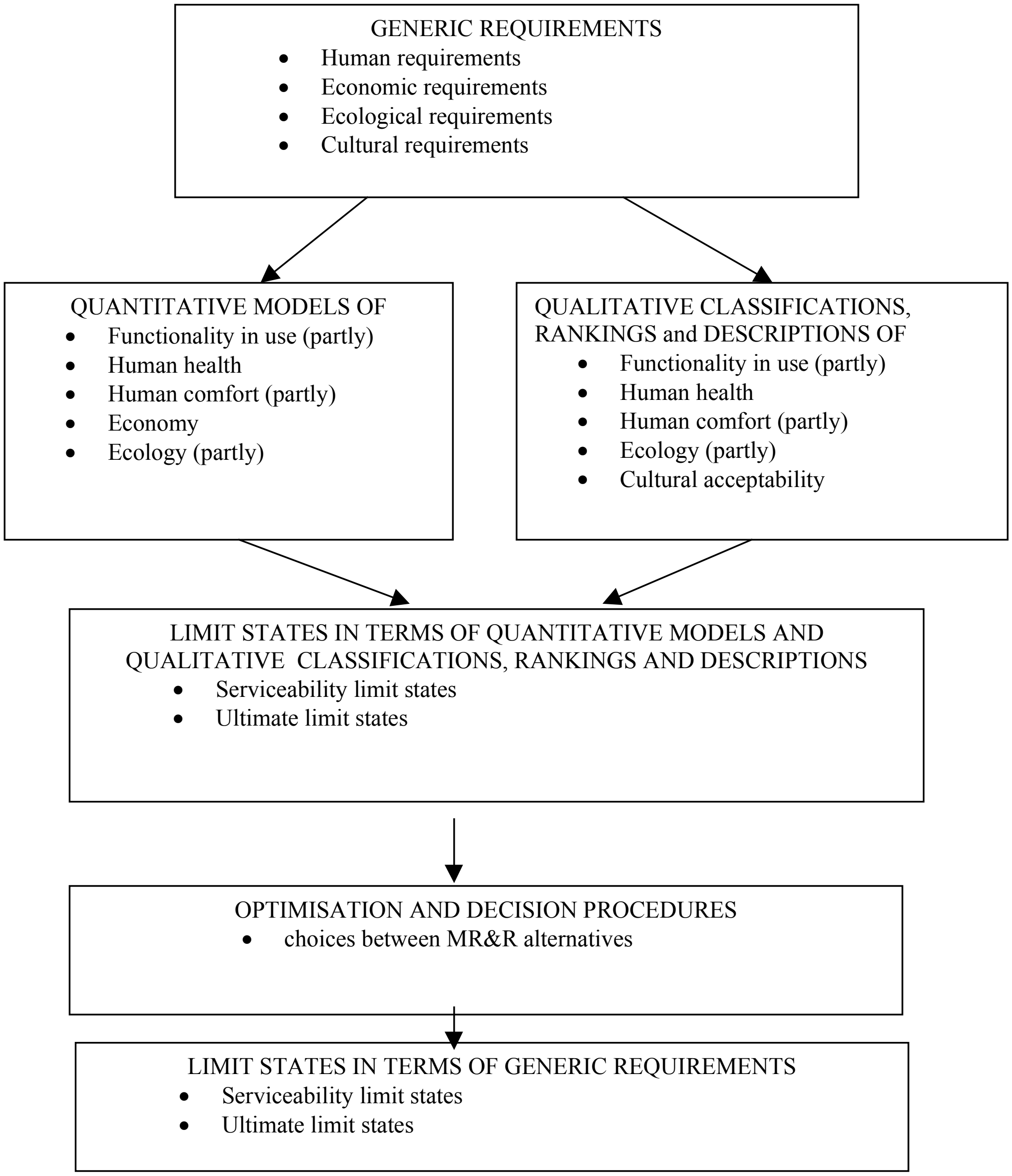


Fig 2. Schedule of the generic procedure of reliability management in Lifecon LMS [1].

The lifetime performance modelling (figure 3.) and the limit state approach are building an essential core of the lifetime management, MR&R (Maintenance, Repair and Rehabilitation) 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. newest specific standard for reliability of structures is Eurocode EN1990:2000 [2]. The mechanical behaviour (safety and serviceability), beside the other categories mentioned above, have to be checked in several phases of the management process. Especially this is important 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 report, 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 not treated in this report.

Modelling of usability and functionality means in life cycle management system 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. Therefore this issue is very central in developing asset management for sustainability, which is the aim of Lifecon LMS.

Main issues of healthiness during the MR&R works is to avoid unhealthy materials [Lifecon D5.1]. During the use of assets (especially in closed spaces as buildings or tunnels) are 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 be also be eliminated though 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 thus are 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 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 resue and recycling of the components and materials after the demolition belong to the ecological indicators. Engineering structures such as bridges, dams, towers, cooling towers are often very massive and their material consumption is an important factor. Their environmental efficiency depends on the selection of environmentally-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 most important 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 they often can be only described qualitatively. 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 as variables and indicators suited geometric dimensions and load bearing capacity etc.. 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 part of the building that is most often changed.

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: Deliverable D2.3
2. Service Life Estimation:
    - Probabilistic service life models: Deliverable 3.2
    - RILEM TC 130 CSL Models: Deliverable D2.1
    - Reference Structure Method: Deliverable D2.2
3. Condition Matrix: Markovian Chain Method: Deliverable D2.2, and Condition Assessment Protocol: Deliverable D3.1.
4. Total and systematic Reliability Based Methodology: Deliverable D2.1
5. Risk Analysis: Deliverable D2.3

3.2 Generic requirements

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

Table 1. Generic classified requirements of structures and buildings [1,3].

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

3.3 Refined techno-economic requirements and indicators

Refined levels of requirements are usually needed in specific applications for parameters in more detailed management planning calculations. An example of such refined requirement and indicator levels are presented in table 2.

The refined techno-economic requirements and indicators can not be presented in generic forms, but they are varying from case to case (for different types of assets and structures, for different use etc.). The definition of these parameters requires specific expertise of each individual case.

Table 2. Refining of the generic requirements into planning parameters.

		GENERIC REQUIREMENTS					
		A Human requirements		**B Lifetime economy**	**C Lifetime ecology**		**D Culture**
		Lifetime functionality	**Lifetime performance**	**Construction and MR&R**	**Environmental impact**	**Recovery and recycling**	**Cultural acceptance in relation to**
REFINED REQUIREMENTS	**1**	Functioning in use (usability)	Static and dynamic safety and reliability in use	Investment economy	Non Energetic resources economy	Recycling of wastes in manufacture of materials, components and modules	Building traditions
	2	Functional connections between spaces	Service life	Construction cost	Energetic resources economy	Ability for Selective dismantling	Life style
	3	Health and internal air quality	Hygro-thermal performance	Operation cost	Production of pollutants into air	“Reuse-ability” of components and modules	Business culture
	4	Accessibility	Safe quality of internal air	Maintenance cost	Production of pollutants into water	“Recycling-ability” of dismantling materials	Aesthetics
	5	Comfort	Safe quality of drinking water	Repair costs	Production of pollutants into soil	Hazardous wastes	Architectural styles and trends
	6	Flexibility in use	Acoustical performance	Restoration costs			Imago
	7	Maintain-ability	Changeability of structures and building services	Rehabilitation costs			Cultural heritage value
	8	Refurbish-mentability	Operability	Renewal costs			

3.4 Limit states

3.4.1 Limit states in terms of techno-economic parameters and models

The origination classes of limit states are as follows:

- Static, dynamic and fatigue
- Degradations

- Obsolescence

Static, dynamic and fatigue limit states mean the traditional calculations of safety and serviceability. These calculations are needed beside the degradation calculations at several phases of the life cycle management: mainly at the condition assessment and MR&R project planning. It is possible to combine the mechanical and durability models, but usually more practical is to separate them. This is so called integrated mechanical and durability modelling method, but in fact even it includes different phases for calculations of the mechanical and degradation behaviour. In the separated method information on some properties, like corrosion of reinforcement, or reduction of dimensions due to loss of concrete cross section are moved from degradation calculations into mechanical calculations. The serviceability limit states and ultimate limit states of concrete structures in relation to this classification are presented in table 3 [1].

Table 3. Generic mechanical, degradation and obsolescence limit states of concrete structures [1].

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 2. Cracking limit state	3. Surface faults causing aesthetic harm (colour faults, pollution, splitting, minor spalling) 4. Surface faults causing reduced service life (cracking, major spalling, major splitting) 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 7. The safety level does not allow the requested increased loads 8. Reduced healthy, but still usable 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: • heavy spalling • heavy cracking causing insufficient anchorage of reinforcement • corrosion of the reinforcement causing insufficient safety.	3. Serious obsolescence causing total loss of usability through: • loss of functionality in use (use of building, traffic transmittance of a road or bridge etc.) • safety of use • health • comfort • economy in use • MR&R costs • ecology • cultural acceptance

3.4.2 Analogy between the models

In order to understand the analogy between the mechanical, durability and obsolescence performance modelling, these methodologies can be compared as presented in table 4 [4,1].

Table 4. Comparison of static and dynamic (mechanical) limit state method, durability limit state method and obsolescence limit state method [4,1].

Mechanical limit state design	Durability limit state design	Obsolescence limit state design
1. Strength class	1. Service life class	1. Service life class
2. Target strength	2. Target service life	2. Target service life
3. Characteristic strength (5 % fractile)	3. Characteristic service life (5% fractile)	3. Characteristic service life (5%fractile)
4. Design strength	4. Design life	4. Design life
5. Partial safety factors of materials strength	5. Partial safety factors of service life	5. (Partial safety factors of service life)
6. Static or dynamic loading onto structure	6. Environmental degradating loads onto structure	6. Obsolescence loading onto structure
7. Partial safety factors of static loads	7. Partial safety factors of environmental loads	7. Partial safety factors of obsolescence loading
8. Service limit state (SLS) and ultimate limit state (ULS)	8. Serviceability and ultimate limit states, related to the basic requirements: Human requirements, lifetime economy, cultural aspects and lifetime ecology	8. Serviceability and ultimate limit states related to obsolescence in relation to the basic requirements: Human requirements, lifetime economy, cultural aspects and lifetime ecology

A generic summary of performance and functionality limit states in different classes of design are presented in table 5 [1].

Table5. Summary of performance and functionality limit states.

<table>
<tr><th colspan="2">A. Performance limit states</th></tr>
<tr><th>Serviceability limit states</th><th>Ultimate limit states</th></tr>
<tr><td>1. Surface cracking</td><td></td></tr>
<tr><td>2. Surface scaling</td><td></td></tr>
<tr><td>3. Deflection</td><td></td></tr>
<tr><td>4. Carbonatisation until reinforcement</td><td></td></tr>
<tr><td>5. Corrosion of reinforcement</td><td>1. Failure under static, dynamic or fatigue loading</td></tr>
<tr><td></td><td></td></tr>
<tr><th colspan="2">B. Functionality limit states</th></tr>
<tr><th>Serviceability limit states</th><th>Ultimate limit states</th></tr>
<tr><td>1. Weakened functionality</td><td>1. Total loss of functionality</td></tr>
<tr><td>2. Weakened economy of operation</td><td>2. Total loss of economy of operation</td></tr>
<tr><td>3. Weakened economy of MR&R</td><td>3. Total loss of economy of MR&R</td></tr>
<tr><td>4. Minor health problems in use</td><td>4. Severe health problems in use</td></tr>
<tr><td>5. Aesthetic change of surface (abrasion, colour changes)</td><td></td></tr>
<tr><td>6. Cultural ineligibility</td><td>5. Total loss of cultural eligibility</td></tr>
<tr><td>7. Weakened ecology</td><td>5. Severe ecological problems or hazards</td></tr>
</table>

3.5 Performance based methodology

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. Using the generic definitions we are able to describe more detailed definitions and criteria of limit states in each specific case separately.

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.

A schedule of the development of the degradation based durability modelling is presented in figure 3 [1].

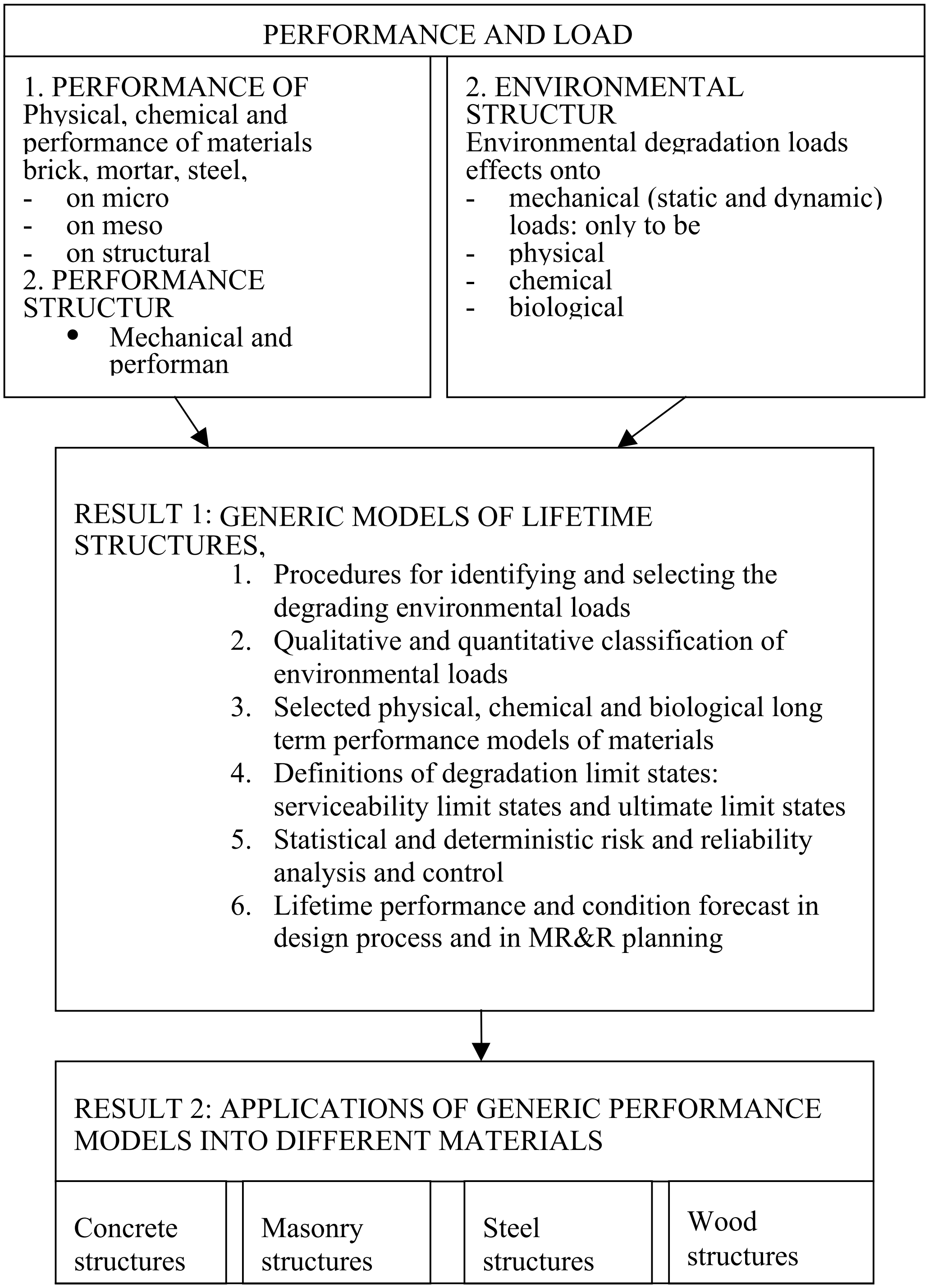


Fig 3. Degradation related performance modelling of structures [1].

The limit states of obsolescence differ form the mechanical and degradation limit states. Some remarks have been presented e. g. in ISO standards [5], and in American standards [6], but real analysis methods have not been presented. There are no international or national normative standards concerning the obsolescence, and no exactly defined limit states of obsolescence.

The obsolescence loading can be defined as the changes of the use, business, technology and working environment, or even as the development of the society around the still-standing structure. All these changes can induce obsolescence loading through individual, local, national, regional or global changes of generic human, economic, ecological and cultural requirements.

The limit states of obsolescence often cannot be described in quantitative means. Therefore we often have to apply qualitative descriptions, criteria and methods [4,1]. Even with these quite inexact means we can reach a level of rational selection and decisions between the alternatives. There is still much potential to develop the methodology, models and tools into more detailed and precise level.

The final objective of the obsolescence analysis is to reduce demolishing of facilities that have not reached their mechanical or durability limit states, and thus promote the sustainable development.

3.6 Modular product systematic

The modular product systematic is aimed for compatible object description for different kinds of objects, like bridges, harbours, airports, tunnels, buildings etc [3,7]. this is applied in several parts of the Lifecon LMS: different levels and optimisation and decision making procedures of Lifecon LMS process [D1.1], conditon assessment [Lifecon D3.1] and MR&R planning [Lifecon D5.1].

In modular systematic the modulation involves division of the whole asset into sub-entities, which to a significant extent are compatible and independent. The compatibility makes it possible to use interchangeable products that can be joined together according to connection rules to form a functional whole of the object.

Typical modules of a building are:

- bearing frame
- envelop
- roofing system
- partition walls and
- building service systems.

Typical modules of a bridge are:

- foundations (incl. pilings)
- supporting vertical structures
- bearing horizontal structures
- deck
- water proofing of the deck
- pavement
- edge beams and
- railings

The modular product systematic is firmly connected to the performance systematic of the object. As an example, the main performance requirements of floors of buildings can be classified in the following way:

1. Mechanical requirements, including
    - static and dynamic load bearing capacity,
    - serviceability behaviour: deflection limits, cracking limits and damping of vibrations
2. Physical requirements, including
    - tightness of insulating parts (against water, vapour etc)
    - thermal insulation between cold and warm spaces
    - fire resistance and fire insulation
    - acoustic insulation
3. Flexible compatibility with connecting structures and installations
    - partitions
    - services: piping, wiring, heating and ventilating installations
4. Other requirements:
    - buildability
    - maintainability
    - changeability during the use
    - easy demolition
    - reuse, recycling and wasting.

In case of bridges the modulation, specification of major performance properties and design service life cost estimation can be done applying the schemes presented in table 6.

Table 6. Specification of performance properties for the alternative structural solutions on a module levels; as an example a bridge.

Structural assembly (Module)	Central performance properties in specifications
1. Substructures • foundations, • retaining walls	Bearing capacity, target service life, estimated repair intervals, estimated maintenance costs, limits and targets of environmental impact profiles.
2. Superstructures • Bearing structural system: o vertical o horizontal	Bearing capacity, target service life, estimated repair intervals, estimated maintenance costs, limits and targets of environmental impact profiles.
3. Deck overlayers • water proofing • concrete topping • pavement	Target values of moisture insulation, target service life, estimated repair intervals, estimated maintenance costs, limits and targets of environmental impact profiles, estimated intervals of the renewal.
4. Installations • railings • lights etc.	Target service life, estimated repair intervals, estimated maintenance costs, limits and targets of environmental impact profiles, estimated intervals of the renewal.

4 Statistical methodology under mechanical loading

4.1 Statistical methods

The simplest mathematical model for describing the 'failure' event comprises a load variable $S(t)$ and a response variable $R(t)$ [8,4,3]. This means, that both the resistance R and the load S are time dependent, and the same equations can be used for static reliability and durability. Usually the time is neglected as a variable in static and dynamic calculations; they are included only in fatigue reliability.

In durability related limit states and service life calculations the time is always included as a variable of $R(t)$ and $S(t)$. In principle the variables $S(t)$ and $R(t)$ can be any quantities and expressed in any units. The only requirement is that they are commensurable. Thus, for example, S can be a weathering effect and R the capability of the surface to resist the weathering effect.

If R and S are independent of time, the 'failure' event can be expressed as follows

$$\{\text{failure}\} = \{R(t) < S(t)\} \tag{1}$$

The failure probability P_f is now defined as the probability of that 'failure':

$$P_f = P\{R<S\} \tag{2}$$

Either the resistance R or the load S or both can be time-dependent quantities. Thus the failure probability is also a time dependent quantity. Considering $R(\tau)$ and $S(\tau)$ are instantaneous physical values of the resistance and the load at the moment τ, the failure probability in a lifetime t could be defined as (Sarja and Vesikari1996):

$$P_f(t) = P\{R(\tau)<S(\tau)\} \text{ for all } \tau \leq t \tag{3a}$$

The determination of the function $P_f(t)$ according to the Equation 3a is mathematically difficult. That is why R and S are considered to be stochastic quantities with time-dependent or constant density distributions. By this means the failure probability can usually be defined as:

$$P_f(t) = P\{R(t)<S(t)\} \tag{3b}$$

According to the equation 3b the failure probability increases continuously with time as schematically presented in figure 4 [8].

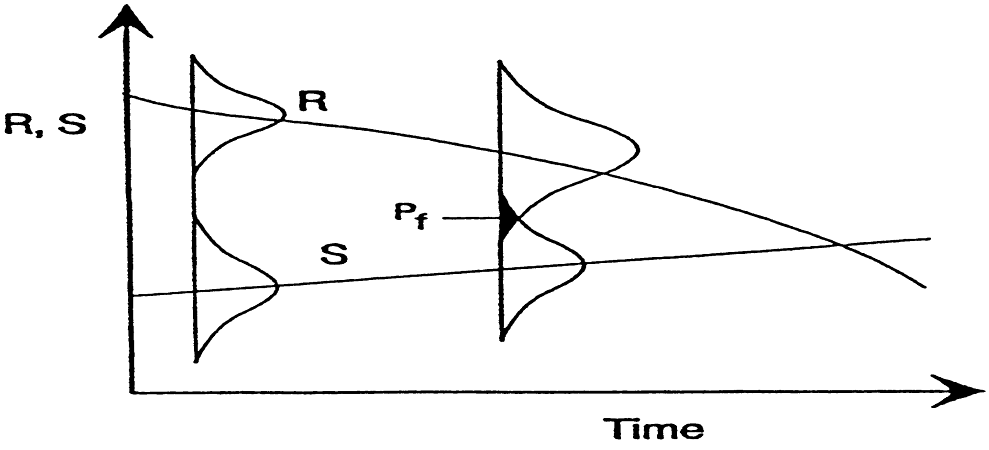


Fig 4. The increase of failure probability. Illustrative presentation [8].

Considering continuous distributions, the failure probability P_f at a certain moment of time can be determined using the convolution integral:

$$P_f(t) = \int F_R(s,t) f_S(s,t) ds \qquad (4)$$

where
$F_R(s)$ is the cumulative distribution function of R,
$f_S(s)$ the probability density function of S, and
s the common quantity or measure of R and S.

The integral can be approximately solved by numerical methods.

In static and dynamic calculations the time is not a variable, but the reliability is calculated at the moment t=0.

In durability calculations the time is a variable of the resistance $R(t)$, but usually the environmental degradation load $S(t)$ is considered to be constant. The value of S is depending on the environmental exposure conditions and actual design life of the structure. The environmental loads are classified in the standards, for concrete structures the standard EN 206 can be used [9].

Mathematical formulation for applied statistical degradation methods are presented in the Model Code of JCSS (Joint Committee on Structural Safety) [10].

The statistical reliability calculations are serving as important basis for applied safety factor methods, which are now in common use. The statistical method is used in special cases, when the reliability has to be analysed in very individual terms. In such a case the material parameters and dimensions have to be determined in so high number of samples, that statistical values (mean value and standard deviation) can be calculated. In ordinary design or condition assessment this is not possible, and the safety factor method is then applied.

The reliability index and the corresponding probability of failure can be calculated analytically only in some special cases. Usually the equations are solved with suited numerical methods of partial differential equations, or with simulations.

4.2 Statistical reliability requirements of structures

The statistical reliability methodology and requirements are defined in the European standard EN 1990. This standard is based on partial safety factor method, but the reliability requirements are expressed also in terms of statistical reliability index β. The general definition of the reliability index β of standard normal distribution is defined as a factor, which fulfils the equation:

$$P_f = \Phi(-\beta) \qquad (5)$$

where Φ is the cumulative distribution function of the standardised Normal distribution.

The requirements of the standard EN 1990 for the reliability index are shown in Table 7 for the design of new structures, as well as for the safety of existing structures [2] .

Because these are are European normative requirements, it is extremely important to use these reliability requirements as bases for all statistical and deterministic limit states methods, which are used for reliability control of mechanical, durability and obsolescence reliability of assets and structures in Lifecon LMS. In degradation manegement direct statistical calculations the values of safety index can be appliedv directly [Lifecon D3.2]. In deterministic limit state calculations, which will be treated in this report, the lifetime safety factor is calculated with this statistical base, and then applied deterministically in practice. In usability management with obsolescence mothodology the risk analysis method is applied statistically applying these safety index values, or it can be calculated deterministically applying Quality Function Deployment (QFD) method or Multiple Attribute Decision Aid (MADA) method together with lifetime safety factor method as a determisnistic limit state method.

Table 7. Recommended minimum values for reliability index β (eq. 5) in ultimate limit states and in serviceability limit states, according to EN 1990: 2002[2].

Reliability Class	**Minimum values for β**			
	1 year period		**50 years period**	
	Ultimate limit states	Serviceabilility limit states	Ultimate limit states	Serviceabilility limit states
RC3/CC3: High consequence for loss of human life, *or* economic, social or environmental consequences very great	5,2	No general recommendation	4,3	No general recommendation
RC2/CC2: Medium consequence for loss of human life, *or* economic, social or environmental consequences considerable	4,7	2,9	4,7 Fatigue: 1,5 to 3,8 1)	1,5
RC1/CC1: Low consequence for loss of human life, *or* economic, social or environmental consequences small or negligible	4,2	No general recommendation	3,3	No general recommendation

5 Deterministic safety factor methods

5.1 Safety factor method for static, fatigue and dynamic loading

The partial safety factor has already been in common European codes and use already about three decades. The latest updating of this methodology is presented in EN 1990 [2], and there is no need to present this methodology in this report.

5.2 Lifetime safety factor method for durability

In practice it is reasonable to apply the lifetime safety factor method in the design procedure for durability, which was first time presented in the report of RILEM TC 130 CSL [8,11]. The lifetime safety factor method is analogous with the static limit state design. The durability design using the lifetime safety factor method is related to controlling the risk of falling below the target service, while static limit state design is related to controlling the reliability of the structure against failure under external mechanical loading.

The durability design with lifetime safety factor method is always combined with static or dynamic design and aims to control the serviceability and service life of a new or existing structure, while static and dynamic design controls the loading capacity.

5.2.1 Durability limit states

The lifetime safety factor design procedure is somewhat different for structures consisting of different materials, although the basic design procedure is the same for all kinds of materials and structures. Limit states can be the same as in static design, but some generalised limit states, including e. g. visual or functional limit states, can be defined. In this way the principle of multiple requirements, which is essential for integrated life cycle design, can be introduced.

Limit states are divided into two main categories:

1. Performance limit states
2. Functionality limit states

The performance limit states affect the technical serviceability or safety of structures, and the functional limit states affect the usability of structures. Both of these, but especially the latter is often connected to obsolescence.

The performance limit states can be handled numerically, but the functional limit states can not always be handled numerically but only qualitatively.

Investigations in practice have shown, that about 50% of all demolished buildings or civil infrastructures have been demolished because of obsolescence, and the same amount because of insufficient technical performance or safety. A short summary of the parameters of durability limit states is presented in table 5.

5.2.2 Design life

Design life is a specified time period, which is used in calculations. Ordinary design life is 50 years (EN 1990) for buildings and 100 years for civil engineering structures. In special cases even longer design life cycles can be used. However, after 50 years the effect of increased design life cycle is quite small and it can be estimated as the residual value at the end of the calculation life cycle. Temporary structures are designed for a shorter design life, which will be specified in each individual case. The classification of design life of EN1990: 2002 is presented in table 8.

Table 8. Classification of EN 1990: 2002 for design life of structures [2].

Class 1: 1–5 years	Special case temporary buildings
Class 2: 25 years	Temporary buildings, e. g. stores buildings, accommodation barracks
Class 3: 50 years	Ordinary buildings
Class 4: 100 years	Special buildings, bridges and other infrastructure buildings or where more accurate calculations are needed, for example, for safety reasons
Class 5: over 100 years	Special buildings e. g. monuments, very important infrastructure buildings

5.2.3 Reliability calculations

The design service life is determined by formula (*Sarja and Vesikari 1996 [8,11], modified:Sarja 2001 [12] and Sarja 2002[4]*):

$$t_{Ld} = t_{Lk} / \gamma_{tk} >= t_g \qquad (6)$$

where t_{Ld} is the design service life,
t_{Lk} the characteristic service life
γ_{tk} the lifetime safety factor, and
t_g the target service life.

Using the lifetime safety factor, the requirement of target service life (corresponding to a maximum allowable failure probability) is converted to the requirement of mean service life.

The mean service life is approximated by service life models which show the crossing point of the degradation curve with the limit state of durability (Fig 5). The mean service life evaluated by the service life model divided by the central lifetime safety factor is *design life, which* must be greater than or equal to the requirement for the design life (also called target service life).

$$t_{Ld} = \mu(t_L) / \gamma_{t0} \qquad (7a)$$

$$t_{Ld} \geq t_g \qquad (7b)$$

where t_{Ld} is the design service life.

γ_{t0} central safety factor

When using ordinary characteristic values the equations get the following formulations:

$t_{Ld} = t_{Lk} / \gamma_{tk} \geq$ required design life (target service life) (Table3) (8a)

$t_{Ld} = t_{L}k / \gamma_{tk} \geq$ required design life (=target service life) (Table3) (8b)

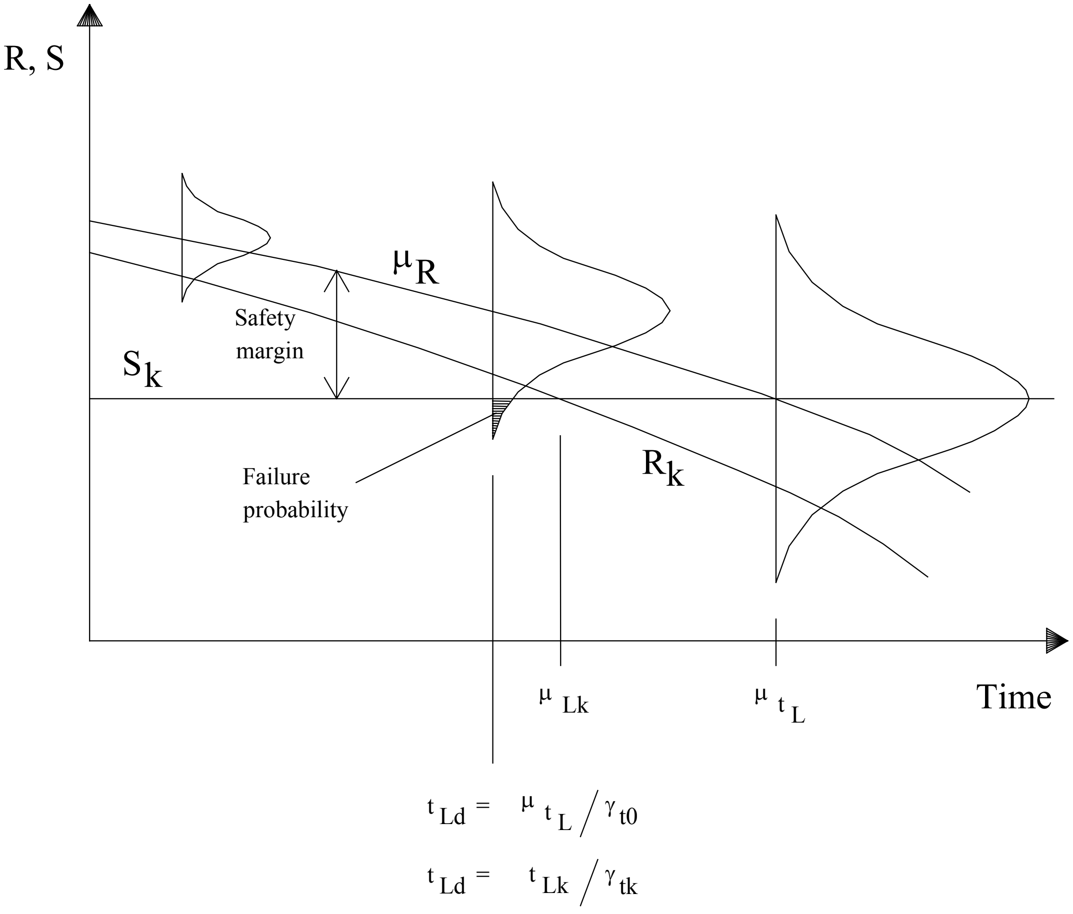


Fig 5. The meaning of lifetime safety factor in a performance problem.

The lifetime safety factor depends on the maximum allowable failure probability. The lifetime safety factor also depends on the form of service life distribution. Fig 8. illustrates the meaning of lifetime safety factor when the design is done according to the performance principle. The function $R(t) - S$ is called the safety margin.

Performance behaviour can always be translated into degradation behaviour. By definition, degradation is a decrease in performance. The transformation is performed by the following substitutions:

$$R(0) - R(t) = D(t) \tag{9}$$

$$R(0) - S = D_{max}$$

or

$$R(0) - R_{min} = D_{max}$$

Let us consider that the degradation function is of the following form:

$$\mu_{D(t)} = a \cdot t^n \tag{10}$$

where	$\mu_{D(t)}$	is	the mean value of degradation,
	a		the constant coefficient,
	t		time, and

n degradation mode coefficient .

The exponent n may in principle vary between $-\infty$ and $+\infty$. The values of n are defined as follows:

- Accelerating degradation process: $n > 1$
- Declerating degradation process: $n<1$
- Linear degradation process: $n=1$

The coefficient a is fixed when the mean service life is known:

$$\alpha = D_{max} / \mu_{tL} \tag{11}$$

Degradation is assumed to be normally distributed around the mean. It is also assumed that the standard deviation of D is proportional to the mean degradation, the coefficient of variation being constant, V_D. Fig 6 shows the degradation as a function of time.

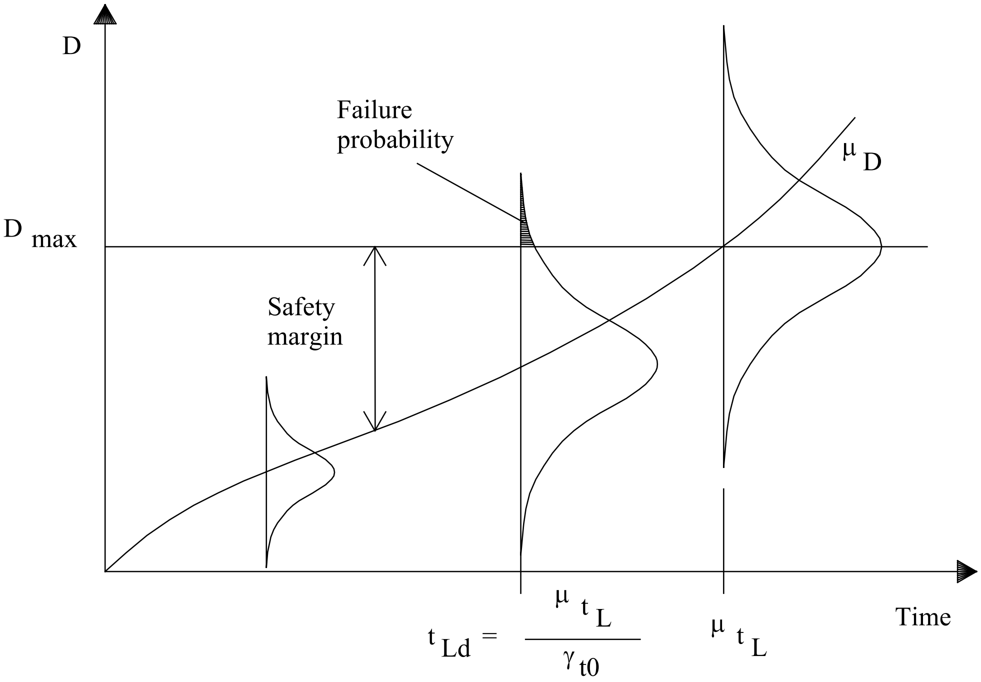


Fig 6. The meaning of lifetime safety factor in a degradation process.

The safety index β of standard normal distribution can be expressed as a function of mean values of R and S, and standard deviation of the difference $R_0 - S_0$, as follows:

$$\beta = (\mu_R - \mu_S) / SQR\,(V_R^2 + V_S^2) \tag{12a}$$

In the degradation models we apply the statistical bases only for the capacity, because the environmental load is defined only as classified magnitudes. Applying into the degradation, and assuming S to be constant we get an estimate

$$\beta = \frac{D_{\max} - D_g}{V_D D_g} = \frac{\left(\frac{D_{\max}}{D_g} - 1 \right)}{V_D} \tag{12b}$$

where $D_{\max}$ is the maximum allowable degradation,
D_g the mean degradation at t_g, and
V_D the coefficient of variation of degradation.

From Fig 6. and from equation 12b we get:

$$\frac{D_{\max}}{D_g} = \frac{\left(\gamma_{t0} t_g\right)^n}{\left(t_g\right)^n} = \gamma_{t0}^{\ n} \tag{13}$$

By assigning this to equation (12b) we obtain the central lifetime safety factor and mean value of the design life:

$$\gamma_{t_0} = (\beta \cdot V_D + 1)^{1/n} \tag{14}$$

$$t_{Ld} = \mu_{tL} / \gamma_{t_0}$$

where t_{Ld} is the design life
μ_{tL} mean value of the service life
β the safety index
V_D the coefficient of variation of the degradation

The lifetime safety factor depends on statistical safety index β (respective to the maximum allowable failure probability at t_g), the coefficient of variation of D (=V_D) and the exponent n. Thus the lifetime safety factor is not directly dependent on design life (target service life) t_g itself.

If the degradation process is accelerating, n<1. In the case of decelerating degradation n>1. In the case of linear degradation process n=1. The selection of the value of n can be done when knowing the degradation model. Often the degradation process in the degradation models is assumed to be linear. In these cases, or always when no exact information on the degradation process is known, the value n=1 can be used.

The mean design life can be transformed into characteristic design life with the form:

$$t_k = t_0 \ (1 - k \ V_t) \tag{15}$$

$$t_{Ld} = t_{Lk} / \gamma_{tk} = \mu_{tL} / \gamma_{t_0}$$

where $t_{Lk}$is the characteristic service life
μ_{tL} the mean value of the service life
t_{Ld} design life

k	a statistical factor depending on the statistical reliability level expressed as a fractile of the cases under the characteristic value (usually the fractile is 5%, and k = 1,645)
V_t	coefficient of variation of the service life (if not known, an estimate ν_D = 0,15-0,30 can usually be used).

The characteristic lifetime safety factor γ_{tk} can be calculated with the equation

$$t_{Ld} = t_{Lk} / \gamma_{tk} = \mu_{tL} / \gamma_{t0} \tag{16}$$

$$\gamma_{tk} = \gamma_{t0} * t_{Lk} / \mu_{tL} = (\beta \cdot V_D + 1)^{1/n} * (1 - 1{,}645 \cdot V_{tLd})$$

where		
	β	is the safety index
	V_D	the coefficient of variation of the degradation (usually. 0,2-0,4)
	V_{tLd}	the coefficient of variation of the design life (usually 0,15-0,30)

Looking at the equations 14 and 16 we can see, that there is a correlation between ν_D and ν_t.

In equation 14 we obtain, that the standard deviation of $\sigma(t_d) = \sigma(V_D)$. This means that

$$V_{td} = V_D / \gamma_{t0} = V_D / (\beta \cdot V_D + 1)^{1/n} \tag{17}$$

Assuming again, that n=1 we get the values of central and characteristic lifetime safety factors, which are presented in Table 9. Examples of central and characteristic safety factors for different limit states and reliability calasses in the cases $\nu_D = 0{,}3$ and $\nu_D = 0{,}4$ are presented in Table10. In practice it is recommended to use the characteristic values of the parameters, because they are used also in the static and dynamic calculations.

Table9. Central and characteristic safety factors as function of reliability index and degradation coefficient of variation.

0,35	0,14	2,47	1,89
0,40	0,15	2,68	2,02
0,50	0,16	3,10	2,28
0,60	0,17	3,52	2,53
0,20	0,11	1,76	1,43
0,25	0,13	1,95	1,54
0,30	0,14	2,14	1,65
0,35	0,15	2,33	1,75
0,40	0,16	2,52	1,86
0,50	0,17	2,90	2,08
0,60	0,18	3,28	2,29
0,20	0,12	1,66	1,33
0,25	0,14	1,83	1,41
0,30	0,15	1,99	1,50
0,35	0,16	2,16	1,58
0,40	0,17	2,32	1,66
0,50	0,19	2,65	1,83
0,60	0,20	2,98	1,99
0,20	0,13	1,58	1,25
0,25	0,14	1,73	1,31
0,30	0,16	1,87	1,38
0,35	0,17	2,02	1,44
0,40	0,19	2,16	1,50
0,50	0,20	2,45	1,63
0,60	0,22	2,74	1,75
0,20	0,15	1,30	1,00
0,25	0,18	1,38	1,00
0,30	0,21	1,45	1,00
0,35	0,23	1,53	1,00
0,40	0,25	1,60	1,00
0,50	0,29	1,75	1,00
0,60	0,32	1,90	1,00

Table 10. Central and characteristic safety factors in the cases $V_D = 0,3$ and $V_D = 0,4$. An application of EN1990: 2002.

<table>
<tr><td rowspan="3">Reliability Class/ Consequence Class</td><td rowspan="3" colspan="2">Safety index β</td><td colspan="8">Lifetime safety factor</td></tr>
<tr><td colspan="4">1 year reference period</td><td colspan="4">50 years reference period</td></tr>
<tr><td colspan="2">Central safety factor
γ_0</td><td colspan="2">Characteristic safety factor
γk</td><td colspan="2">Central safety factor
γ_0</td><td colspan="2">Characteristic safety factor
γk</td></tr>
<tr><td colspan="11"><i>Ultimate limit states</i></td></tr>
<tr><td></td><td>1 year reference period</td><td>50 years reference period</td><td>$V_D = 0,3$</td><td>$V_D = 0,4$</td><td>$V_D = 0,3$</td><td>$V_D = 0,4$</td><td>$V_D = 0,3$</td><td>$V_D = 0,4$</td><td>$V_D = 0,3$</td><td>$V_D = 0,4$</td></tr>
<tr><td>RC3/CC3: High consequence for loss of human life, <i>or</i> economic,</td><td>5,2</td><td>4,3</td><td>2,56</td><td>3,08</td><td>2,07</td><td>2,42</td><td>2,29</td><td>2,72</td><td>1,80</td><td>2,06</td></tr>
</table>

social or environmental consequences very great										
RC2/CC2: Medium consequence for loss of human life, *or* economic, social or environmental consequences considerable	4,7	3,8	2,41	2,88	1,92	2,22	2,14	2,52	1,65	1,86
RC1/CC1: Low consequence for loss of human life, *or* economic, social or environmental consequences small or negligible	4,2	3,3	2,26	2,68	1,77	2,02	1,99	2,32	1,50	1,66
Serviceability limit states										
RC3/CC3	No general recommendations. Will be evaluated in each case separately									
RC2/CC2	2,9	1,5	1,87	2,16	1,38	1,50	1,45	1,60	1	1
RC1/CC1	1,5	1,5	1,45	1,60	1	1	1,45	1,60	1	1

5.2.4 The procedure from environmental loadings into limit states

The environmental loadings are described as exposure classes, following the classification of European Standard EN 206-1. The exposure classes of the standard EN 206-1 are presented in Table 11 (copied with the allowance of SFS:Standard body of Finland).

Table 11. Exposure classes of environmental loads and actions onto structures.

Classification

Exposure classes related to environmental actions

The environmental actions are classified as exposure classes in table 1. The given examples are informative.

NOTE The exposure classes to be selected depend on the provisions valid in the place of use of the concrete. This exposur classification does not exclude consideration of special conditions existing in the place of use of the concrete or the applicatio of protective measures such as the use of stainless steel or other corrosion resistant metal and the use of protective coatings fc the concrete or the reinforcement.

The concrete may be subject to more than one of the actions described in table 1 and the environmental condition to which it is subjected may thus need to be expressed as a combination of exposure classes.

Table 1 – Exposure classes

Class designation	Description of the environment	Informative examples where exposure classes may occur
1 No risk of corrosion or attack		
X0	For concrete without reinforcement or embedded metal: All exposures except where there is freeze/thaw, abrasion or chemical attack For concrete with reinforcement or embedded metal: Very dry	Concrete inside buildings with very low air humidity
2 Corrosion induced by carbonation		
Where concrete containing reinforcement or other embedded metal is exposed to air and moisture, the exposure shall be classified as follows: NOTE The moisture condition relates to that in the concrete cover to reinforcement or other embedded metal, but in many cases, conditions in the concrete cover can be taken as reflecting that in the surrounding environment. In these cases classification of the surrounding environment may be adequate. This may not be the case if there is a barrier between the concrete and its environment.		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2

Table 1 (continued)

3 Corrosion induced by chlorides other than from sea water

Where concrete containing reinforcement or other embedded metal is subject to contact with water containing chlorides, including de-icing salts, from sources other than from sea water, the exposure shall be classified as follows:

NOTE Concerning moisture conditions see also section 2 of this table.

XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
XD2	Wet, rarely dry	Swimming pools Concrete exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides Pavements Car park slabs

4 Corrosion induced by chlorides from sea water

Where concrete containing reinforcement or other embedded metal is subject to contact with chlorides from sea water or air carrying salt originating from sea water, the exposure shall be classified as follows:

XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to or on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures

5 Freeze/thaw attack with or without de-icing agents

Where concrete is exposed to significant attack by freeze/thaw cycles whilst wet, the exposure shall be classified as follows:

XF1	Moderate water saturation, without de-icing agent	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with de-icing agent	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
XF3	High water saturation, without de-icing agent	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation, with de-icing agent or sea water	Road and bridge decks exposed to de-icing agents Concrete surfaces exposed to direct spray containing de-icing agents and freezing Splash zones of marine structures exposed to freezing

6 Chemical attack

Where concrete is exposed to chemical attack from natural soils and ground water as given in table 2, the exposure shall be classified as given below. The classification of sea water depends on the geographical location, therefore the classification valid in the place of use of the concrete applies.

NOTE A special study may be needed to establish the relevant exposure condition where there is:
- limits outside of table 2;
- other aggressive chemicals;
- chemically polluted ground or water;
- high water velocity in combination with the chemicals in table 2.

XA1	Slightly aggressive chemical environment according to table 2	
XA2	Moderately aggressive chemical environment according to table 2	
XA3	Highly aggressive chemical environment according to table 2	

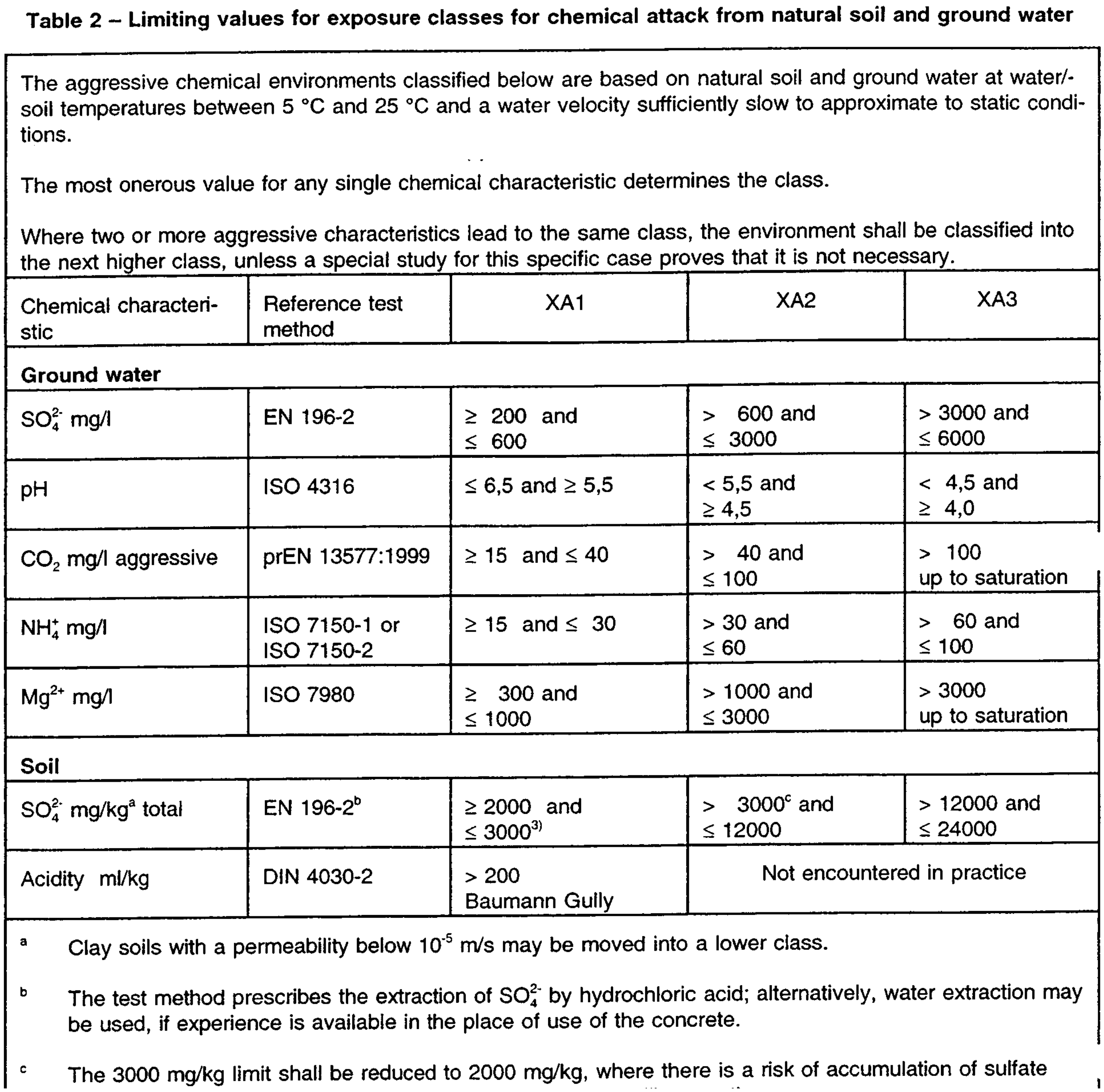


Table 2 – Limiting values for exposure classes for chemical attack from natural soil and ground water

The aggressive chemical environments classified below are based on natural soil and ground water at water/-soil temperatures between 5 °C and 25 °C and a water velocity sufficiently slow to approximate to static conditions.

The most onerous value for any single chemical characteristic determines the class.

Where two or more aggressive characteristics lead to the same class, the environment shall be classified into the next higher class, unless a special study for this specific case proves that it is not necessary.

Chemical characteristic	Reference test method	XA1	XA2	XA3
Ground water				
SO_4^{2-} mg/l	EN 196-2	≥ 200 and ≤ 600	> 600 and ≤ 3000	> 3000 and ≤ 6000
pH	ISO 4316	≤ 6,5 and ≥ 5,5	< 5,5 and ≥ 4,5	< 4,5 and ≥ 4,0
CO_2 mg/l aggressive	prEN 13577:1999	≥ 15 and ≤ 40	> 40 and ≤ 100	> 100 up to saturation
NH_4^+ mg/l	ISO 7150-1 or ISO 7150-2	≥ 15 and ≤ 30	> 30 and ≤ 60	> 60 and ≤ 100
Mg^{2+} mg/l	ISO 7980	≥ 300 and ≤ 1000	> 1000 and ≤ 3000	> 3000 up to saturation
Soil				
SO_4^{2-} mg/kg[a] total	EN 196-2[b]	≥ 2000 and ≤ 3000[3)]	> 3000[c] and ≤ 12000	> 12000 and ≤ 24000
Acidity ml/kg	DIN 4030-2	> 200 Baumann Gully	Not encountered in practice	

[a] Clay soils with a permeability below 10^{-5} m/s may be moved into a lower class.

[b] The test method prescribes the extraction of SO_4^{2-} by hydrochloric acid; alternatively, water extraction may be used, if experience is available in the place of use of the concrete.

[c] The 3000 mg/kg limit shall be reduced to 2000 mg/kg, where there is a risk of accumulation of sulfate

A summary of actual degradation factors, processes and performance limit states for design as well as for maintenance and repair planning for durability is presented in Table 12 [8].

Table 12. Typical durability related performance limit states of concrete structures [8].

Degradation factor	Process	Degradation	Limit states	
			Serviceability	Ultimate
Mechanical				
Static loading	Stress, strain, deformation	Deflection, cracking, failure	Deflection Cracking	Failure
Cyclic or pulsating loading	Fatigue, deformation	Reduced strength, cracking, deflection, failure	Deflection Cracking	Fatigue failure
Impact loading	Peak loading, repeated impact, mass forces	Increase of load vibration, deflection, cracking, failure	Deflection, cracking, vibration	Failure
Physical				
Temperature changes	Expansion and contraction	Shortening, lengthening, cracking at restricted deformation	Surface cracking, surface scaling	
Relative Humidity (RH) changes	Shrinkage, swelling	Volume changes, shortening and lengthening, surface cracking, surface scaling, structural cracking in case of restricted deformation	Surface cracking, surface scaling, structural cracking	
Freezing - melting cycles	Ice formation, ice pressure, swelling and shrinking	Cracking, disintegration of concrete	Surface cracking, surface scaling, strength weakening	Decrease of ultimate capacity
Combined de-icing – freezing – melting cycles	Heat transfer, salt induced swelling and internal pressure	Cracking of concrete, scaling of concrete	Surface cracking, surface scaling	
Floating ice	Abrasion	Cracking, scaling	Surface cracking, surface scaling, surface abrasion	
Traffic	Abrasion	Rutting, wearing, tearing	Surface abrasion	
Running water	Erosion	Surface damage	Surface abrasion, surface scaling	
Turbulent water	Cavitation	Caves	Surface scaling, weakening of concrete	Decrease of ultimate capacity

Degradation factor	Process	Degradation	Limit states	
Chemical				
Soft water	Leaching	Disintegration of concrete	Surface abrasion, surface cracking, surface scaling	
Acids	Leaching, Neutralisation of concrete	Disintegration of concrete, depassivation of steel	Surface abrasion, surface cracking, surface scaling, steel corrosion	Decrease of ultimate capacity
Carbon dioxide	Carbonation of concrete	Depassivation of steel	Steel corrosion	Decrease of ultimate capacity
Sulphur dioxide	Sulfate reactions, formation of acids	Disintegration of concrete	Surface cracking, surface scaling, weakening of concrete	Decrease of ultimate capacity
Nitrogen dioxide	Formation of acids	Disintegration of concrete	Surface cracking, surface scaling, weakening of concrete	Decrease of ultimate capacity
Chlorides	Penetration, destruction of passive film of steel	Depassivation of steel, stress corrosion of steel	Steel corrosion, secondary effects: surface cracking, surface scaling	Decrease of ultimate capacity
Oxygen + water	Corrosion of depassivated steel	Loss of cross sectional area of reinforcing steel, internal pressure in concrete due to expansion of steel, weakening of the steel surface	Surface cracking, surface scaling, aesthetic colour changes of surface	Decrease of ultimate capacity due to loss of cross section area of steel and loss of bond between reinforcing steel and concrete
Sulphates	Crystal pressure	Disintegration of concrete	Cracking, scaling, weakening of concrete	Decrease of ultimate capacity
Silicate aggregate, alkalis	Silicate reaction	Expansion, disintegration	Cracking, scaling, weakening of concrete	Decrease of ultimate capacity
Carbonate aggregate	Carbonate reaction	Expansion, disintegration	Cracking, scaling, weakening of concrete	Decrease of ultimate capacity

Degradation factor	Process	Degradation	Limit states	
Biological				
Micro-organisms	Acid production	Disintegration of concrete, depassivation of steel	Surface abrasion, surface cracking, surface scaling, steel corrosion	Decrease of ultimate capacity
Plants	Penetration of roots into concrete	Internal pressure, growing micro-organisms	Surface cracking, surface scaling	
Animals	Mechanical surface loading	Abrasion	Surface abrasion, surface scaling	
People	Painting of surfaces, impact and abrasion loading of surfaces	Penetration of colours into pores, abrasion	Aesthetic change of surface, scaling of surface	

A designer must determine which degradation factors are decisive for service life. Preliminary evaluations of rates of degradation for different factors may be necessary. The models presented in the report may be applied in these evaluations.

The following degradation factors are dealt with [8]:

1. corrosion due to chloride penetration
2. corrosion due to carbonation
3. mechanical abrasion
4. salt weathering
5. surface deterioration
6. frost attack

Additionally there exist some internal degradation processes, such as alkaline-aggregate reaction, but they are not treated here as they can be solved by a proper selection of raw materials and an appropriate design of concrete mix.

Degradation factors 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:

1. Loss of concrete leading to reduced cross-sectional area of the concrete.
2. Corrosion of reinforcement leading to reduced cross-sectional area of steel bars.

Corrosion may occur at cracks 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.

5.2.5 Application of factor method into environmental loads

The classifications, which are described above, do not always directly show the impact of the environmental loads in quantity. The method of ISO standard ISO/DIS 15686-1 can be applied in calculating the service life (design life) in specific conditions [5]. This method is called in ISO/DIS 15686-1 "The factor method". The factor method includes the following factors:

- A: quality of components
- B: design level
- C: work execution level
- D: indoor environment
- E: outdoor environment
- F: in-use conditions
- G: maintenance level

Estinated service life (ESLC) is calculated with the equation:

ESLC = RSLC x factorA x factorB x factorC x factorD x factorE x factorF x factorG

where RSLC is the Reference service life.

For the purpose of reliability based durability design this is applied in the form:

$$t^*_{Ld} = D \, x \, E \, x \, t_{Ld} \qquad (18)$$

where t^*_{Ld} is the modified design life

D the indoor environmental load intensity factor

E the outdoor environmental load intensity factor

The reference service life is a documented period in years that the component or assembly can be expected to last in a reference case under certain service conditions. It may be based on:

- service life calculation models, which are described above
- data basing on experiments, experiments, theoretical calculations or combinations of these; provided by a manufacturer, a test house or an assessment regime; building codes may also give typical service life of components

The modifying factors: the indoor environmental load intensity factor D, and the outdoor environmental load intensity factor E, are in some cases included in service life models. This is the case in most of the Lifecon/Probabilistic service life models (Lifecon Deliverable 3.2) and Lifecon/RILEM TC130 CSL (Lifecon Deliverable D2.1) models.

The factor D is a deviation from assumed indoor conditions. Often, especially in buildings, the indoor environmental load is very small, and must not be calculated. For example in factories the environmental load can be even extremely high, for example because of acids or other chemicals, which are emmissioned from the chemical processes.

The factor E means usually the environmental load of local level, but also the load of structural level, for example the direction of the surface (horizontal/vertical/inclined), the point of compass (often South is more loading), salt-spray zone etc.. Factor E can be used also for combination of environmental loads (e. g. combination of wetting and freezing).

Usually the values of the factors are either =1, or vary between 0,8 and 2. In extreme conditions the values can be even higher.

5.2.6 Degradation models

The damages are determined using the design life, t_{Ld}, as time. Selected calculation models are presented in the appendix of the TC 130-CSL report [8].

A designer must determine which degradation factors are decisive for service life. Preliminary evaluations of rates of degradation for different factors may be necessary.

In Lifecon system the following three groups of degradation models are presented in separate reports:

1. "Probabilistic service life models": Lifecon deliverable D3.2: *"Instructions on methodology and application of models for the prediction of the residual service life for classified environmental loads and types of structures in Europe."*
2. "RILEM TC 130 CSL models": [[Lifecon D2.1]/(*Sarja and Vesikari (Editors), 1996) [8]: "Durability Design of Concrete Structures."*
3. "Reference structure method": [Lifecon D2.2]: *"Statistical condition management and financial optimisation in lifetime management of structures."*

Characteristic properties of these models are as follows:

- "Probabilistic service life 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 "Probabilistic service life models" 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 method" 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 on the compatibility of entire chain of the procedure of reliability calculations.

Main criteria in selecting the degradation model for each specific use are e. g.:

- availability of statistical data of variables of each model
- availability of data or testing method for the coefficients of each model

- accuracy of the model when using the available data in relation to the required accuracy level
- costs of IT tools and the work in calculations.

Some of these criteria can be evaluated roughly beforehand, but often some comparative test calculations are needed.

5.2.7 Calculation procedure and phases of this process

General phases of the service life and durability are as follows:

1. specification of the target service life and design service life
2. analysis of environmental effects
3. identification of durability factors and degradation mechanisms
4. selection of a durability calculation model for each degradation mechanism
5. calculation of durability parameters using available calculation models
6. possible updating of the calculations of the ordinary mechanical design
7. transfer of the durability parameters into the final design

The phases are presented as a schedule in figure 7. [8].

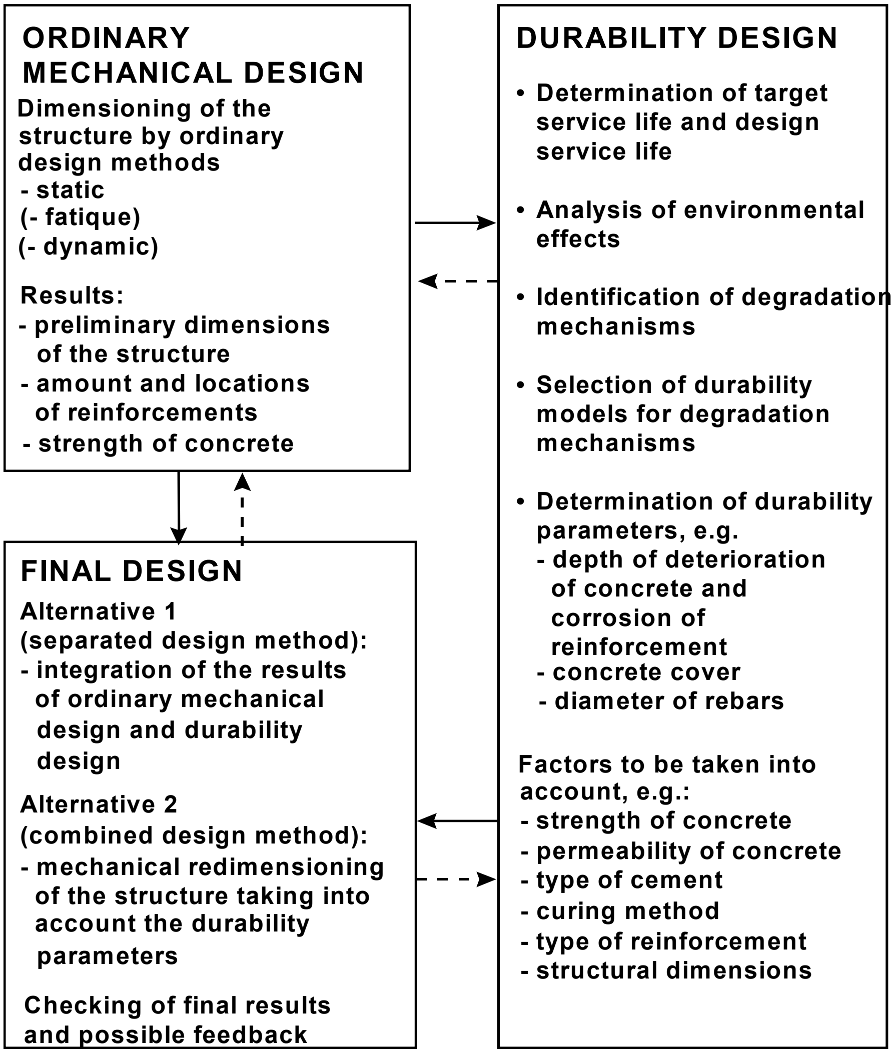


Fig 7. Flow chart of the durability design procedure [8].

The content of the phases of durability design procedure is as follows :

Phase1: Specification of the design life

The design life is defined corresponding to the requirements given in common regulations, codes and standards in addition to possible special requirements of the client. Typical classes of design life are 10, 25, 50, 75, 100 etc. years. The safety classification of durability design is presented in Table 3.

The calculated design life is compared with the required design life (also called target service life) is with formula:

$t_{Ld} = {}^{\mu}t_L \; / \; \gamma t_0 \geq$ design life (required service life) (19a)

or

$t_{Ld} = t_{Lk} \; / \gamma tk \geq$ required service life

Applying the environmental load intensity factors [5] of equation 18 we get the final result:

$$t^*_{Ld} = D \times E \times t_{Ld} \tag{19b}$$

where t_{Ld} is design life

μ_{t_L} calculated or experimental mean value of the service life

$t_{L\,k}$ calculated or experimental characteristic value of the service life (5% fractile)

γ_{t_0} central lifetime safety factor

γ_{tk} characteristic lifetime safety factor

t^*_{Ld} modified design life

D Indoor environmental load intensity factor

E Outdoor environmental load intensity factor

In some cases the environmental intensity factors are included in service life models. This is the case in most of the the Lifecon/Probabilistic service life models (Lifecon Deliverable 3.2) and Lifecon/RILEM TC130 CSL (Lifecon Deliverable D2.1) models.

Phase 2: Analysis of environmental loads

The analysis of environmental effects includes identification of the climatic conditions such as temperature and moisture variations, rain, condensation of moisture, freezing, solar radiation and air pollution, and the identification of geological conditions such as the location of ground water, possible contact with sea water, contamination of the soil by aggressive agents like sulphates and chlorides. Man-made actions such as salting of roads, abrasion by traffic etc. must also be identified.

Phase 3: Identification of degradation factors and degradation mechanisms

Based on the environmental effect analysis the designer identifies the degradation factors to which the structure will most likely be subjected. Some kind of degradation process is usually assumed to take place in both the concrete and the reinforcement.

Phase 4: Selection of durability models for each degradation mechanism

A designer must determine which degradation factors are decisive for service life. The models presented in the report may be applied in these evaluations. In *concrete structures exposed to normal outdoor conditions* the effects of degradation mechanisms can be classified into the following structural deterioration mechanisms:

1. Corrosion of reinforcement at cracks, causing a reduction in the cross-sectional area of steel bars.
2. Surface deterioration or frost attack, causing a reduction in the cross-sectional area of concrete.

Phase5: Calculation of durability parameters through calculation models

Damage is determined using the design life, t_{Ld}, as time. Selected calculation models are presented in the appendix of the TC 130-CSL report (*Sarja and Vesikari, 1996*).

Phase 6: Possible updating of calculations in ordinary mechanical design

Some durability parameters may influence the mechanical design. An increase in concrete dimensions, increases the dead load, thus increasing the load effects on both the horizontal and vertical structures.

Phase 7: Transfer of durability parameters to the final design

The parameters of the durability design are listed and transferred to the final design phase for use in the final dimensioning of the structure.

Phase 8: Final design

The mechanical design and the durability design are separated. The ordinary structural design (phase1) produces the mechanical safety and serviceability parameters whereas the durability design (phase 2) produces the durability parameters. Both of these groups of parameters are then combined in the final design of the structure.

EXAMPLE

Setting up the design problem

The beam presented in Fig 8. is presented as an example on durability design calculations *(Sarja&Vesikari (editors), Durability design of concrete structures, 1996)* [8]. This presentation is modified, corresponding to the modifications, which have been done later *(Sarja 2000, 2001 and 2002)*[1,13,4]

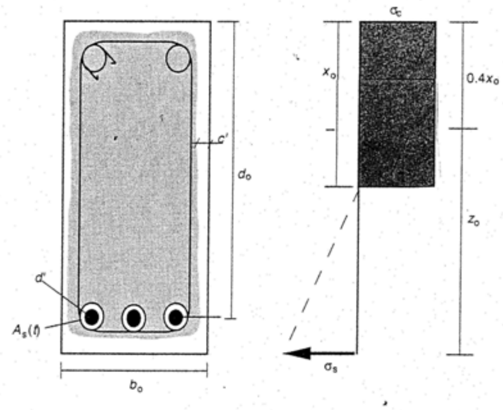


Fig 8. Beam of the example design calculations.

The beam is to be designed for the following loads:

$Mg = 10 + 0.1 \cdot d$ kNm (d in mm)

$Mp = 50$ kNm

The cross-section of the beam is assumed to be rectangular with the width of b (≈ 300 mm) and efficient height d. At the lower edge of the beam are three steel bars. The yield strength of steel is 400 MPa· The characteristic compressive strength is 40 MPa, the air content is 2% (not air-entrained), and the binding agent is Portland cement.

The beam is supposed to be maintenance free so that the corrosion of steel bars in the assumed cracks or the degradation of the concrete cover will not prevent the use of the column during its service life. The cross-section of hoops (stirrups) must not be completely corroded at cracks. The concrete cover must be at least 20 mm after the service life and the cover must not be spalled off because of general corrosion.

Ordinary mechanical design

The ordinary mechanical design of the beam is performed using traditional design principles:

$$R_d \geq S_d \tag{20}$$

$$S_d = \gamma_g \cdot M_g + \gamma_p \cdot M_p \tag{21}$$

$$R_{ds} = A_s\ z\ f_y / \gamma_s \text{ (the stress of steel is decisive)} \tag{22}$$

$$R_{dc} = b\ x\ z\ f_c / (2\ \gamma_c) \text{ (the stress of concrete is decisive)} \tag{23}$$

$$x = d\ \mu\ n\ (-1 + \mathrm{SQR}\ (\ 1 + 2/(\mu\ n))\ ) \tag{24}$$

$$z = d - 0.4\ x \tag{25}$$

$$n = E_s / E_c$$

$$\mu = \frac{A_s}{b\ d} = \frac{N_s\ \pi\ D^2/4}{b\ d} \tag{26}$$

A_s is the cross-sectional area of steel bars:

$$A_s = 3 \cdot \pi \cdot D^2/4 \tag{27}$$

Taking D = 15 mm we get:
$A_s = 530\ mm^2$

By setting R_{ds} equal to S_d we get:

d = 2083 mm

However, increasing the diameter of the steel bars quickly reduces the efficient height. By replacing D = 20 mm we get:
$A_s = 942\ mm^2$
d = 543 mm

Durability design

The design life (target service life) is 50 years. The central lifetime safety factor is assumed to be 3.3. Thus the mean service life, t_0, is 165 years.

We apply the degradation model of corrosion degradation [8], as presented in Appendix 2.

All sides of the beam are assumed to be exposed to frost action. The environmental factor for frost attack, c_{env}, is 40 and the anticipated curing time is 3 days.

The curing factor is:

$$c_{cur} = \frac{1}{0.85 + 0.17 \cdot \log_{10}(3)} = 1.074 \qquad (28)$$

As concrete is made of Portland cement we conclude:
$c_{age} = 1$

Inserting these values into Formula 17 of Appendix 2 we get:

$$c' = 0.117 \cdot t \text{ (mm)} \qquad (29)$$

At the same time corrosion is occurring in steel bars at cracks. The rate of corrosion is evaluated as 0.03 mm/year:

$$d' = 0.03\ t \text{ (mm)} \qquad (30)$$

The durability design parameters are as follows (depending on the design service life):

Separated design method (t_d = 50 years, t_0 = 165 years):
The depth of deterioration:
$c' = 0.117 \cdot 165 = 19.3$ mm
The required concrete cover is:
$C_{min} = 20 + 19.3$ mm $= 39.3$ mm
We choose C = 40 mm
The depth of corrosion at cracks:
$d' = 0.03 \cdot 165 = 5.0$ mm
The diameter of hoops must be at least:
$D_{hmin} = 2 \cdot 5.0$ mm $= 10.0$ mm
We choose D_h = 10 mm.

The corrosion cracking limit state time of the concrete cover is then checked. The following values of parameters are inserted into the formula:
C = 40 mm (separated design method) or 35 (combined design method)
$C_h = C - D_h = C - 10$ mm
f_{ck} = 40 MPa
c_{env} = 1
c_{air}= 1
D_h = 10 mm
r = 12 μm

By the separated method we get t_0 = 165 years, which equals to the design life (50 years). So the concrete cover of 40 mm is adequate. So the concrete cover (35 mm) is increased to 40 mm. Then the design life is 50 years which fulfils the requirement.

Final design

Separated design method:

The width of the beam at the beginning of service life is twice the deterioration depth of concrete added to the width obtained in the ordinary design:

$b_o = b + 2 \cdot b' = 300 + 2 \cdot 19.3 = 339$ mm

The effective height of the beam is increased by the depth of deterioration:

$d_o = d + b' = 543 + 19.3$ mm $= 562$ mm

The minimum diameter of the steel bars is:
$D_{omin} = 20 + 2 \cdot 5.0$ mm $= 30.0$ mm
We choose $D_o = 30$ mm

5.3 Reliability requirements of existing structures

5.3.1 Design life

In MR&R planning the design life periods of EN 1990-2002 can be basically applied. However the total design life has to be prolonged in case of old structures. This leads to a new term: “Residual design life”. The residual design life can be decided case by case, but it is usually the same or shorter than the design life of new structures. The residual design life can be optimised using Multiple Attribute Decision Making procedure. Proposed values of design life for MR&R planning are presented in table 8.

5.3.2 Reliability requirements for service life

The reliability requirements for service life are different from the requirements for structural safety in mechanical limit states. Therefore it is recommended to use for mechnical safety the safety indexes of EN 1990-2002 as presented in table 8, and for corresponding reliability classes the safety indexes of service life in durability limit states and in obsolescence limit states as presented in table 13.

It is important to notice, that in each case of durability and obsolescence limit states, in addition the safety of mechnical (static, dynamic and fatigue) limit states has to be checked separately. Therefore the loss of human lives has not been mentioned in table 13, but it is mentioned in the reliability index requirements in table 8.

Because durability works in interaction with structural mechanical safety, the recommended reliability indexes of durability service life are close to the level of requirements for mechanical safety. The obsolescence does not usually have direct interaction to the structural mechanical safety, why the safety index recommendations are lower. The mechanical safety requirements of table 8 have to be checked separately always in cases when obsolescence is caused by insufficient mechanical safety level in comparison to increased loading requirements, or increased safety level requirements.

The required lifetime safety coefficients of durability limit states and obsolescence limit states can be found from table 9 using the safety indexes of table 13. For the safety index 1,5 the lifetime safety factor is 1. This means, that the characteristic service is directly applied as design life.

Table 13.Recommended minimum values for reliability index β (eq. 5) in ultimate limit states and in serviceability limit states of durability and obsolescence.

Reliability Class of structures	**Minimum values for reliability index β**			
	Durability limit states		**Obsolescence limit states**	
	Ultimate limit states	Serviceabilility limit states	Ultimate limit states	Serviceabilility limit states
RC3/CC3: High consequence for loss of human life, *or* economic, social or environmental consequences very great	4,7	3,3	3,3	1,5
RC2/CC2: Medium consequence for loss of human life, *or* economic, social or environmental consequences considerable	4,3	1,5	1,5	1,5
RC1/CC1: Low consequence for loss of human life, *or* economic, social or environmental consequences small or negligible	3,3	1,5	1,5	1,5

6 Performance under obsolescence loading

6.1 Principles

Obsolescence means the inability to satisfy changing functional (human), economic, cultural or ecological requirements. Obsolescence can affect the entire building or civil infrastructure facility, or just some of its modules or components.

The obsolescence analysis and control is aiming to guarantee the ability of the buildings and civil infrastructures to maintain the ability to meet all current and changing requirements with minor changes of the facilities. Lifetime design aims at minimising the need of early renewal or demolition.

Obsolescence is a real world problem, which is coming from everyday world of events and ideas, and may be perceived differently by different people. These can not often be constructed by the investigators as the laboratory problems ((degradation or static and dynamic stability) can be. As there is no direct threat to human life resulting from obsolescence, there are no set limits for obsolescence. Neither is there international or national normative standards concerning the issue. The responsibility to deal with obsolescence is thus left to the owners of the facilities. Consequently, when there are no standards or norms to follow, the decisions (corporate strategic, MR&R, etc.) are readily made on economic grounds only, which too often leads to premature demolishing of sound facilities. It has been estimated that about 50 % of all demolishing cases concerning buildings and civil infrastructures are due to obsolescence. In case of modules or component renewals the share of obsolescence is still higher.

Although analogy between the limit states of statics and dynamics, degradation and obsolescence can be found (see table 4), the nature of obsolescence problem is *philosophically* different from the two others. While in the first two cases the limit states are reached because some real loads (e.g. environmental loads, live loads, etc.) are acting on the structure, in the obsolescence case there are no *actual tangible* loads causing the crossing of limit states. Instead, the obsolescence loading can be defined as the development of the society around the still-standing structure. This development that causes obsolescence includes human requirements, functional, economic, ecological and cultural changes. Behind these changes is the entire social, economic, technological and cultural change of the society. Some examples of different types of obsolescence are listed below.

- Functional obsolescence is due to changes in functions and use of the building or its modules. This can even be when the location of the building becomes unsuitable. More common are changes in use that require changes in functional spaces or building services systems. This raises need for flexible structural systems, usually requiring long spans and minimum numbers of vertical load bearing structures. Partition walls and building services systems which are easy to change are also required.
- Technological obsolescence is typical for building service systems, but also the structure can be a cause when new products providing better performance become available. Typical examples are more efficient heating and ventilation systems and their control systems, new information and communication systems such as computer networks, better sound and impact insulation for floorings, and more accurate and efficient thermal insulation of windows or walls. Health and comfort of internal climate is the requirement which is increased in importance. The risk of technological obsolescence can be avoided or reduced by estimating future technical development when selecting products. The effects of technical

obsolescence can also be reduced through proper design of structural and building service systems to allow easy change, renewal and recycling.

- Economic obsolescence means that operation and maintenance costs are too high in comparison to new systems and products. This can partly be avoided in design by minimising the lifetime costs by selecting materials, structures and equipment which need minimum costs for maintenance and operation. Often this means simple and safe products that are not sensitive to defects and or their effects. For example, monolith external walls are safer than layered walls.
- Cultural obsolescence is related to the local cultural traditions, ways of living and working, aesthetic and architectural styles and trends, and imago of the owners and users.
- Ecological obsolescence happens often in case of large infrastructural projects. In large projects this is often related to high waste and pollution production or loss of biodiversity. In case of buildings we can foresee in the future problems especially in the use of heating and cooling energy, because heating and cooling is producing for example in Northern and Central Europe about 80 to 90 % of all CO_2 pollution and acid substances into air.

The final objective of obsolescence analysis and optimisation is to reduce demolishing of facilities that have not reached their mechanical (static or dynamic) or durability ultimate limit states, and thus to promote the sustainable development.

6.2 Obsolescence analysis and decision making

6.2.1 Elements of obsolescence analysis

The obsolescence analysis can be divided into three elements:

1. Meaning of obsolescence
2. Factors and causes of obsolescence
3. Strategies and decisions on actions against obsolescence

Meaning of obsolescence

In this part of the analysis - when kept on general level - the owner should ask him/herself, what does the obsolescence really mean with the type of facility in question (bridge, tunnel, wharf, lighthouse, cooling tower, etc.). Before the obsolescence can be made a subject of a deeper study, it must be clearly defined. The task can be facilitated with appropriate questions like:

- How do the different types of obsolescence (functional, technical, social...) show? What are the problems caused by obsolescence? Who suffers (and how) because of obsolescence? (users, owner, environment..?)
- Are there commonly accepted limit states for these different types of obsolescence? If not, how is obsolescence defined? Is the definition a result of a cost-benefit study? Or is the pressure from the public or authorities pushing hard and setting limits, etc? What should the obsolescence limit states be for the facility type in question, and what other viewpoints than just the economic ones should be taken into consideration when defining obsolescence limit states? Who defines the obsolescence limit states? What are the obsolescence indicators?
- Is there data from the past available? What kind of data banks, sources of information or resources are there available for a deeper analysis? Does the decision-maker (facility manager, management team, etc.) have a *comprehensive picture* (including also societal approach, not just technical) of the obsolescence problem?

- Etc.

Of course this part of the analysis is a lot easier if the owner has documented examples of obsolescence cases in his/her facility stock. In any case, the previous task and its results should be duly documented.

Factors and causes of obsolescence

In this part of the obsolescence analysis the possible causes for the different obsolescence types are sought after. This part follows straightforwardly the risk analysis procedure presented in deliverable D2.3, where the causes of adverse incidents - i.e. so called *top events* - are revealed using fault tree analysis. In the obsolescence analysis these top events mean the obsolescence indicators of different obsolescence types. The reader is referred to the deliverable D2.3 for detailed description of the procedure.

The factors and causes of obsolescence can be physical needs, e.g. increased traffic on the route where the bridge is located, new type of ships that cannot dock to the existing wharf, etc. Many times the obsolescence causes can be traced to promulgation of new standards (that require for example stricter sound insulation in floors, etc. Although normally the existing facilities are exempted of these requirements, there will be pressure to follow the new standards). The factors can be fashion-originated: the existing façade of a building looks grim, the building is not located in "the right part of the city", etc.

Although it is obvious that the top-level cause of obsolescence is the general development of society (technological, cultural etc.), it must in this part of the analysis be studied in deeper level. In ideal case the facility owner would become aware of the reasons behind trends, new norms and standards, migration, employment policy and all possible societal causes that have effect on the use of the facilities. After having these factors on hand it is much easier for facility owner to estimate the direction of the general development and plan the future actions for the facility. But as mentioned earlier, this requires quite comprehensive touch to the whole process of facility management, and the resources may be scarce in many organisations.

Strategies and decisions on actions against obsolescence

When the obsolescence indicators of possible obsolescence types and their causes for the facilities are identified, the owner should try to find actions to avoid or defer obsolescence. These actions generally have the purpose of minimising the impacts of obsolescence by anticipating change, or accommodating changes that cause obsolescence before the costs of obsolescence become substantial.

Although obsolescence is best fought *before* entering the operations and maintenance phase in the life cycle of a facility, something can be done to minimise obsolescence costs also when dealing with existing structures. Good maintenance practices have the same effect in maintenance phase as quality assurance in construction phase, enhancing the likelihood that performance will indeed conform to design intent. Training of maintenance staff, preparation and updating of maintenance manuals and use of appropriate materials in maintenance activities contribute to avoiding the costs of obsolescence. Existing and new computer-assisted facility management systems that support condition monitoring, document management and maintenance scheduling, should be able to provide useful information that can help the facility manager to detect problems that could presage obsolescence. An idea of multidimensional "obsolescence index" has been presented as target for research, but so far this issue has been staying on theoretical level.

The obsolescence studies and discussions have concentrated on buildings and on the business inside the building, like schools, hospitals, office or industrial buildings. In these cases the location, inner spaces etc. have great impact on the possible obsolescence, as the use of building can change radically when the tenant or owner changes. The possible strategies include post occupancy evaluation and report cards to achieve performance approaching the optimum of the facility, adaptive reuse, shorter terms for leasing and cost recovery calculations, etc. Often the strategy with obsolescence is "making-do", which means finding low-cost ways to supplement performance that is no longer adequate. Normally making-do is a short-term strategy with high user costs, leading eventually (after high complaint levels, loss revenue, loss of tenants, etc.) to refurbishment of the facility [12].

However, with infrastructure facilities - on which Lifecon is focusing, like bridges, tunnels, wharves, lighthouses, etc. - the situation is not the same, as these facilities normally are already located in the most optimal place to serve that one certain business they were built for. Normally this business (for example port activities, passing traffic through or over obstacles etc.) cannot be totally halted, so the demolishing of obsolete but otherwise sound facility and construction of a new one is not common nor wise solution. One traditional solution (especially with bridges) has been to build a new facility near the old one and keep the old one for lesser service.

6.2.2 Limit states

In order to make possible the analysis of obsolescence, the obsolescence itself must be defined. For that definition limit states are needed. While in stability and durability analyses of structures there appear clear signs *in* the facility when limit states are reached (ruptures, cracks, spalling, corrosion, deflections, vibration, etc.), with obsolescence the case is not that simple. The signs about obsolescence are normally found *outside* of the facility (loss of revenue, complaints from users, traffic jams, increased maintenance costs etc.). The decision when those *obsolescence indicators* have increased excessively, meaning that the limit states have been reached, is difficult and in most cases organisation-specific. However, some qualitative limit states of obsolescence can be defined on generic level. These are presented in table 14.

Table 14. Functional level usability limit states of obsolescence of structures.

Reason of limit state	**Serviceability limit state**	**Ultimate limit state**
1. Human requirements		
Functional usability	Weakened functional usability	Total loss of functional usability
Convenience of use	Weakened convenience	
Healthiness of use	Minor health problems in use	Severe health problems in use
Safety of operation	Weakened safety of operation	Severe problems in safety of operation
2. Economic requirements		
Economy of operation	Weakened economy in operation	Total loss of economy in operation
Economy of MR&R	Weakened economy in MR&R	Total loss of economy in MR&R
3. Cultural requirements		
Cultural requirements of the society	Minor problems in meeting cultural requirements	Severe problems in meeting defined cultural requirements
4. Ecological requirements		
Requirements on the economy of nature: - Consumption of raw materials, energy and water - Pollution of air, waters and soil - Waste production - Loss of biodiversity	- Minor problems in meeting requirements of owners, users and society - Minor environmental problems	- Total loss of meeting the most severe requirements of society - Severe environmental problems

As can be seen in table 14, the difference between service limit state and ultimate limit state in obsolescence analysis is a question of interpretation. For example, there exists no standardised definition for "minor problems" or "severe problems", but they are organisation-specific matters. The obsolescence indicators are the same for service and ultimate limit states, but in ultimate limit state they are just stronger than in service limit state. Using analogy with the traditional static and dynamic limit states definitions, one can come to conclusion that **the *ultimate limit state in obsolescence means that there is no recovery from that state without heavy measures while in service limit state minor actions can return the situation to the pre-obsolete state***. In the traditional static and dynamic analysis reaching the ultimate limit state means permanent deformations in the structure, while in the service limit state the deformations are not permanent.

To proceed in the obsolescence analysis, the generic level limit states of table 14 must be converted into more specific and tangible descriptions. In this conversion the facility type has a decisive role, because the specific obsolescence indicators and their reasons vary a lot depending on the facility type (for example, traffic jam is obviously a bridge-related obsolescence indicator, but cannot be used for lighthouses). In table 15 some obsolescence indicators for two different facility types are listed, categorising also the obsolescence type.

Table 15. Obsolescence indicators for different obsolescence types.

	Functional and human	**Economic**	**Ecological**	**Cultural**
Bridge	- service capability of the bridge or network of bridges in the actual global, regional or local logistic system not adequate - weak capability to transmit the current traffic - weak bearing capacity for present traffic loads - low height for under-going road or water-borne traffic - heavy noise from traffic on bridge - heavy degradations cause uneasiness for users	- high costs for users because of traffic jams - high operation costs (e.g. bascule bridge) - high MR&R (Repair, Rehabilitation and Maintenance) costs	- high production of environmental burdens because of traffic jams - high production of environmental burdens because of need for the use of by-pass roads - high production of environmental burdens because of highly increasing MR&R works - robust intermediate piers and long approach embankments impede free flow of water	- the imago of the bridge does not meet the local imago goals - the bridge is preserved as a cultural monument without adequate possibilities for changes - heavy abutments and intermediate piers block the free view of the under-going roadway users
Building	- the changeability of spaces not enough for the actual or future needs - the accessibility not adequate - not adaptable for modern installations - the quality of internal air does not meet actual health requirements - the emissions from materials cause danger for health - lighting does not meet the requirements of living or working - the living or working comfort does not meet present day requirements	- too high energy costs - too high operation costs - potential residual service life too short in comparison to required repair or rehabilitation cost	- the energy efficiency does not meet the current requirements of owners, users or society - high production of environmental burdens because of highly increasing MR&R works	- the spaces are not adaptable for the current ways of living or working - the architectural quality does not meet the local actual requirements - building does not reflect the imago that user wants to give

6.2.3 Methods for obsolescence analysis and decision making

Although obsolescence is increasing in importance, no standards addressing obsolescence of civil infrastructure or building facilities have been enacted so far. Principled strategies and guidelines for dealing with obsolescence have been presented [5, 12] but the real analysis methods have not been applied. As obsolescence progress of a facility depends on the development of local conditions, as well as on the general development of society during the service life (or residual service life) of a facility, there is lot of uncertainty involved in obsolescence analyses. Like in any uncertainty-filled problem, also in obsolescence situation the case must be structured down to smaller parts, which can be consistently handled. It must be noted that he *obsolescence avoidance thought* should be present in all life cycles of the facility: planning and programming; design; construction; operations, maintenance and renewal; retrofitting and reuse. The obsolescence analysis should be performed before the onset of obsolescence, as a part of the facility owning and management strategy.

The following methods can be applied in obsolescence analysis:

- Quality Function Deployment method (QFD) [Lifecon Deliverables D2.3 and D5.1]
- Life Cycle Costing method (LCC) [Lifecon Deliverable D5.3]
- Multiple Attribute Decision Aid (MADA) [Lifecon Deliverable D2.3]
- Risk Analysis (RA) [Lifecon Deliverable D2.3]

6.2.4 QFD in obsolescence analysis and decision making

Quality Function Deployment method QFD can be used for interpreting any "Requirements" into "Specifications", which can be either "Performance Properties" or "Technical Specifications" [Lifecon Deliverable D2.3].

Thus QFD can serve as an optimising or selective linking tool between:

- changing "Requirements"
- actual and predicted future "Performance Properties" and
- actual and predicted future "Technical Specifications"

of facilities.

In the obsolescence issues QFD can be used for optimising the "Technical Specifications" and/or "Performance Properties" in comparison to changing "Requirements" and their changing ranking and weights. These results can be used for selection between different design, operation and MR&R alternatives for avoiding the obsolescence.

Simply 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, why the Performance Properties often are 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 many efforts for secondary factors.

The following procedure can be applied in LIFECON LMS when using QFD for analysis of functional requirements against owner's and user's needs, technical specifications against functional requirements, and design alternatives or products against technical specifications:

1. Identify and list factors for “What” and “How”
2. Aggregate the factors into Primary Requirements
3. Evaluate and list priorities or weighting factors of “What`s”
4. Evaluate correlation between “What`s” and “Hows”
5. Calculate the factor: correlation times weight for each “How”
6. Normalise the factor “correlation times weight” of each “How” for use as a priority factor or weighting factor of each “How” at the next steps

The obsolescence analysis and decision making procedure includes two steps:

1. Define the individual "Requirements" corresponding to alternative obsolescence assumptions
2. Aggregate the individual "Requirements" into "Primary Requirements"
3. Define the priorities of "Primary Requirements" of the Object for alternative obsolescence assumptions
4. Define the ranking of alternative solutions for avoiding the obsolescence. One of these solutions is the demolition
5. Select between these alternatives using the priorities from step 1
6. Decide between the alternative solutions for avoiding the obsolescence, or demolishing the facility.

The QFD method is described in more details in Lifecon Deliverable D2.3, and applied into MR&R planning in Lifecon Deliverable D5.1.

6.2.5 LCC in obsolescence analysis and decision making

Life cycle costing LCC can be effectively used in obsolescence analysis and decision-making between alternative obsolescence avoidance strategies and actions. It can be either alone, focusing on economic obsolescence options, or one part of the multiple analysis and decision-making, connected to other methods: QFD, MADA or FTA.

The methodology of LCC in this connection is the same as presented for general MR&R planning and decision making in Lifecon Deliverable D5.3. In obsolescence issues the alternatives are different obsolescence options, and alternative strategies and actions for avoiding the economic obsolescence.

Because economic obsolescence usually is only one of several categories of obsolescence, beside LCC also other methods: QFD, MADA or FTA is applied as mentioned above.

6.2.6 MADA in obsolescence analysis and decision making

Multiple Attribute Decision Aid MADA method is described in detail in Lifecon Deliverable D2.3.

In order to “measure” the influence of obsolescence factors and options into the ranking and choice between alternative strategies and actions for avoiding obsolescence, the method of sensitivity analysis of MADA can be applied.

Sensitivity analysis with Monte-Carlo simulation consists then in four steps (Fig 9.):
1. Random assessment of the weights or alternatives assessments simulating small variations (e.g. ±5%, ±10% ...)
2. Application of the Multi-Attribute Decision Aid methodology

3. Ranking of alternatives
4. Statistical analysis of the various rankings.

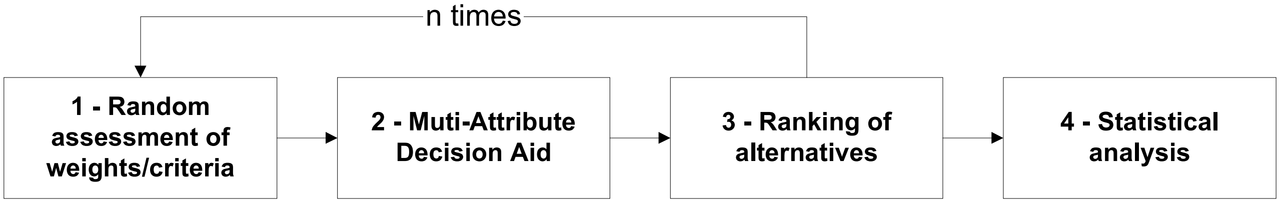


Fig 9: Monte-Carlo simulation in sensitivity analysis of MADA [Lifecon Deliverable D2.3].

A simulated weight/alternative assessment is obtained by multiplying the initial weight/alternative assessment (given by the user) by a multiplicative factor (variation) modelling small variations.
For instance, an initial weight W=30, subjected to small variations [-10%, +10%], will vary in the range [30 × 0, 9; 30 × 1, 1], i.e. [27, 33].

These small variations can be calculated by means of a bounded Gaussian distribution defined with:

$$\begin{cases} \text{Mean}: \mu = 1 \\ \text{Standard deviation}: \sigma = \text{variation}/3 \end{cases}$$

It is then bounded in lower values and upper values respectively by (1–variation) and (1+variation).
The bounds and standard deviation are chosen that way to include 99, 7% of the values (99, 7% of a Gaussian distribution is included between (μ–3σ) and (μ+3σ)).

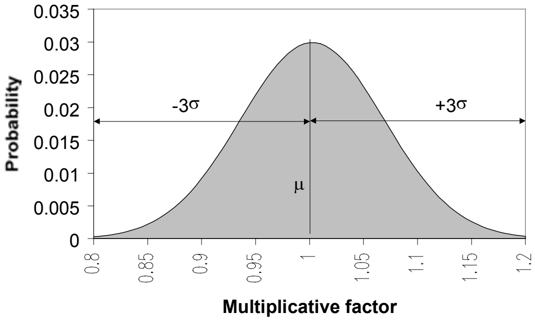


Fig 10. Example of multiplicative factor (Variation 20%) [Lifecon Deliverable D2.3].

After n simulations, the various ranking of alternatives of strategies and actions, and analyse the variations will be carried out.

6.2.7 FTA in obsolescence analysis and decision making

The use of Fault Tree Analysis (FTA) is explained with some examples of different cases.

Case 1: Bridge

In this illustrative example the top event is the first obsolescence indicator in table 15, namely "service capability of the bridge or network of bridges in the actual global, regional or local logistic system is not adequate":

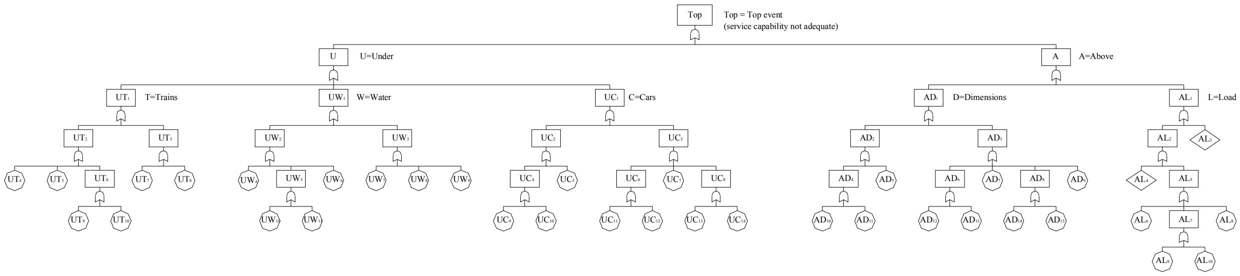
Top event clarification:
Primary function of a bridge is to transmit traffic over an obstacle (another route, railway, ravine, etc.) *and* at the same time to make possible the transit under the bridge. So the service capacity refers both to over-going and under-passing traffic. Primary parameters of traffic are volume and weight, the corresponding counterparts of the bridge being free space (horizontal and vertical) and load bearing capacity, respectively. This leads to the conclusion:

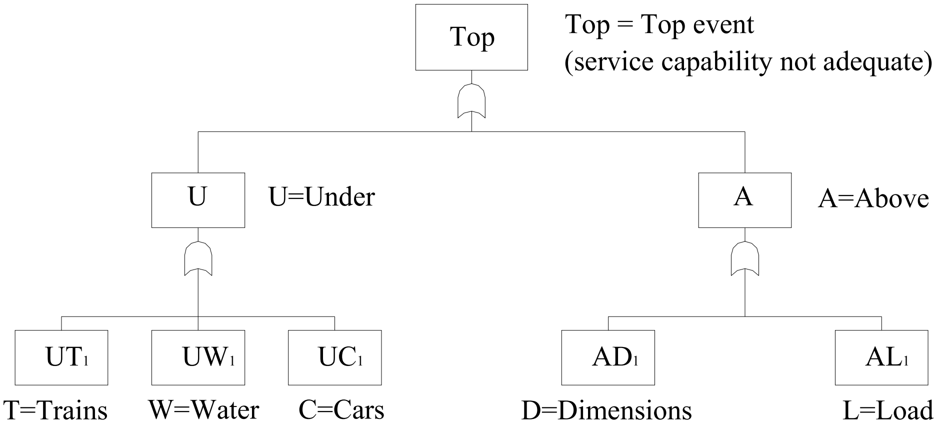
The top event happens when the *dimensions* or the *load bearing capacity* of the bridge do not meet the demands anymore. Two cases must be identified, i.e. traffic over the bridge and traffic under the bridge. For the under-passing traffic (vessels, trains, vehicles) the only important parameter of the bridge is free space as the traffic does not have contact with the bridge. For the over-passing traffic also the load bearing capacity of the bridge is very important.

Note: Of course there are also other requirements that the bridge has to fulfil, like aesthetics, MR&R economy, ecological demands etc. and consequently the bridge can be obsolete regarding those issues. However, in this example only the service capacity was of concern.

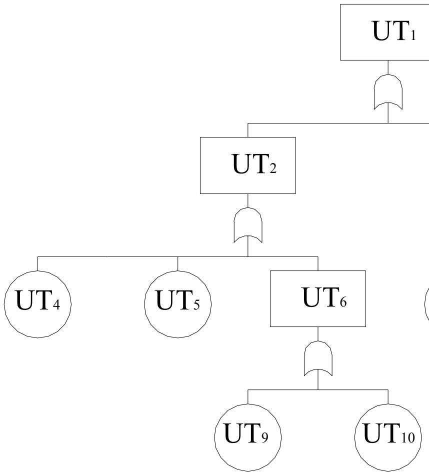
After this short reasoning, at the latest, the scope of the analysis should be defined: is the analysis going to be carried out for the whole stock of bridges, for the bridges on some certain area or route, or for just one certain bridge. Logically, the more general the scope, the more branches the fault tree will have. In this illustrative example the obsolescence problem will be studied on the "whole stock of bridges" (i.e. network) level. The fault tree for an individual bridge would of course be much smaller, because useless branches can be cut off immediately from the tree.

The resulting fault tree is shown in the figure 11 below. First the whole tree is displayed to illustrate the possible extent of the analysis, and then it is shown in more detailed pieces to make the texts readable.

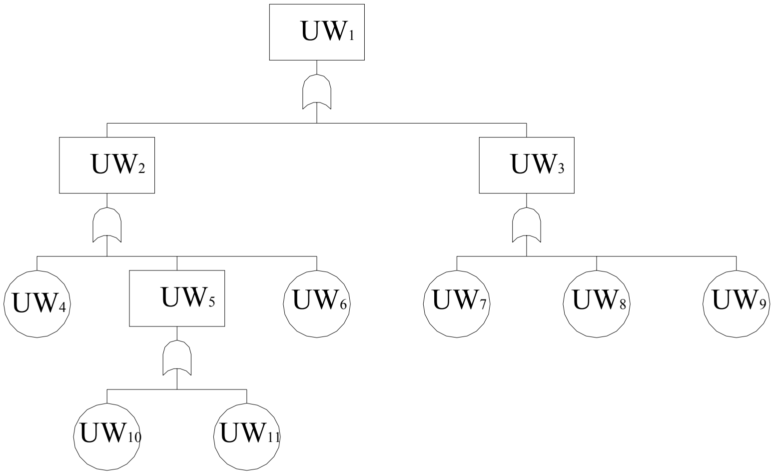




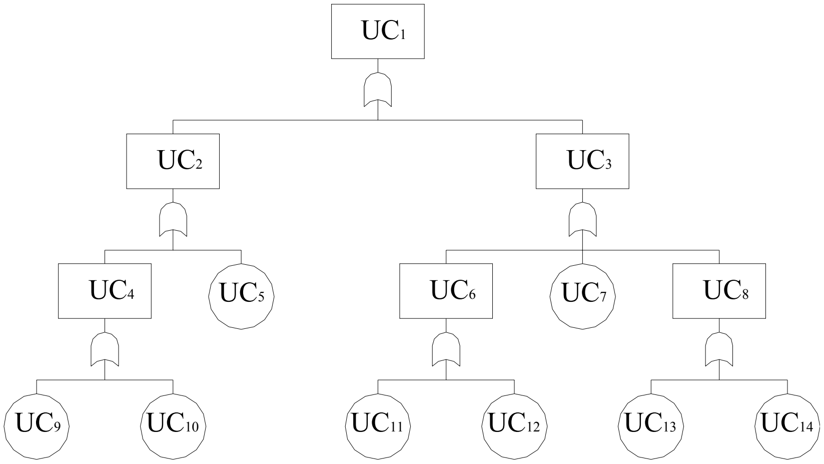
Abbr.	**Explication of the event**
U	Service capability not adequate for the traffic **U**nder the bridge
A	Service capability not adequate for the traffic **A**bove the bridge
UT_1	Service capability not adequate **U**nder the bridge for railway traffic (**T**rains)
UW_1	Service capability not adequate **U**nder the bridge for **W**ater-borne traffic
UC_1	Service capability not adequate **U**nder the bridge for road traffic (**C**ars)
AD_1	Service capability not adequate **A**bove the bridge due **D**imension-related causes
AL_1	Service capability not adequate **A**bove the bridge due **L**oad-related causes



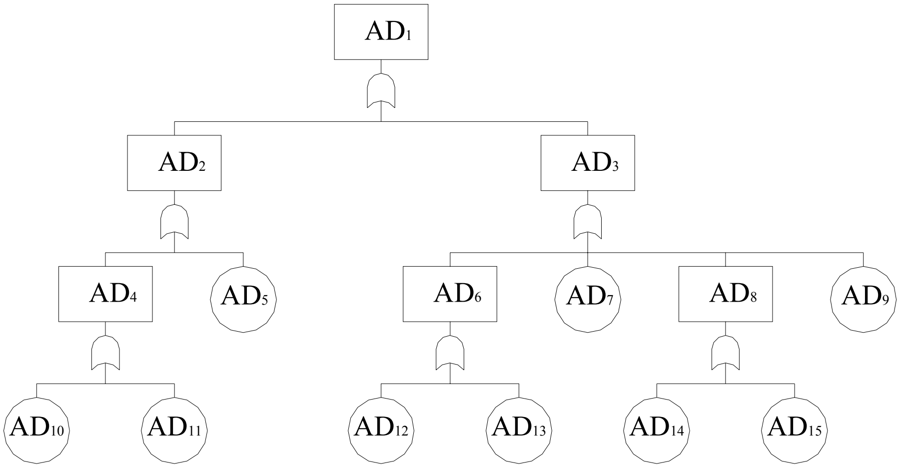
Abbr.	Explication of the event
UT_1	Service capability not adequate **U**nder the bridge for railway traffic (**T**rains)
UT_2	Vertical clearance for railway traffic limited
UT_3	Horizontal clearance for railway traffic limited
UT_4	Special cargo track (e.g. harbour activities) needs higher clearance
UT_5	Electrification problem: no room for installations (wires etc.) under the bridge
UT_6	Railway norms concerning vertical clearance are to be changed
UT_7	More tracks wanted but horizontal clearance does not allow that
UT_8	Wider clearance needed for special cargo tracks (e.g. harbour activities)
UT_9	Railway norms to be changed on international level
UT_{10}	Railway norms to be changed on national level



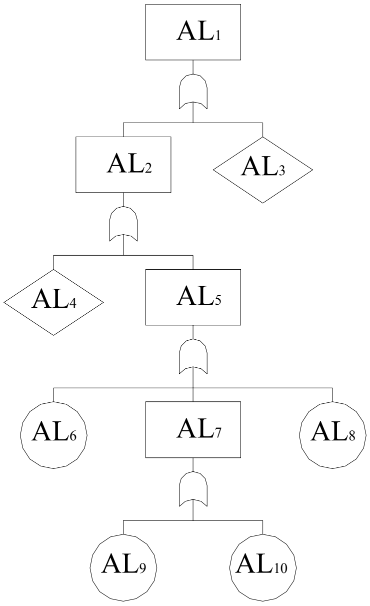
Abbr.	Explication of the event
UW_1	Service capability not adequate **U**nder the bridge for **W**ater-borne traffic
UW_2	Vertical clearance for water-borne traffic limited
UW_3	Horizontal clearance for water-borne traffic limited
UW_4	New water-level regulation policy keeps the water level very high
UW_5	Commercial water traffic needs higher clearance than what is the current situation
UW_6	Recreational yachting increases, with higher motor and sailing boats
UW_7	New route for seagoing ships requires wider navigation channel
UW_8	Intermediate piers badly situated in the middle of the watercourse
UW_9	Narrow navigation channels between abutments and piers cause difficult currents (e.g. for slow towboats, log floating, etc.)
UW_{10}	Deep-water channel to be opened, higher ships to be expected on watercourse
UW_{11}	Log floating to be commenced, towboats need higher clearance



Abbr.	Explication of the event
UC_1	Service capability not adequate **U**nder the bridge for road traffic (**C**ars)
UC_2	Vertical clearance for under-passing road traffic limited
UC_3	Horizontal clearance for under-passing road traffic limited
UC_4	Road traffic norms concerning vertical clearance on normal roads are to be changed
UC_5	Special loads route (e.g. minimum height 7.2 m) network to be extended, including the under-passing road in question, need for higher clearance
UC_6	Stricter safety standards call for wider clearance between columns and abutments
UC_7	Change of the existing under-passing road into a "wide lane road", but the clearance between columns is too narrow for that
UC_8	Change of the existing two-lane under-passing road into multilane road
UC_9	Road traffic norms to be changed on international level
UC_{10}	Road traffic norms to be changed on national level
UC_{11}	Standard to be changed on international level
UC_{12}	Standard to be changed on national level
UC_{13}	Too much traffic for two-lane road, more lanes needed
UC_{14}	Change from normal road to motorway



Abbr.	Explication of the event
AD_1	Service capability not adequate **A**bove the bridge due **D**imension-related causes
AD_2	Vertical clearance on bridge limited
AD_3	Horizontal clearance on bridge limited
AD_4	Road traffic norms concerning vertical clearance on normal roads are to be changed
AD_5	Special loads route (e.g. height 7.2 m) network to be extended, need for higher clearance on the (truss) bridge in question
AD_6	New standard call for wider lanes
AD_7	Change of the existing road into a "wide lane road", but the horizontal clearance between railings is too narrow for that
AD_8	Change of the existing two-lane road into multilane road
AD_9	Pedestrians need a lane of their own, separated (e.g. elevated) from traffic lanes
AD_{10}	Road traffic norms to be changed on international level
AD_{11}	Road traffic norms to be changed on national level
AD_{12}	Standard to be changed on international level
AD_{13}	Standard to be changed on national level
AD_{14}	Too much traffic for two-lane road, more lanes needed
AD_{15}	Change of the road from normal road to motorway



Abbr.	Explication of the event
AL_1	Service capability not adequate **A**bove the bridge due **L**oad-related causes
AL_2	Loads increased
AL_3	Load bearing capacity decreased
AL_4	Overloads increased
AL_5	Legal loads increased
AL_6	Road class change from lower to higher
AL_7	Change of standards for normal road traffic loads
AL_8	Special loads (harbour, mine, foundry, factory)
AL_9	Standard to be changed on international level
AL_{10}	Standard to be changed on national level

Fig 11. Fault tree in obsolescence analysis.

After finding out the primary reasons of obsolescence (circles in figure 11), decisions can be made about countermeasures. There exist no thumb rules "do this, avoid that", but the decisions are case- and organisation-specific. The general Lifecon recommendation is that demolition of obsolete but otherwise sound facilities should be avoided as far as possible.

Case 2: Building

Another short obsolescence analysis example relates to the last obsolescence indicator of table 15, which are related to buildings: "Building does not reflect the imago that user wants to give".

This example "Building does not reflect the imago that user wants to give" is more difficult to analyse, but eventually can be handled with the same procedure as the bridge example above. The idea is again to split the problem into "smaller pieces" (or parameters) in a structured way, and to find out the possible causes why the value of those parameters and their sub-parameters do not fit into user's imago.

The splitting of the top event into smaller pieces could follow the following reasoning:
The parameters of the building that have effect on the imago of the user are mainly

- location
- outlook
- internal spaces, surfaces, decorations, hallways etc
- Comfort feeling generally: inside and outside the building.

Each of those three main contributors can be further divided, for example the outlook of the building can be further split to the following five sub-contributors:

- Style of the building (castle, storehouse, box...)
- Colour of the building (colourful, trendy, old-fashioned, grim...)
- Dimensions of the building (overall size of the building, doors/windows, height, width...)
- Materials of the building (stone, brick, concrete, steel...)
- Condition of the building (brand new, worn, near to collapse...)

This way the analysis goes on until the fundamental level is reached. After finishing the fault tree it can be seen which basic factors contribute to the contradiction between the present building and the imago promotion of the user. Depending on the source data the relative importance of the basic factors can be estimated and consequently countermeasures launched. All the time those factors must be studied with imago-orientated approach, i.e. throughout the analysis it must be studied how the identified parameters affect the imago of the user. Parameters that have no effect on the imago will be excluded from this imago-related obsolescence analysis, although these excluded parameters might have considerable effect on the overall business of the user. These contradictions must be taken into account in other analyses (e.g. in multi-attribute decision analyses) on corporate strategy level. An example of this kind of contradiction might be following:

The company wants to give imago that they are open and very accessible to customers, and consequently have decided to have very large windows in the facade and open-plan office. However, the workers feel uncomfortable working close to windows, where all the passers-by can see them through the window, there is nasty draft especially during cold days near the windows and the open-plan office cause a lot of interruptions in work. If the company has not deemed workers' satisfaction as an imago factor, it will be excluded from the imago analysis, although it surely has effect on the business of the company.

7 Conclusions

The lifetime oriented and predictive design and MR&R (Maintenance, Repair and Rehabilitation) planning can be based on lifetime performance principle, applying theory of mechanical (static and dynamic), durability (degradation) and obsolescence limit states. The mechanical limit state design is the traditional basic methodology for designing the new structures to fulfil the generic requirements of safety and serviceability. Durability limit state design is aiming to guarantee the long-term serviceability and safety towards human requirements, economy, cultural aspects and ecology. The obsolescence limit state design is aiming to guarantee the ability of the buildings and civil infrastructures to have an ability to meet all current and changing requirements with minor changes of the facilities, thus avoiding the need of early renewal or demolition.

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Lifecon reports are produced in an interactive co-operation between the partners. The issues are discussed in several plenary and Working Package meetings, which have helped in identifying the needs of methodology. Also interactions between the method descriptions and applications of these methods have strengthened the presentation this report, which is quite integrating in the nature.

Especially I would mention the roles of Mr. Erkki Vesikari and Mr. Tommi Rissanen from VTT. Mr. Erkki Vesikari has a long time, since ten years, worked in co-operative development of the safety factor methodology, which has served as a starting point to the description of this method in this report. Mr. Tommi Rissanen has written the application of risk analysis on obsolescence analysis, optimisation and decision making, which is presented in Chapter 6.2.7.

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Appendixes:
1. Terms and definitions
2. Example

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 (ENV 1504-9:1996)	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 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
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 - Durability failure	Loss of the ability of a structure or its parts to perform a specified function. 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) - Serviceability limit state - irreversible serviceability limit states - reversible serviceability limit states - Ultimate limit state	States beyond which the structure no longer fulfils the relevant design criteria. State which corresponds to conditions beyond specified service requirement(s) for a structure or structural member are no longer met. serviceability limit states where some consequences of actions exceeding the specified service requirements will remain when the actions are removed serviceability limit states where no consequences of actions exceeding the specified service requirements will remain when the actions are removed 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 account of the specific in use conditions.

Attribute - Multiple attributes	A property of an object or its part, which will be used in optimisation and selective decision making between alternatives. 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.
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 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 NOTE: Activities to restore the structure after an accidenttal 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, plus 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.
Environmen-tal 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.
Environmen-tal 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.
Environmen-tal 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 ψF_k
Design value of an action *(Fd)* (EN 1990-2002)	Value obtained by multiplying the representative value by the partial safety factor γ_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 Rk) (EN 1990-2002)	Value obtained by dividing characteristic value by a partial factor γ_m or γx, or, in special circumstances, by direct determination
Nominal value of a material or product property (X_k or Rk) (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.
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.
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 tens of years)
Decision making	Methodology for rational choices between alternatives, basing on defined requirements and criteria.

APPENDIX 2: SELECTED DEGRADATION MODELS of RILEM TC 130 CSL

Degradation model for a corrosion process [8]

Two limit states can be identified with regard to service life:

A) The service life ends when the steel is depassivated. This rule is usually applied to all chloride induced corrosion because the local attack penetration rate is still not safely quantified and, therefore, the uncertainties on the propagation period are high. So the service life is limited to the initiation period only (time for the aggressive agent to reach the steel and induce depassivation).

This rule is also applied to all prestressing steels. The tensile stress of tendons is normally so high that no reduction in the cross-sectional area is permissible and as a result of surface corrosion there is a risk of stress corrosion cracking.

In the cases where no corrosion is allowed the following formula for service life can be used:

$$t_L = t_0 \qquad (12)$$

where t_L is the service life, and
t_0 the initiation time of corrosion

B) The limit state is based on cracking of the concrete cover due to oxides generated during corrosion. In this case the service life includes a certain propagation period of corrosion during which the cross-sectional area of steel is progressively decreased, the bond between steel and concrete is reduced and the effective cross-sectional area of concrete is diminished due to spalling of the cover. This approach is applied in the cases where generalised corrosion is developing due to carbonation.

The service life based on cracking of the concrete cover is defined as the total of the initiation time of corrosion and the time for the cracking of concrete cover until a certain limit.

$$t_L = t_0 + t_1 \qquad (13)$$

where t_1 is the propagation time

The propagation time t_1 ends when a certain maximum allowable loss of the cross-sectional area or loss of bond or crack width is reached. These values will depend upon the particular detailing and geometry of each element.

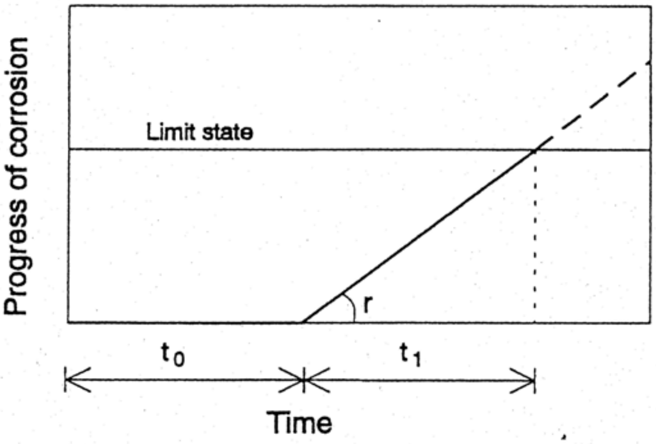

Fig 1. Determination of service life with respect to corrosion of reinforcement.

At cracks, originated from the beginning of service life, the initiation time t_0 is much shorter than in an uncracked cover or even $t_0 = 0$. In this case it may be written:

$$t_L = t_1 \qquad (14)$$

where t_1 is the free corrosion time.

Models for estimating t_0 and t_1 are being presented below. When developing these models the assumption that concrete surfaces are free from coatings and sealants has been provided.

The initiation time of corrosion

Chloride induced corrosion

The most common sources of chlorides are the sea water (marine environments) and deicing salts. The case of admixed chloride is not considered here.

As a result of chloride penetration a gradient develops near the concrete surfaces. The time at which the critical chloride content (threshold value) reaches the steel surface and depassivates it, can be regarded as the initiation time of corrosion.

The gradient of chloride content is often described by an error function model which fulfils the condition of Fick's second law of diffusion:

$$C_x = C_s \left(1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D \cdot t}}\right)\right) \qquad (15)$$

where C_x is the chloride content at certain depth x,

C_s the chloride concentration at the concrete surface,
x the depth from the surface of the structure,
D the diffusion coefficient, and
t time

The initiation time for corrosion is obtained from the formula:

$$C_{th} = C_s \left(1 - \mathrm{erf}\left(\frac{c}{2\sqrt{D \cdot t_0}}\right)\right) \qquad (16)$$

where C_{th} is the critical chloride content,
c the concrete cover, and
t_0 the initiation time of corrosion.

This formula may be simplified by using a parabola function:

$$C_x = C_s \left(1 - \frac{x}{2\sqrt{3 D \cdot t}}\right)^2 \qquad (17)$$

Then the formula for the initiation time of corrosion may be written in the following form:

$$t_0 = \frac{1}{12 \cdot D} \cdot \left(\frac{c}{1 - \sqrt{C_{th}/C_s}}\right)^2 \qquad (18)$$

Many standards require threshold values not higher than 0.4% (Cl^-) per weight of cement for reinforced concrete and 0.2% for prestressed concrete. This corresponds approximately to 0.05 to 0.07 by weight of concrete (0.025 - 0.035 for prestressed concrete)

Concerning values of C_s, field experiences have shown that this amount is time dependent at early ages but tends to a maximum after some years. For the sake of calculations it is usually considered a constant value. Normal values may be about 0.3 - 0.4 per weight of concrete.

The coefficient of diffusion results about 10^{-7} - 10^{-8} cm^2/s

Stress corrosion cracking

The phenomenon of stress corrosion cracking is fortunately not common. It may develop in prestressing wires subjected to corrosive agents leading to a brittle fracture with almost no loss in the cross-sectional area. The stress corrosion is incubed in very small surface cracks.

Local steel depassivation is needed to produce surface cracks in which the stress corrosion can incube. Therefore protecting the prestressing steels from aggressive agents is crucial to their service life which is always limited to the initiation time of corrosion. As regards to chlorides intrusion the calculation rules presented in Chapter 2.4.3.1 can also be applied to prestressing steels.

Carbonation induced corrosion

The carbon dioxide of air penetrates into concrete neutralising its alkaline substances and produces a carbonation front which advances towards the interior. When this carbonation front reaches the reinforcement, the passive film on steel becomes unstable and dissolves, enabling the generalised corrosion to occur.

The initiation time of corrosion is defined as the period of time needed for a complete carbonation of concrete cover.

The rate of carbonation is usually assumed to be related to the square root of the time:

$$d = K_c \sqrt{t} \tag{19}$$

where d is the depth of carbonation at time t,
K_c the carbonation coefficient,
t the time or age.

The initiation time of corrosion can be determined as follows:

$$t_0 = \left(\frac{d}{K_c}\right)^2 \tag{20}$$

The carbonation coefficient depends on the strength of concrete, binding agents, cement content and environmental conditions (humidity and temperature). There are several formulae to model the carbonation rate. Some of them are analytical others empirical.

Based on the Fick's first law the following expression can be derived for the depth of carbonation /22/:

$$x = \sqrt{\frac{2\,D\,(C_1 - C_2)}{a}\,t} \tag{21}$$

where x is the carbonation depth (m),
a the amount of alkaline substance in the concrete,
D_c the effective diffusion coefficient for CO_2 at a given moisture distribution in the pores (in m^2/sec),
$C_1 - C_2$ the concentration difference of CO_2 between air and the carbonation front (in kg/m3), and
t the time.

This calculation procedure has been extended by Bakker /4/ for the cases of fluctuating wetting and drying cycles. During wet conditions the carbonation front cannot progress. During dry conditions moisture evaporates and enables further progression of the carbonation front.

According to Bakker the time t in Formula 136 is substituted by t_{eff} which is determined as follows:

$$t_{eff} = (t_{d1} + t_{d2} - (x_1/B)^2 + t_{d3} + \ldots\ldots. t_n - (x_{n-1}/B)^2) \qquad (25)$$

$$B = \sqrt{\frac{2\,D_v\,(C_3 - C_4)}{b}} \qquad (26)$$

where x_n is the carbonation depth after nth wetting and drying cycle (m),
t_{dn} the length of nth drying period,
D_v the effective diffusion coefficient for water vapour at a given moisture distribution in the pores (in m^2/sec),
$C_3 - C_4$ the moisture difference between air and the evaporation front (in kg/m^3), and
b the amount of water to evaporate from the concrete (in kg/m^3)

If the drying and wetting periods are of equal length the time passed after n cycles is:

$$t_n = n \cdot t_d + (n-1) \cdot t_w \qquad (27)$$

where t_w is the length of the wetting periods and
t_d the legtht of drying periods.

A theoretical model based on the theory of "moving boundaries", has been presented by Tuutti /25/. The theory deals with diffusion processes in non-steady-state conditions where CO_2 reacts with concrete in such a way that concrete serves as a sink for CO_2. Another theoretical model for the combined effects of frost attack and carbonation has been presented by Fagerlund, Somerville and Tuutti /9/.

Experimental models for evaluating the depth of carbonation have been presented by Häkkinen and Parrot. According to Häkkinen the depth of carbonation is determined by Formula 135 the coefficient of carbonation being determined as follows /12/:

$$K_c = c_{env} \cdot c_{air} \cdot a \cdot f_{cm}{}^{b} \qquad (28)$$

where c_{env} is the environmental coefficient,
c_{air} the air content coefficient,
f_{cm} the mean (cubic) compressive strength of concrete (MPa), and
a, b parameters depending on the binding agent.

Instead of the mean compressive strength, the characteristic strength can be used by applying the following relationship /6/:

$f_{cm} = f_{ck} + 8$ (29)

Tables 1 and 2 show values for the environmental load and air content coefficient respectively:

Table 1. Environmental load coefficient for determination of carbonation rate.

Environment	c_{env}
Structures sheltered from rain	1
Structures exposed to rain	0.5

Table 2. Air content coefficient for determination of carbonation rate.

Air porosity	c_{air}
Not air entrained	1
Air entrained	0.7

The parameters a and b in Formula 28 are presented in Table 3 .

Table 3. Parameters a and b.

Binder	a	b
Portland cement (p.c.)	1800	-1.7
p.c.+ fly ash 28%	360	-1.2
p.c.+ silica fume 9%	400	-1.2
p.c.+ blast furnace slag 70%	360	-1.2

According to Parrot the depth of carbonation is determined on the basis of the oxygen permeability of concrete /18/:

$$d = \frac{64 \cdot K^{0.4} \cdot t^{n}}{c^{0.5}} \qquad (30)$$

where K is the oxygen permeability of concrete at 60% RH,
t the time,
c the alkaline content in the cement, and
n the attenuation factor (root power).

Propagation period

General rule

Corrosion begins when the passive film is destroyed as a result of falling pH due to carbonation, or as a result of the chloride content rising above the threshold close to the reinforcement. The volume of corrosion products is many times that of the original metal. The greater need for volume causes tensile stress in concrete around the steel bar leading to cracking or spalling of the concrete cover.

When corrosion develops three main phenomena appear:
- a decrease in the steel cross section,
- a decrease in the steel/concrete bond, and
- cracking of the concrete cover and therefore a decrease in the concrete load-bearing cross section

To determine the length of service life the critical threshold value of the load-bearing capacity has to be defined as related to the aforementioned distressing phenomena. This critical threshold can often be expressed as the critical loss of bar radius provoked by corrosion and, therefore, the propagation period may be quantified in the following manner /1/:

$$t_1 = \frac{\Delta R_{max}}{r} \qquad (31)$$

where t_1 is the propagation time of corrosion (years),
ΔR_{max} the maximum loss of the radius of steel bar, and
r the rate of corrosion.

Cracking time of concrete cover

In the case of generalised corrosion the critical loss of bar radius is based on the cracking of concrete cover. The propagation (cracking) time can be approximated by the following formula /24/:

$$t_1 = 80 \frac{C}{D \cdot r} \qquad (32)$$

where C is the thickness of concrete cover (mm),
D the diameter of the rebar (mm), and
r the rate of corrosion in concrete (µm/year).

The rate of corrosion in concrete depends strongly on the ambient conditions. Important environmental factors are relative humidity and temperature. The rate of corrosion of reinforcement in concrete can be evaluated using the following formula:

$$r = c_T \cdot r_o \qquad (33)$$

where c_T is the temperature coefficient.
r_o the rate of corrosion at $+20^oC$.

Primary factors that affect the rate of corrosion in concrete at $+20^oC$ are the relative humidity of air (or concrete) and the chloride content. Other factors such as the w/c ratio and the type of cement may also have some influence. The values of the corrosion rate in anodic areas of reinforcement presented in Table 6 can be taken as approximate average values. They are determined on the bases of the experimental data in source /25/.

Table 4. Rate of corrosion in carbonated and chloride contaminated concrete (anodic areas).

Relative humidity RH %	Carbonated concrete μm/year	Chloride contaminated concrete μm/year
99	2	34
95	50	122
90	12	98
85	3	78
80	1	61
75	0.1	47
70	0	36
65	0	27
60	0	19
55	0	14
50	0	9

The moisture content of concrete surrounding the reinforcing steels is a complex mixture of various climatic and structural effects. The equilibrium relative humidity of concrete in aerial conditions is affected by annual and daily variations of the relative humidity of air, condensation of moisture on the surfaces, rain, splash and melting water, density of concrete and depth from the surface (concrete cover).

The chloride content has also a great influence on the moisture content and the rate of corrosion in concrete. However, the propagation time is normally completely omitted if chlorides are present. The data for chloride contaminated concrete in Table 6 is given mainly for comparison.

The average relative humidity in structures exposed to rain can be evaluated as being about 95% (unless the frequency of rains is extremely low) and for structures completely sheltered from rain about 90%. Consequently the rate of corrosion in carbonated concrete at 20 ^{o}C would be about 50 μm/year in structures exposed to rain and about 12 μm/year in structures sheltered from rain.

The temperature coefficients determined on the bases of the findings and average daily temperatures for some European cities are presented in Table 5. The evaluated rates of corrosion according to Formula 33 are also given.

Table5.Temperature coefficients and evaluated rates of corrosion for some cities in Europe.

City	c_T	Rate of corrosion µm/year	
		exposed to rain	sheltered from rain
Sodankylä (Northern Finland)	0.21	11	2.5
Helsinki	0.32	16	4
Amsterdam	0.47	24	6
Madrid	0.73	37	9

The effect of direct sun shine on the surface temperatures of structures has not taken into account in Table 5. This effect may be considerable, however. Local microclimatic features should be taken into account when evaluating the rate of corrosion.

It is well known that the rate of corrosion slowly reduces with time. However, as there is not much data available about this phenomenon, constant corrosion rate is recommended in durability design.

Propagation time of corrosion at cracks

If the concrete cover is cracked from the beginning (due to shrinkage, mechanical stress etc.) and the crack width is larger than 0.1 ... 0.3 mm, corrosion normally starts without any initiation period. If the steel bars are exposed all around, even corrosion is expected on all sides.

A constructor may set a limit for the minimum diameter of steel bars or the maximum depth of corrosion correspondingly. This may depend on the type of reinforcement – main reinforcement, transverse reinforcement, stirrups etc. – and the actual stresses in steel bars. No corrosion in prestressing tendons is permissible.

The propagation time at cracks is calculated from the following formulae:

$$t_1 = \frac{s_{max}}{r} \qquad (34)$$

$$t_1 = \frac{D - D_{min}}{2 \cdot r} \qquad (35)$$

where t_1 is the propagation time of corrosion at a crack,
r the rate of corrosion at a crack,
s_{max} the maximum allowable depth of corrosion, and
D_{min} the minimum diameter of the steel bar.

The rate of corrosion in cracks represents an extremely complicated problem, which is not yet fully understood. In the absence of more precise data the assumption that the average corrosion rate is of the same order of magnitude as in uncracked concrete is applied. Accordingly the following values for the mean corrosion rates are recommended in the calculations:

A when the only aggressive action is carbonation:
- RH = 90 - 98% ⇒ corrosion rate = 5-10 µm/year
- RH < 85% ⇒ corrosion rate ≤ 2 µm/year

B in chloride contaminated environments:
- RH = 100% ⇒ corrosion rate ≤ 10 µm/year
- RH = 80 - 95% ⇒ corrosion rate = 50-100 µm/year
- RH < 70% ⇒ corrosion rate ≤ 2 µm/year