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Instructions for quantitative classification of environmental degradation loads onto structures

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Preface

This report constitute NBI's final report regarding the task "Instructions for quantitative classification of environmental degardation loads onto structures" from the EU-project "G1RD-CT-2000-00378- Life Cycle management of Concrete Infrastructures for improved Sustainability (LIFECON)". Svein E. Haagenrud acted as Task leader and the project had 17 partners from Finland, Norway, Sweden, UK, Germany and France. Other Norwegian project partners were Kystdirektoratet, Interconsult AS, Millab Consult A.S. and Norwegian University of Science and Technology.

Svein Haagenrud

Project leader

Abstract

This report provides relevant *systematic* and *requirements* for quantitative classification of environmental loading onto structures, and overview of *existing systems for environmental classification*, as well as *sources* of environmental exposure data, and methods for their assessment and modelling on various geographical scales. *Instructions/guidelines* for how to characterise the environmental loads on concrete structures on object and network level are given, serving as basis for developing and testing a quantitative classification system for environmental loading. For most European countries environmental data and models are available from meteorological offices and the environmental research area, and these data and the work performed are directly applicable for LIFECON. The present LMS prediction module contains such modelling of environmental data and of service life functions for a range of the supplementary materials in concrete structures, such as for example galvanized (and coated) steel.

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

List of Contents

Preface 3

List of terms, definitions and symbols 7

1. Introduction 8
  1.1 State of the art 8
  1.2 Need of progress 8
  1.3 Objectives and Deliverables of WP 4 9

2. Classification system for Concrete based on EN 206 10
  2.1 EN 206-1 10
  2.2 Strategies for developing quantitative classification based on EN 206-1 11
  2.3 Provisions for implementation of EN 206-1 on national level 16
    2.3.1 General 16
    2.3.2 Inspection of existing marine structures in Norway, especially Gimsøystraumen bridge 16
  2.4 Field studies to develop quantitative exposure classification for EN 206-1 20

3. Degradation models and environmental degradation factors in LIFECON 29
  3.1 Holistic degradation model and environmental agents. 29
  3.2 Degradation models and needed environmental data (from D4.1) 31

4. Systematic and options for Classification of environmental degradation factors and corrosivity 40
  4.1 Introduction 40
  4.2 Systems for classification of generic aggressivity 40
    4.2.1 EOTA - Annex A Building context (EOTA, 1999) 40
    4.2.2 ISO 15686 Service Life Planning-Part 4 40
  4.3 Systems for classification of atmospheric corrosivity of specific materials 41
    4.3.1 ISO 9223-26 Classification of atmospheric corrosivity for metals 41
    4.3.2 ISO DIS 12944-2 Paints and varnishes 42
  4.4 Discussion of feasibility for LIFECON 42

5. Methods and data for assessments, modelling and mapping of degradation agents 42
  5.1 Summary 42
  5.2 IT based systems available for LMS 43
    5.2.1 ENSIS - Air quality and corrosion cost information systems 43
    5.2.2 Australia 44
    5.2.3 Computational Fluid Dynamics models (CFD) 44
  5.3 Sources and geographical levels of data 45
    5.3.1 Introduction 45
    5.3.2 Environmental research frameworks are important for LIFECON 45
  5.4 Network level-macro, regional and local scale 46
    5.4.1 Climatic data 46

- 5.4.2 Pollutants 46
- 5.4.3 Chlorides 48
- 5.5 Example Germany - mapping air pollution, actual corrosion rates and exceedances 51
  - 5.5.1 Mapping Critical Loads & Critical Levels in Germany 51
  - 5.5.2 Mapping results for LIFECON 52
- 5.6 Object level-atmospheric micro scale 54
  - 5.6.1 Climatic data-driving rain from prEn 13013 54
  - 5.6.2 Pollutants 55
- 5.7 Modelling and mapping of damage functions and service life 56

6. Guidance for characterisation (and subsequent classification) of exposure environment on structures in LIFECON 57
  - 6.1 Object level 57
  - 6.2 Network level-regional level 59
  - 6.3 Proposal for measurement program for validation of exposure assessment around bridge deck and tunnels 59

7. Conclusions 60

8. References 61

List of terms, definitions and symbols

LMS = Life Cycle Management System

ERF = Environmental Risk Factor module of LMS

SLP = Service Life Prediction module of the LMS

ENSIS = Environmental Surveillance and Information System

1. Introduction

1.1 State of the art

Existing systems for quantitative classification of environmental loading related to durability for building materials and components are described (see Chapter 4). For *quantitative* classification of atmospheric environmental loads there are two *options* as shown by description of the existing and emerging classification systems within ISO and EOTA. Some systems tries to classify the *generic atmospheric aggressivity* on a global to local scale (ISO 15686 "Service Life Planning - Part 4" and EOTA, 1999), without specific knowledge of damage functions, but based on overall experience of materials degradation at large. The other option and systematic is material (family) specific and based on knowledge of their damage functions, such as ISO 9223 that are specific for metals.

These systems should be discussed in order to check out if they can be feasible and adopted also for the purpose of concrete structures. This will be done in D4.4, which is to be published in Final form as part of the Cluster report within the LIFETIME project.

The main basis for classification in LIFECON should be the new European standard -"EN 206-1 Concrete - Specification, performance, production, and conformity"- that was recently endorsed (CEN, 2001). This contains an agreed *qualitative* classification system as a synthesis of "best available" knowledge, and is therefore described in detail (Chapter 2). It covers the relevant degradation mechanisms and exposures in atmospheres, fresh water, seawater, and soil, indicating the decisive character of moisture and chloride. The natural approach would be to try to develop the EN 206-1 further into a quantitative system.

1.2 Need of progress

In general, requirements for establishing and implementing quantitative classification systems for durability of materials and components are:

1. Well defined and relatively simple damage functions for the materials in question
2. Availability of environmental exposure data/loads, including methods and models for assessing their geographical distribution
3. User friendly IT systems for storage, processing and modelling of the environmental loads, and service lives onto the concrete infrastructures, on object and network level

For concrete, and for many of the supplementary materials, the relevant damage functions are provided by D4.1 (and D3.2) and given in chapter 5, defining also the necessary environmental degradation factors for classification. The Duracrete concrete models are complex and will have to be simplified for classification purposes.

As shown in chapter 5 the requirements for availability of environmental data and for IT systems are fulfilled and no longer barriers for exploitation. It is shown that environmental data and models are available from meteorological offices and the environmental research area, and that these data and the work performed are directly applicable for LIFECON. The present environmental exposure module of LMS contains such modelling of environmental loads and service life functions for some of the supplementary materials, such as galvanised (coated) steel.

In order to develop the quantitative classification two strategies have been chosen. Firstly, a more practical approach of validation, where the EN 206-1 system should be tested out on the chosen objects and compared with detailed environmental characterisation of the same objects using the available data and methods for environmental characterisation. An EN 206-1 harmonized protocol for the 11 selected objects is therefore also given in chapter 3. Such studies should be undertaken in many countries to develop the needed national annexes for a proper implementaion of EN 206-1 across Europe, see item 2.3. A first sketch of how such as system might look like, based on best available knowledge and experience, is provided in the present report.

Secondly, a more teoretical classification based upon parametric sensitivity analysis of the complex Duracrete damage functions under various set conditions. In this way the determining factors are singled out and classified. This is performed in D3.2 (Lay, 2003), and shown in context in D4.4.

Chapter 6 gives instructions for how to characterise the exposure environments of these objects, on object and on network level, based on the descriptions in chapter 5. A condition assessment protocol with respect to environmental characterisation of the selected sample of objects is outlined.

1.3 Objectives and Deliverables of WP 4

The objectives of the WP4 are “to provide and synthesise the necessary classification of environmental degradation loads for developing and exploiting the models of WP3.” WP4 will develop methods and data for assessing, modelling, mapping and classification of environmental risk factors on different geographical levels based on damage functions.

Further, from Annex 1 of Contract the following *overall objective* can be added “To produce the Draft Standard Proposal: Classification of Environmental Exposure...” The deliverables planned for WP4 are thus:

- D4.1 Definition of necessary environmental degradation load parameters.
- D4.2 Instructions for quantitative (characterisation) 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 location.
- D4.4 Generic report on methodology and methods of quantitative classification of environmental loads onto structures for LIFECON and for Cluster report: “European Guide for Lifetime Design and Management of Civil Structures and Buildings”. (To be published within LIFETIME).

Discussions during the course of the project have shown that it may be difficult to get a consistent description just from short headlines, and therefore a more detailed description of the relationship between the deliverables are given:

- D4.1 - provides the relevant damage functions as basis for defining the type and formats for the relevant environmental degradation agents for classification, on object and network level. This is largely based on input from D3.2
- D4.2 - provides relevant *systematic* and *requirements* for quantitative classification, *overview of sources* of environmental exposure data and methods for their assessment and modelling on various geographical scales, and *instructions/guidelines* for how to characterise the environmental loads on concrete structures on object and network level, as basis for later classification.
- D4.3 - characterisation of relevant environmental loading onto chosen objects, on object and network level, exhibited in the GIS based Environmental Risk Factor module at least for one country (Norway).
- D4.4 - report containing both the methodology for classification, and the proposal (standard) for quantitative classification of *environmental loads onto concrete structures in Europe.(To be published within LIFETIME Cluster report)*

Environmental characterisation and classification is needed to enable sound prediction of service lifes and maintenance intervals both on object and network level in the LMS system.

2. Classification system for Concrete based on EN 206

2.1 EN 206-1

The need to classify the exposure corrosivity for concrete has been an issue of great concern for many years. Based on existing knowledge and experience the new European standard EN 206-1 Concrete - Specification, performance, production, and conformity was recently endorsed (CEN, 2001), superseding the previous ENV 206:1990. Many items were subject to revisions, one of them being "extension of the classification systems for concrete especially with respect to environmental conditions".

The established classification system is given in the EN 206-1, chapter 4 - Classification, of the standard, and is characterized by the following;
- Covers the relevant degradation mechanisms - carbonation, chloride, freeze/thaw, chemical
- Classification is focused on the various stages of corrosion propagation
- Covers exposures in atmospheres, fresh water, sea-water, and soil, indicating the decisive character of moisture and chloride
- Includes only *qualitative* descriptions of exposure classes *except* for chemical attack from natural soil and ground water (Table 2)
- The systematic describes "informative examples of constructions, or categories of exposures, where the exposure class may occur."
- Requirements for concrete relating to durability exposure classes are also defined, specifying *constituent materials, water cement ratio, cement content, compressive strength class*

The classification tables from the EN 206-1 are given in Table 1 and Table 2.

2.2 Strategies for developing quantitative classification based on EN 206-1

A quantitative classification system should be rather simple and easy to use in order to get some quantitative figures that allow for assessments or calculation of probability of degradation. Such systems exist for some materials like for example metals and alloys (ISO, 1992). For concrete this becomes extremely difficult due to the complexity of the degradation and thus the degradation models (see item 3.2 and D3.2). This was a topic of very much discussion during the first period of the project. It takes considerable knowledge and vast amounts of systematic data and experience to simplify the now complex models.

Two main strategies were followed in the development. Firstly, a more practical approach of validation, where the EN 206-1 system should be tested out on the chosen objects and compared with detailed environmental characterisation of the same objects using the available data and methods for environmental characterisation. By extensive assessments of the degradation modes and the compliant environmental exposure, it was hoped that enough data would be available to give ground for a thorough proposal on quantitative classification. An EN 206-1 harmonized protocol for the 11 selected objects is therefore also given in chapter 3. Such studies should be undertaken in many countries to develop the needed national annexes for a proper implementation of EN 206-1 across Europe, see item 2.3. A first sketch of how such a system might look like, based on best available knowledge and experience, is provided in the present report.

To establish a clearer picture and a better ground for creating a quantitative system a very rough sketch for quantitative classification of exposure classes for *carbonation induced* corrosion, based on “best available “knowledge and experience, and a simplification of the complex models in D3.2 was established (see also item 3.2). This should illustrate a possible structure of such as system. It was realised that not enough compliant environmental and condition assessment data would be available to give ground for a thorough proposal on quantitative classification. As a second strategy it was therefore decided to perform sensitivity analysis of the ingoing parameters in the degradation models, in order to decide upon their importance, and hopefully give ground for proposals of classes and boundaries. This has been done recently by Sascha Lay (D3.2, Draft3, 2003). The results from this will be put in D4.4.

For the corrosion process it is the moisture content and the resistivity of the concrete that determine the rate of the corrosion, i.e. the derived parameters containing the same RH and TOW parameters, see Carbonation model in Table 3. For the high-risk classes of XC3 and XC4 the sketched classifications on object/element level are shown in Table 4. A detailed discussion of the proposal is left for the final system proposal in D4.4.

Table 1 Exposure classes from EN 206-1

Class designation	Description of 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's free/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 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
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:		
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		
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 salts
XF3	High water saturation, without de-icing agent	Horizontal concrete surfaces exposed to rain and freezing.
XF4	High water saturation, with de-icing agent	Road and bridge decks exposed to de-icing agents. Concrete surfaces exposed to direct spray containing de-icing agents and freezing. Splash zone 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 seawater depends on the geographical location; therefore the classification valid in the place of the 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 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 ^{0} C and 25 ^{0} C and at 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 characteristic lead to the same class, the environment shall be classified into the next 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^{2-}_4 mg/l	EN 196-2	≥ 200 and ≤ 600	> 600 and ≤ 3000	> 3000 and ≤ 5000
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	≥ 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
Mg2+ mg/l	ISO 7980	≥ 300 and ≤ 1000	>1000 and ≤3000	>3000 up to saturation
Soil				
SO^{2-}_4 mg/kg [1]total	EN 196-2[2]	≥ 2000 and ≤ 3000[3]	> 3000 and ≤ 12000[3]	> 12000 and ≤ 24000
Acidity ml/kg	DIN 4030-2	> 200 Baumann Gully	Not encountered in practice	

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

[2] The test method prescribes the extraction of SO^{2-}_4 by hydrochloric acid; alternatively, water extraction may be used, if experience is available in the place of use of the concrete.

[3] The 3000mg/kg limit is reduced to 2000 mg/kg, where there is a risk of accumulation of sulphate ions in the concrete due to drying and wetting cycles or capillary suction.

Table 3 Decisive parameters for carbonation

Mechanism	Decisive parameters	Formats	Data needed	
			Network level	Object/element
Carbonation ingress	RH	RH (mean value-std.deviation)	global distribution	local intensity factor[1], such as South, f=0,9-exposed to wind f=0,95-sheltered from wind North, f=1,05-exposed to wind f=1,15-sheltered from wind
	TOW	TOW (fraction of days with rain events>2,5 mm)	global distribution	local intensity factor, such as Horizontal surface: f=1,0 Vertical surface: f=0,8

Table 4 Proposed classifications on object/element level

Class designation (Ref Table 4-1)	Sub-class	RH		Condensation	TOW
		mean (%)	St.d (%)		
XC3 (moderate humidity)	a	>75	<15	none	none
	b	75-85	<15	occasional	none
	c	85-95		frequent	none
XC4 (Cyclic wet and dry)	a	75-85	<15	occasional	occasional
	b	85-95	<15	frequent	occasional
	c	75-95		occasional/frequent	frequent

---

[1] Combined, accounting for drying due to radiation and wind

2.3 Provisions for implementation of EN 206-1 on national level

2.3.1 General

At the 3rd DuraNet workshop “Service Life Design of Concrete Structures – from theory to Standardisation”, Fluge (2001) presented the paper “Marine chlorides - A probabilistic approach to derive provisions for EN 206-1”. The following is an excerpt from this paper of issues of direct relevance for the WP4 objectives.

“To get EN 206-1 operational in the various European Countries, a “National Annex” for each of these nations had to be issued. These annexes comprise provisions depending on geography and well-established regional traditions and experience, but also where it was not practical to achieve European consensus. In Norway, the national standardisation body, The Norwegian Council for Building Standardisation – NBR, established a code committee to work out these requirements.

2.3.2 Inspection of existing marine structures in Norway, especially Gimsøystraumen bridge

Having in mind Norway’s long coast and numerous marine structures, the provisions needed to achieve a relevant set of requirements to ensure the expected in-field performance of chloride exposed structures (exposure classes XS), was considered a key issue.

To derive these provisions, the code committee concentrated on an assessment of the performance of existing structures. These assessments were based on in-field observations processed by the means of a mathematical model for ingress of chlorides in concrete, ref the Duracrete model, Table 9.

During 1999 to 2001, a Norwegian R&D project named “Lifecycle of Concrete Structures” headed by the Norwegian Public Road Administration, compiled and assessed the work done during the 1990s on field-performance of marine concrete structures. These activities comprise offshore structures and a great number of coastal bridges and harbour works.

In particular, the Gimsøystraumen bridge was thoroughly inspected and reported. The bridge was built in 1979 - 81 and inspected and repaired a decade later.

2.3.2.1 Chloride load

The effect of the environment is represented in the surface concentration, $C_{S,}$ in Fick’s second law. This parameter identifies the representative chloride concentration at the concrete surface during the time of exposure. The C_S depends both on the salinity of the water, possibly the porosity of the surface layer (and thus the amount of saline pore water) and the length of wetting versus drying in the splash zone.

Real structures normally experience some abnormality in the achieved chloride profile, probably due to not continuous exposure to spray/splash of seawater combined with periods of washout due to rain.

Typically the measured C_{max} on a bridge girder is distributed over the section as seen from Figure 1. The variations are obviously a result of differences in the microclimate. The influence of rain on the windward side is clear.

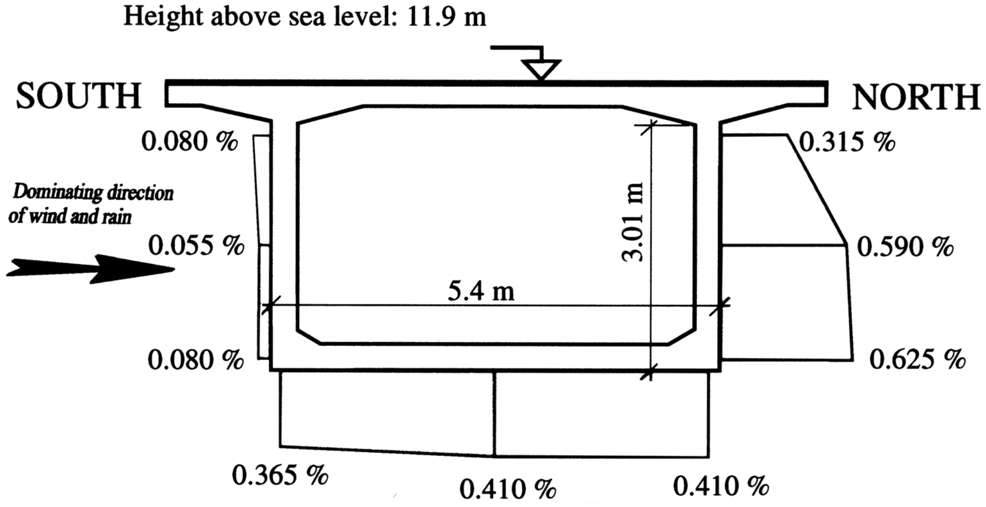

Figure 1 Gimsøystraumen bridge. Influence of microclimate on the environmental load. Cs is given in % of concrete mass (Fluge et al, 2001)

The main inspection/condition survey of the Gimsøystraumen bridge was performed in 1992 at an age of 11 years (4000 days). This included:
- More than 4600 chloride analysis at 920 locations
- 752 of them on the super structure
- 168 on the columns

During the condition survey the following tests were performed:
- Drilled concrete powder (4 holes per test) for chloride analysis
- Measured concrete cover by covermeter
- Chiselling for recording real concrete cover (calibration of the covermeter)
- Evaluation of the level of reinforcement corrosion.
- Recording of electrical potential and electrical resistance in the cover.

Regression analyses were performed in order to determine the chloride load, C_s , and the apparent diffusion coefficient, $D_{app.}$

2.3.2.2 *Influence of height above sea level.*

Figure 2 shows maximum recorded chloride content, C_{max}, at different heights above sea level and include both windward and leeward effects. The data represents, in addition to those from the Gimsøystraumen bridge, also measurements from 35 other coastal bridges representing 850 chloride profiles. In the figure we distinguish between 4 environmental zones:

0 – 3 m above sea level
3 – 12 m above sea level
12 – 24 m above sea level
> 24 m

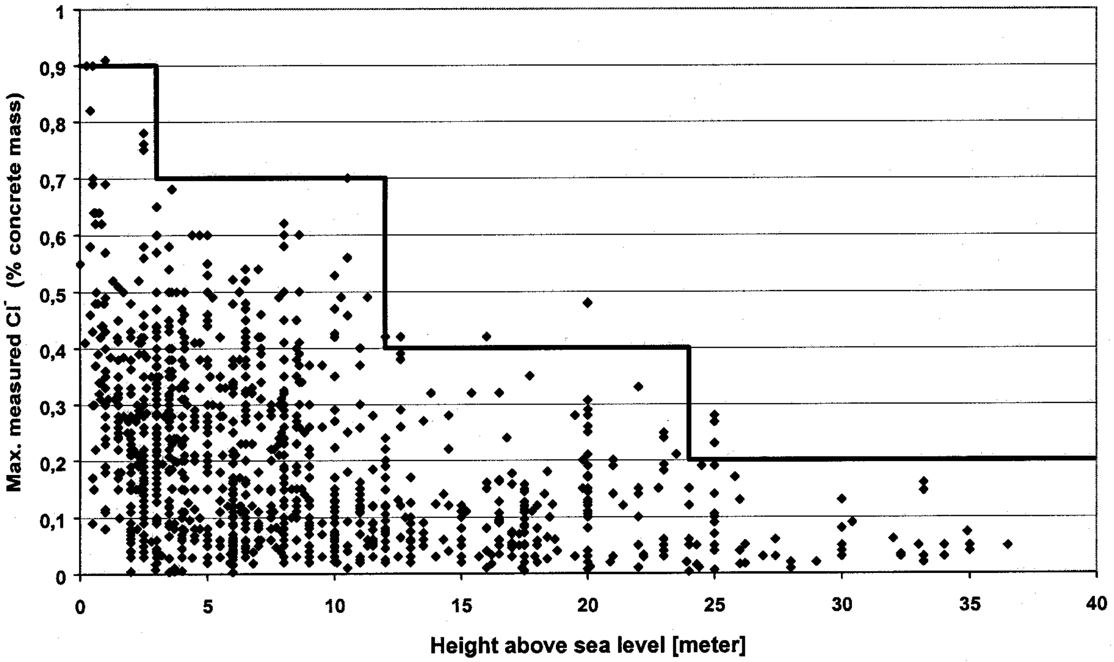

Figure 2 Chloride concentration, Cmax, as function of height above sea level. Values given in Cl⁻ (%) of concrete mass (Fluge, 2001)

The measured profiles have been analysed to derive the C_s – values and these computed data have been used as basis for the further discussions in this paper. In Figure 3 the computed C_s values for the leeward side of the Gimsøystraumen bridge are given. Make notice to the high C_s values over the massive parts of the structure over the columns.

In Table 5 the characteristic C_s is given for 4 zones with different height above sea level. In this presentation, characteristic C_s is defined as $C_{s\ char.} = C_{s,mean} + 1.3\sigma_s$ (10 % of the population has higher concentrations than $C_{s\ char.}$).

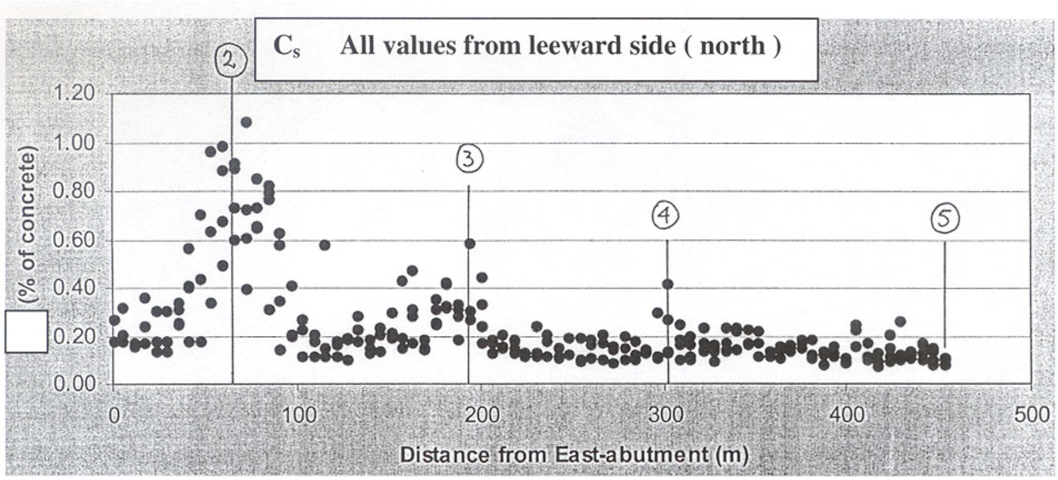

Figure 3 Computed Cs – values for the leeward side of the Gimsøystraumen bridge(Fluge, 2001)

Table 5 Chloride content Cl^- in % of concrete mass

Zone Height above sea level in meter	Concrete load mean values C_s	Standard deviation σ_s	Design value C_{sn} $C_s + 1.3\ \sigma_s$
0 – 3	0.51	0.23	0.81
3 – 12	0.36	0.24	0.67
12 – 24	0.22	0.19	0.47
> 24	0.17	0.10	0.30

2.3.2.3 Threshold value for initiation of corrosion

During the inspection of Gimsøystraumen -bridge in 1992, concrete cover was chiselled away in 110 locations in order to both measure real concrete cover and to evaluate the level of rebar corrosion. The evaluation of rebar corrosion was based on the following corrosion levels:

A: No sign of corrosion
B: Signs indicting depassivation
C: Corrosion
D: Heavy corrosion
E: Severe corrosion, pitting etc.

Figure 4 sums up the findings on both Gimsøystraumen -bridge and other coastal bridges. Corrosion level C indicates start of corrosion and is in our work defined as “failure”. Hence a threshold value of C_{crit} = 0.72 % Cl^- of weight of cement, or 0.13 % Cl^- of concrete mass, has been used in the further computations.

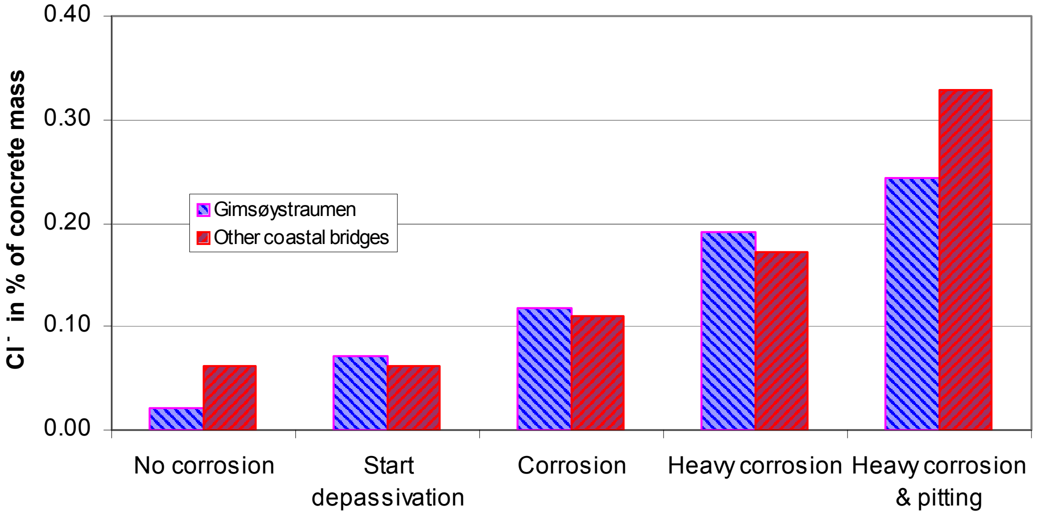

Figure 4. Corrosion levels observed at the Gimsøystraumen bridge and from the general survey of 35 other Norwegian coastal bridges versus chloride content in the concrete. The registrations are based on visual inspection of the rebars after chiselling off the concrete cover at some 300 locations.

2.4 Field studies to develop quantitative exposure classification for EN 206-1

The EN 206-1 system and the first sketch of a proposal (item 2.2), show that quantitative classification of environmental exposure of concrete objects is very complicated. A construction will have many classes dependent on such things as:

- The main type of environment (marine, rural, soil, etc) and the resulting degradation mechanisms (carbonation, etc). Those mechanisms can occur simultaneously.
- Orientation of the component/elements (Category of Location (CoL) in the structure is different (vertical, horizontal, sheltered, submerged, height etc) and covers the whole spectre of possible exposures.
- Micro- environment, the Norwegian assessments of bridges shows clearly the effect of wind and thus the height and distance (Fluge, 2001). Cole (see item 5.4.3) gives the models for sea-salt transport.
- Supplementary materials - a concrete structure always contains supplementary materials, such as steel, painted and/or galvanized, other metals, polymers etc, all of which have their own degradation modes, in addition to influencing the total durability of the structure/components in their combination.

One way a quantitative classification system for environmental exposure can be developed is thus by extensive assessment of the degradation modes and the microenvironment on a sufficient sample of objects in practise. This implies also that National annexes, describing the environmental classes in relation to geography, have to be developed, as shown by the work by the Norwegian Building Standardisation Organisation (Fluge, 2001).

The EN 206-1 should therefore be tested out on the chosen objects, and then eventually the qualitative classes should be replaced by more quantitative classes by way of *comparison of the observed degradation on the objects with the characterisation of environmental parameters on the same objects.*

Thus, in order to develop the instructions for such consistent characterisation (and subsequent classification) of the exposure environment the condition assessment protocol for the selected sample of objects has to be developed with respect to EN 206-1 and quantitative environmental characterisation, see illustrations in Figure 5. The selected objects and the harmonized description towards EN 206-1 is given below, while methods for characterisation of relevant environmental parameters are described in Chapter 7.

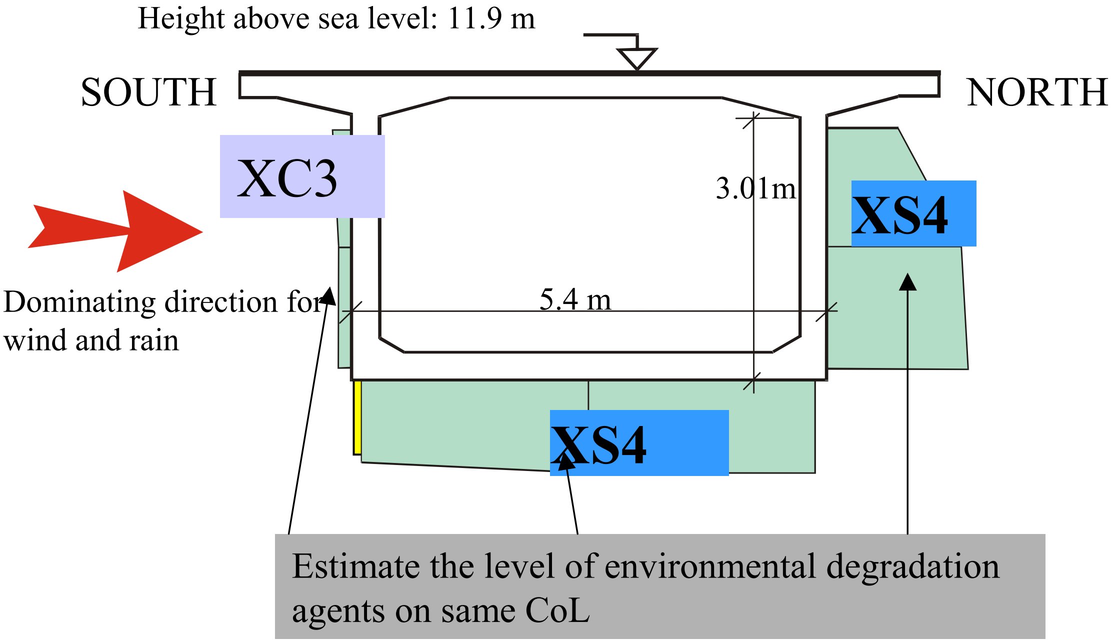

Figure 5 Illustration of assessment approach towards quantitative environmental characterisation. The various components with categories of location are classified according to EN 206-1, and DoD are recorded. Then the environmental loads, C_s, are estimated by methods and models given in chapter 5.

Exposure classes from EN 206-1describes the structures nominated for assessments in LIFECON (from D6.1), while the criteria for selecting the sample of 11 objects for detailed case studies is given below. In order to be able to do a comparative assessment of degradation and exposure environment the condition assessment protocol with respect to EN 206-1 and quantitative environmental characterisation are further developed, see item 2.4.3.

The EN 206-1 classes are allocated to the main structure based on the descriptions taken from D6.2, and a best possible guess towards the EN 206-1 exposure class description. These will definitely have to be re-evaluated and expanded in the field assessments. Further, when dividing the structure into components the corresponding EN 206-1 classes have to be attained to the components. Those can differ substantially from the main structure due to category of location, micro -environment, etc. This approach is chosen also in the developed guidelines for choice of exposure classes in the Swedish national Annex to EN 206-1 (Svenska Betongföreningen, 2002).

Also the Degree of Deterioration (DoD), according to WP3, should be recorded for the same components, facilitating then also the basis for doing quantitative classification.

A total of 20 structures were nominated, covering
- 15 bridges, 3 buildings, 1 wharf and 1 lighthouse.
- 5 countries from north and central Europe: Sweden, Norway, Finland, Germany and UK,
- three degradation mechanisms, carbonation, chloride and chloride/freeze/thaw
- and three main exposure types or locations: maritime, urban and non-urban
- a range of conditions from no visible corrosion to severe corrosion with cracking and spalling

After nomination it was decided to select a few for case studies and validation.

The selected objects for case studies are shown in Table 7:
- One carbonation mechanism was nominated and selected as a case study, Structure No.3
- One wharf was nominated and selected as a case study, Structure No.1
- Three structures with no visible corrosion were nominated; of these only one has comprehensive data and also has central European location. Structure No. 6 was selected
- Three young structures with low level of cracking and a combination of chloride, carbonation and freeze/thaw were nominated, Structures No.12, No.16 and No.17. Structure No.16 was selected as having the more comprehensive data available
- To compliment the structures selected to date an urban bridge with a high degree of damage, Structure No.8, was selected.
- Structure No.19 was selected to provide a second building and a second maritime structure as well as being from a fifth country.
- An additional bridge was selected to cover the age and condition of those to be used in the validation procedure. Structure No.9 was selected.
- A tunnel structure was supplemented to those already nominated at the Munich meeting. As tunnels had been specifically identified for investigation in the LIFECON proposal this was selected as a case study, classified as Structure No.21.
- The owners/users felt that an additional structure was required and as such structure No.2 was selected.

Table 6 Structures nominated for assessments in LIFECON

No.	Name	Structure Type	Age	Degradation Mechanism	Condition	Location	Environment	Exposure Condition	Socio/ Ecological Impact	Range of Data	Availa-bility of Data
1	Ormsund	Wharf	15-20	Chloride	Extensive corrosion, delamination, spalling	North European	Maritime	Severe	Severe disruption	Comp	***
2	Hamborsund	Lighthouse	50	Chloride Carbonation		North European	Maritime	Severe	Severe disruption	Comp	**
3	Congress Centre	Building	30-40	Carbonation	Spalling	North European	Urban	Light	Moderate disruption	Routine	**
4	Midland Links	Viaduct	30-40	Chloride	Extensive corrosion, spalling, repair (CP)	North European	Urban/ Industrial	Severe	Severe disruption	Comp Routine	* **
5	Waghausel	Overpass		Chloride	Rust staining, cracking	Central European	Non-urban	Moderate	Severe disruption	Comp	**
6	Hofham	Bridge (reinforced)	38	Chloride	No visible deterioration	Central European	Non-urban (rural)	Moderate	Low level disruption	Comp	***
7	Munich-City	FootBridge (reinforced)	31	Chloride	spalling	Central European	urban	Moderate	Low level disruption	Comp	***
8	Faeltskaersled	Bridge (reinforced)	40	Chloride	Rust staining, cracking, damage to waterproofing	North European	Urban	Severe	Severe disruption	Comp	***
9	Backbron	Bridge (reinforced)	63	Chloride	Extensive corrosion, cracking,	North European	Non urban	Severe	Moderate disruption	Comp	***

					spalling repairs						
10	Kvarnbron	Bridge Pre-stressed	24	Chloride Frost	Slight cracking, frost damage	North European	Non Urban	Severe	Severe disruption	Comp	***
11	Joakims Backe	Bridge	38	Chloride, Freeze/thaw	Frost damage Corrosion of balusters	North European	Non Urban	Moderate	Low level disruption	Comp	***
12	T-1934	Bridge (reinforced)	17	Chloride, Carbonation, Freeze/thaw	surface staining/fine cracking	Northern European	Urban	Severe	Low level disruption	Routine	***
13	Vuolle H-118	Bridge (Arch/Vault)	62	Chloride, Carbonation	water leakage, cracking	Northern European	Non-Urban, inland	Severe	Severe disruption	Routine Comp	***
14	Oripohja H-714	Bridge (reinforced)	40	Chloride, Freeze/thaw	delamination	Northern European	Non-Urban, inland	Severe	Severe disruption	Routine	***
15	Vikkiniitty H-1078	Bridge (reinforced)	33	Chloride, Carbonation	Decadex treatment since 1993, delamination	Northern European	Non-Urban, inland	Severe	Low level disruption	Routine	***
16	Ojoinen H-2486	Bridge (reinforced)	17	Chloride, Carbonation, Freeze/thaw	surface staining/fine cracking	Northern European	Non-Urban, inland	Severe	Moderate disruption	Routine Comp	***
17	AuringonlahdeH-2493	Bridge (reinforced)	10	Chloride, Carbonation, Freeze/thaw	no visible deterioration	Northern European	Non-Urban, inland	Severe	Severe disruption	Routine	***
18	Ounasjoki L-1905	Bridge (reinforced)	11	Carbonation	no visible deterioration	Northern European, Lapland	Urban	Severe	Moderate disruption	Routine	***
19	Cooling Water structures	Building	~30 yrs	Chloride	Cracking, spalling	Northern European	Maritime, industrial	Severe	Low level disruption	Visual inspection	*** *

										If problems found, routine data	
20	Turbine Hall structures	Building	~30 yrs	Chloride, carbonation?	No visible deterioration	Northern European	Maritime, industrial	Moderate	Low level disruption	Visual inspection If problems found, routine data	***
21	*Oslo City Centre*	*Tunnel*	~40 yrs	*Water leakage*	*Subsidence*	*North European*	*Urban*	*Severe*	*Severe*	*Routine*	**

Table 7 Selected sample of objects in LIFECON

Object location				Object Type			Type of Environment		Degradation mode			Exposure classes from EN 206-1	
No.	Country	Name	Region	Object	Element/component	Age	Main	EOTA[2]	Deg. Mec[3]	Effects	DoD	Class	Desciption of Environment
Maritime													
1	No	Ormsund	NE	Wharf	Deck PIllar etc.	15-20	Maritime	B/A?	Chloride from sea	Extensive corrosion, delamination, spalling	To be recorded, ref WP3	XS3	Tidal, splash and spray. Parts of a marine structure
2	NO	Homborsund	NE	Lighthouse	Wall Window	50	Maritime	B/A?	Chloride from sea	No registration	?	XS1	Airborne salt, no direct contact. Structures near to or on the coast
									Carbonation			XC4	Cyclic wet and dry. Subject to water contact
Maritime/industrial													
19	UK	Cooling water structure	NE	Building	Wall Window	30	Maritime/industrial	B/C?	Chloride from sea	Cracking, spaling	?	XS1	Airborne salt, no direct contact. Structures near to or on the coast
									Carbonation			XS4	Cyclic wet and dry. Subject to water contact
Urban													
3	UK	Congress centre	NE	Building	Wall	30-	Urban	B/C?	Carbonation	Spallin	?	XC3?	Moderate humidity –

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[2] EOTA Temperature limatic zone

[3] Degradation Mechanism

					Window	40				g			Concrete inside buildings, external sheltered from rain
8	SE	Fältskärsleden	NE	Bridge	Superstructure Beam Deck	40	Urban	B/A?	Chloride from sea	Rust staining, cracking, damage	?	XS3	Tidal, splash and spray. Parts of a marine structure
12	Fi	T-1934	NE	Bridge	Superstructure Beam Deck	17	Urban	B/A?	Chloride other than from sea	Surface staining, fine cracking	?	XD3?	Cyclic wet and dry. Parts of bridges exposed to spray containing Chlorides
									Carbonation			XC4?	Cyclic wet and dry. Subject to water contact, not within XC2
									Freeze/thaw			XF3?	High water saturation, without de-icing agents, horizontal surfaces
21	NO	Oslo City Centre	NE	Tunnel		40	Urban		Not given	Water leakage, subsidence			
Rural													
6	GE	Hofham	CE	Bridge	Superstructure Beam Deck	38	Rural	B/C?	Chloride other than from sea	No visible deteoriation	?	XD3?	Cyclic wet and dry. Parts of bridges exposed to spray containing Chlorides

9	SE	Backbron	NE	Bridge	Superstructure Beam Deck	63	Rural	B/A?	Chloride from sea	Extensive corrosion	?	XS3	Tidal, splash and spray. Parts of a marine structure
16	FI	Ojonen H-2486	NE	Bridge	Superstructure Beam Deck	17	Rural	B/A?	Chloride other than from sea	Surface staining, cracking	??	XD1	Cyclic wet and dry-parts of bridges exposed to spray containing chlorides
									Carbonation			XC4?	Cyclic wet and dry. Subject to water contact
									Freeze/thaw			XF3?	High water saturation, without de-icing agents, horizontal surfaces
17	FI	Auringonlahde H-2493	NE	Bridge	Superstructure Beam Deck	10	Rural		Chloride other than from sea	No visible deterioration	?	XD1	Cyclic wet and dry-parts of bridges exposed to spray containing chlorides
									Carbonation			XC4?	Cyclic wet and dry. Subject to water contact
									Freeze/thaw			XF3?	High water saturation, without de-icing agents, horizontal surfaces

3. Degradation models and environmental degradation factors in LIFECON

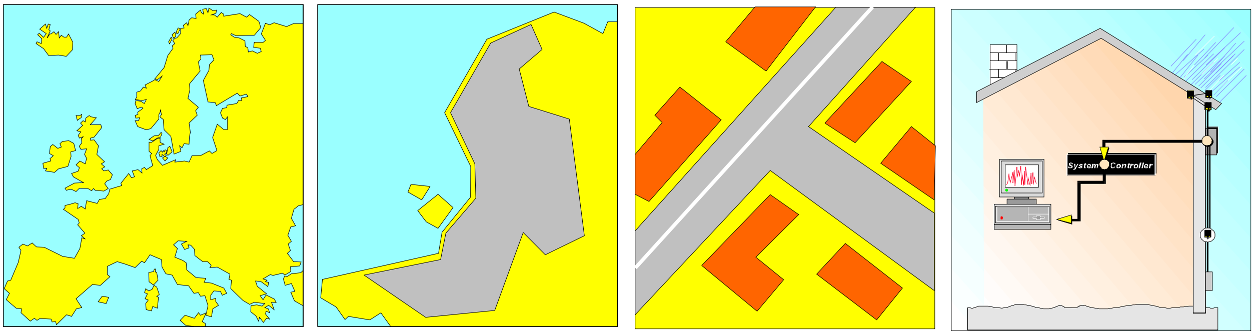
3.1 Holistic degradation model and environmental agents.

The degradation of the concrete structure are influenced by a whole set of factors such as environmental degradation factors, type and quality of the concrete, protective treatment, etc.

The relationship between the environmental degradation agents and the observed effects are expressed as dose-response functions. The dose-response functions are not directly suitable for service life assessments. To transform the degradation into service life terms, performance requirements or limit states for allowable degradation before maintenance or complete renewal of material or component, have to be decided. The dose-response function then transforms into a damage function, which is also a performance over time function, and a service life assessment can be made.

The establishment of the limit state is complicated, and can be discussed both from a technical, economic and environmental point of view, as reflected in the LIFECON objectives.

However, in order to characterise and report the right type and form of the environmental degradation agents, they have to be related to the degradation mechanism and dose-response functions for the specific materials in question. Further, a holistic approach modelling the physical processes controlling the corrosion needs to be considered across a wide range of physical scales, from macro through meso/regional to local, micro and lastly micron. These scales are defined in line with CIB, see Figure 6, (from Haagenrud, 1997), EOTA (1999) and recently Cole, Figure 7, (from Cole, 2003), which also is in accordance with the definitions put forward for concrete in the BriteEuram project BE95-1347, see Figure 8. Macro refers to gross meteorological conditions (polar, subtropical etc.), meso or regional refers to regions with dimensions up to 100 km, local is in the immediate vicinity of a building, while micro refers to the absolute proximity of a material surface, see Figure 6 and Figure 7.



Macro-Europe map **Meso-**urban area **Local-**road / building **Micro-**building

Figure 6 Exposure environment on different geographical scales (Haagenrud, 1997).

Surface response then refers to largely physical responses of a surface such as deposition and retention of pollutants or condensation and evaporation. Micron then refers to interactions within the concrete/metal/oxide/electrolyte interfaces. In this approach, models on different dimensional scales are linked together so that the models on the micron level are informed by models on the macro-, meso-, micro- and surface response regimes.

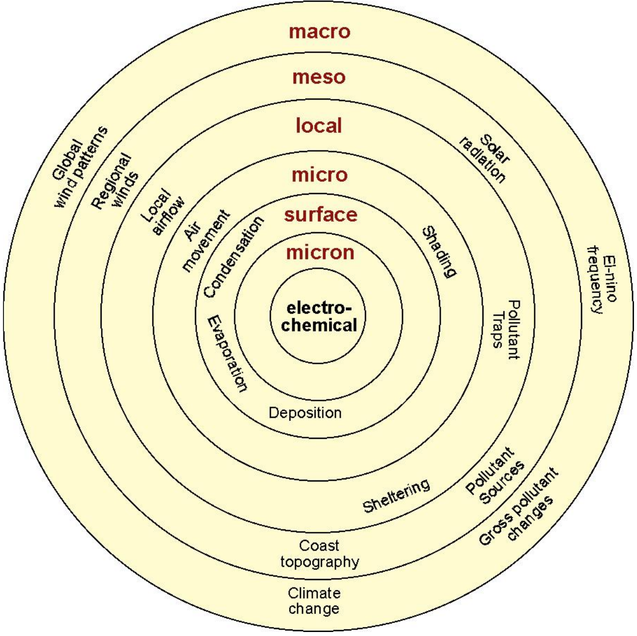


Figure 7 Framework for holistic model of corrosion, from Cole (2003)

To make precise predictions of the deterioration of a concrete structure the knowledge of the surface conditions are not enough. The response in the structure from the environmental actions should be recorded. The above definitions and models are therefore in accordance with degradation concept for concrete as described in f.ex the BriteEuram project BE95-1347, Figure 8, and which has been the basis for developing the Duracrete models as shown in WP3.

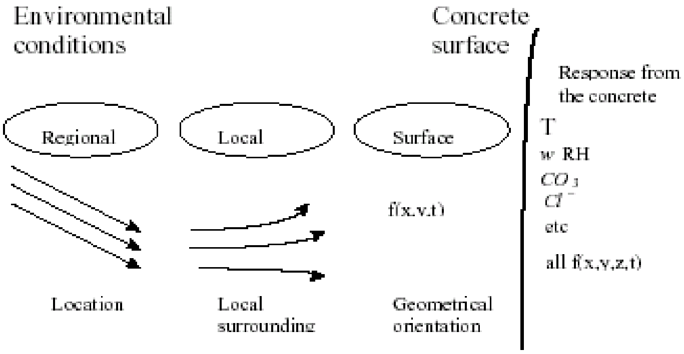


Figure 8 Environmental conditions and the response from the structure (BriteEuram project BE95-1347)

3.2 Degradation models and needed environmental data (from D4.1)

Table 8 shows the needed environmental data as extracted (in D4.1) from the Duracrete models for object level (D3.2) and the "Vesikari" models for network level, and damage functions for some of the most important supplementary materials. These are the primary data, while Table 9 to Table 15 lists the complete functions with derived parameters (example k_{RH} or W from carbonation equation) and formats for the parameters.

The characterisation will concentrate on the primary parameters. As for the format it will be given as mean values with standard deviations. This will also be the format for the parameters of classification in the sensitivity analysis of the Duracrete models, as performed in D3.2 (item 2.2).

Table 8 Relevant environmental data for degradation models linked to concrete structures

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

(X) = contained as derived parameter

Table 9 Input data for carbonation depth

Degradation model Carbonation depth	$X_c = \sqrt{2k_{RH}k_c\left(k_t R_{ACC}^{-1} + \varepsilon_t\right)\Delta C_s}\,\sqrt{t}\left(\frac{t_0}{t}\right)^w$				
Input parameter (primarily)	Sub model		Input data	Time period	Data source
KRH, influence of moisture at the concrete surface [-]	$K_{RH} = \left(\frac{1-RH^f}{1-RH_{ref}^f}\right)^g$		RH, relative humidity [%]	Daily mean	Nearby meteorological station
			RH_{ref}, relative humidity, reference [%]		
w, weather exponent taking into account the micro climate [-]	Horizontal $w = a_W TOW^{b_w}$	Time of wetness [-] ToW = (hrain > 2.5 mm/day)/365	Hrain, days with rain > 2.5 mm [-]	Yearly	Nearby meteorological station
	Vertical $w = \frac{\left(P_{splash} TOW\right)^{b_w}}{2}$	Time of wetness [-] ToW = (hrain > 2.5 mm/day)/365	Hrain, days with rain > 2.5 mm [-]	Yearly	Nearby meteorological station
		Psplash, probability of a splash event [-] Psplash = sum{d(w+r)}/ sum{d(r)}	d(w+r), days with wind in considered direction during a rain event of hrain > 2.5 mm [-]	Yearly	Nearby meteorological station
			d(r), days with rain events of hrain > 2.5 mm [-]	Yearly	Nearby meteorological station
ΔC_S, CO_2 concentration of the atmosphere [kg	$\Delta C_S = C_{S,ATM} + \Delta C_{S,Em}$		CS,atm back ground level of CO2 concentration [kg CO2/m³]	Yearly mean	Environmental research institute

CO_2/m^3]			ΔCS,em local addition [kg $CO2/m^3$]	Yearly mean	Local measurements

Table 10 Input for Chloride concentration at different depths

Degradation model Chloride concentration at depth x at age t [g/l]		$C(x,t) = C_{s,\Delta x} \cdot \left[1 - erf\left(\frac{x - \Delta x}{2\sqrt{t \cdot D_{eff}(t)}}\right)\right]$				
Input parameter (primarily)	Sub-model			data	Time period	Data source
C_s, Δx chloride concentration on surface towards depth Δx [g/l]	Off-shore structures $C_s = C_{sea}$			C_{sea}, chloride content of seawater [g/l]	Yearly	Hydrological Institute
	Roads $Cs = C_{road}$	Croad = nCr/hs		n, number of de-icing salt application incidents [-]	Monthly	Road administration office
				Hs, precipitation during salt application period [l/m²]	Monthly	Nearby meteorological station
			Cr = 1000(-9.56+0.52SF +0.38SL+0.14FD-0.20ID)/w Average amount of de-icing salt for each application incident [g/m²] or eq. 1[4] from D 3.2	SF, number of days with snow fall > 0.1 mm [-]	Monthly	Nearby meteorological station
				SL, number of days with a snow layer > 100 mm [-]	Monthly	Nearby meteorological station
				FD, number of days with a average daily temperature > 0° C [-]	Monthly	Nearby meteorological station
				ID, number of days with ice on road surface [-]	Monthly	Road administration office

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[4] $C_{\Delta x,mean}(a,h) = 0.465 - 0.051*\ln(a+1) - (0.00065*(a+1)^{-0.187})*h$, see also page 47

				w, average spread width (street width) [m]	Monthly	Road administration office
D_{app}, apparent diffusion coeffi-cient of co the time of ir [m²/s]	$D_{eff}(t) = k_{RH} \cdot D_{RCM,0} \cdot k_t \cdot k_T \cdot \left(\frac{t_0}{t}\right)^n$			kRH, moisture influence on Diffusion coefficient		
			$k_T = \exp\left(b_T\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right)$	T, temperature [K]	Monthly	
				Tref, reference temperature [K]		

Table 11 Input for propagation loss of rebar diameter

Degradation model Propagation of corrosion, loss of rebar diameter [mm]	$\boxed{P(t) = V_{Corr}\alpha t}$					
Input parameter	Sub model			Input data	Time period	Data source
Vcorr, corrosion rate [mm/year]	Icorr, corrosion current [mA/cm²]	ρ(t), resistivity of concrete at time t [Ωm]	Kr,t temperature factor [-]	T, temperature [K]	Monthly mean	Nearby meteorolo-gical station
			Kr,rh humidity factor [-]	RH, humidity [%]	ly mean	Nearby meteorolo-gical station
			Kr,cl chloride factor [-]	Ccl, chloride content [g/l]		Local measure-ments
	ToW, time of wetness [-] ToW = (hrain > 2.5 mm/day)/365			Hrain, days with rain > 2.5 mm [-]	Yearly	Nearby meteorolo-gical station

$$V_{Corr} = 0{,}0116 * i_{Corr}$$

$$i_{Corr} = \frac{k_0}{\rho(t)} F_{Cl} F_{Galv} F_{o^2}$$

$$K_{R,T} = \frac{1}{1 + K(T-20)}$$

$$\rho(t) = \rho_0 k_C k_t k_{R,T} k_{R,RH} k_{R,Cl} \left(\frac{t}{t_0}\right)^n =$$

$$k_{R,RH} = \left(\frac{100}{RH}\right)^a$$

$$V_{Corr} = V_{Corr,a} TOW$$

Table 12 Input for frost attack

Degradation model Frost-attack/(internaldamage), $Pf(t)=P\{S(t)>Scr\}$ failure probability [-]				
Input parameter (primarily)	**Sub model**	**Input data**	**Time period**	**Source**
$S(t)$, actual degree of saturation [-]	$S_{max}(t)$, maximum degree of saturation within a given time [-] $S_{max}(t) = Sk+bt_{max}$	t_{max}, longest wetting period within the considered period [-]	Monthly	Nearby meteorological station

Table 13 Input for deterioration of zinc coated galvanised steel

Dose-response function $ML = 1.4[SO_2]^{0.22}\exp\{0.018Rh + f(T)\}t^{0.85} + 0.029Rain[H^+]t$ Zinc coated galvanised steel				
Input parameter (primarily)	**Sub model**	**Input data**	**Time period**	**Source**
f(T), temperature dependency [-]	f(T) = 0.062(T-10) when T<10°C	T, temperature [°C]	Yearly, mean	Nearby meteorological station
	f(T) = -0.021(T-10) when T ƒ10°C			
SO_2		SO_2, atmospheric concentration [µg/m³]	Yearly, mean	Environmental research institute
RH		RH, relative humidity [-]	Yearly, mean	Nearby meteorological station
Rain		Rain, precipitation [m]	Yearly	Nearby meteorological station
[H+]		[H+], concentration at surface [g/l]	Yearly, mean	Environmental research institute

Table 14 Input for deterioration coil coated steel

Dose-response function Coil coated steel	$(10\text{-ASTM}) = (0{,}0084[SO_2] + 0{,}015Rh + f(T))t^{0{,}43} + 0{,}00082Rain \cdot t^{0{,}43}$			
Input parameter (primarily)	**Sub model**	**Input data**	**Time period**	**Source**
f(T), temperature dependency [-]	$f(T) = 0.040(T-10)$ when $T<10°C$	T, temperature [°C]	Yearly, mean	Nearby meteorological station
	$f(T) = -0.064(T-10)$ when $T>10°C$			
SO_2		SO_2, atmospheric concentration [µg/m³]	Yearly, mean	Environmental research institute
RH		RH, relative humidity [-]	Yearly, mean	Nearby meteorological station
Rain		Rain, precipitation [m]	Yearly	Nearby meteorological station

Table 15 Input for mass loss aluminium

Dose-response function (4-year) Aluminium	$4ML = 0.85 + 0.028\ ToW\ [SO_2]\ [O_3]$ (unsheltered) $4ML = -0.03 + 0.053\ ToW\ [SO_3]\ [O_3] + 74\ [Cl-]$ (sheltered)			
Input parameter (primarily)	**Sub model**	**Input data**	**Time period**	**Source**
ToW	Time of wetness [-] ToW = (h_{rain} > 2.5 mm/day)/365	H_{rain}, days with rain > 2.5 mm [-]	Yearly	Nearby meteorological station
SO_2		SO_2, atmospheric concentration [µg/m³]	Yearly, mean	Environmental research institute
O_3		O_3, atmospheric concentration [µg/m³]	Yearly, mean	Environmental research institute
Cl^-		Cl^-, atmospheric deposition [mg/m², day]	Yearly, mean	Environmental research institute

4. Systematic and options for Classification of environmental degradation factors and corrosivity

4.1 Introduction

Characterising and subsequently classifying the exposure environment in order to assess the aggressivity towards building materials and components have been attempted for about three decades, and some systems do exist. Some of the most relevant systems are described in the following, as basis for a discussion on whether the degradation agents chosen and their class boundaries are relevant and feasible for describing the generic environmental risk of degradation of the different concrete constructions.

For *quantitative* classification of atmospheric environmental loads there are two *options* as shown by description of the existing and emerging classification systems within ISO and EOTA. Some systems try to classify the *generic atmospheric aggressivity* on a global to local scale (ISO 15686 “Service Life Planning - Part 4” and EOTA), without specific knowledge of damage functions, but based on overall experience of materials degradation at large. The other option and systematic is material (family) specific and based on knowledge of their damage functions, such as ISO 9223 that are specific for metals. This is the preferred systematic (ref objectives), but requires that the type and format of the ingoing environmental agents are defined, and that the function(s) are relatively simple for practical purposes.

4.2 Systems for classification of generic aggressivity

Below are quoted the European based system proposed by EOTA and the global system proposed by ISO/TC59/SC14 “Design Life”.

4.2.1 EOTA - Annex A Building context (EOTA, 1999)

Quoted from the EOTA document on “Working Life of Building Products”: “The wide variation in European climatic conditions and in the user stresses imposed on structures depending upon type of structure and use intensity will make it necessary with many construction products to restrict their usage to defined situations in order that these achieve the predicted working life.”

Then follows examples of possible sub-divisions of climatic zones in Europe, of orientation of products/components in structures, of internal exposure environments in buildings, etc. The EOTA-proposed macro climatic sub-division is used in the condition assessment protocol for environmental characterisation of selected objects, see Table 17.

4.2.2 ISO 15686 Service Life Planning-Part 4

The suggestions for classification are from ISO/WD 15686-4 Buildings – Service Life Data Sets – Part 4 (ISO WD, 2002). It contains a proposal for:

1. Simplified Global climatic classification with respect to two main factors, *rainfall/humidity and temperature*.
2. Simplified Global pollutant classification divided into two main areas, *industrial pollution* and *marine pollution.* The pollutant classification is with the following definitions:
    - Severe Marine (SM). Airborne salinity exceeds a daily average of 300 mg/m^2/day.

    - Marine (M). Average daily airborne salinity is between 60 and 300 $mg/m^2/day$.
    - Severe industrial (SI). Airborne SOx level exceeds 200 $mg/m^2/day$.
    - Industrial (I). Airborne SOx level is between 60 and 200 $mg/m^2/day$.
    - Severe Industrial and Marine (SI+M). Airborne salinity exceeds 300 $mg/m^2/day$ and SOx level exceeds 200 $mg/m^2/day$.
    - Light Marine or Industrial. Either:
        - Airborne salinity is between 15 and 60 $mg/m^2/day$.
        - Airborne SOx level is between 10 and 60 $mg/m^2/day$.
        - Rain water pH<5.5
    - Benign (B). All the following must be met:
        - Airborne salinity < 15 $mg/m^2/day$
        - Airborne SOx < 10 $mg/m^2/day$
        - Rain water pH> 5.5

   From those classes a combined system can be established by combining the climate with its subclass versus the pollutant source. The environment can be defined by a three-figure number where the first number defines the pollutant sources (severe marine and severe industrial (SM+SI=1) to benign (B=9), the second defines the major climatic class (1 for dry to 4 for very humid), and the third defines the sub-class (1 for cold to 3 for hot).
3. Detailed classification of moisture from rainfall and relative humidity. Another, more detailed approach for classification of moisture is to use the Annual Rainfall and Annual Relative Humidity.
4. Detailed pollutant classification of Airborne Salinity, frequency of significant salt deposition/frequency of rain.

4.3 Systems for classification of atmospheric corrosivity of specific materials

4.3.1 ISO 9223-26 Classification of atmospheric corrosivity for metals

The standards ISO 9223–9226 *Corrosion of metals and alloys – Corrosivity of atmospheres* have been developed for the classification of atmospheric corrosivity of metals and alloys. The development was based on the Czech classification philosophy, where the approach was used as early as 1975 to map the atmospheric corrosivity for the North Bohemian region (Knotkova, 1996). Based on a huge amount of experimental data for empirical dose-response functions the standards use both the approach of classifying the degradation factors and the corrosion rates.

The **ISO 9223 – Classification**, specifies the key factors in the atmospheric corrosion of metals and alloys, which are *time-of-wetness (τ), sulphur dioxide (P) and air-borne salinity (S).* Corrosivity categories (C), are defined on basis of these three factors and used for the classification of atmospheres for the metals/alloys-unalloyed steel, zinc and copper, and aluminium. TOW is described in five classes, classification of SO_2 and chloride is done in four classes, and the corrosivity in five classes. The classification can be used directly to evaluate the corrosivity of atmospheres under known conditions of these environmental factors, and for technical and economical analyses of corrosion damage and choice of protection measures.

The ISO 9223 approach has since the mid 80-ies been used by many researchers to classify and map the atmospheric corrosivity (Haagenrud, 1997).

4.3.2 ISO DIS 12944-2 Paints and varnishes

The ISO 9223 approach for classification of the atmospheric corrosivity has also, with complementary amendments, been used for an appropriate description of the degradation environment for non-metals, such as the ISO DIS 12944-2: Classification of environments. This standard deals with the classification of the principal environments to which steel structures are exposed, and the corrosivity of these environments. It defines atmospheric-corrosivity categories, based on ISO 9223 and ISO 9226.

4.4 Discussion of feasibility for LIFECON

The semi-quantitative/generic aggressivity approach, -combining the IS0 15686-4 and EN 206-1 approach by trying to attach some quantitative values of main degradation factors (such as T, rain, RH, salinity, CO2, radiation) to the various exposure classes, i.e. like the soil and groundwater classes, is one optional avenue for a quantitative classification system. Those classes may also give guidance for the limiting values for the atmospheric exposure.

The LIFECON project should discuss whether these systems in terms of degradation agents and class boundaries, are feasible and appropriate for the needed quantitative classification system for concrete structures. As it is an overall, generic system for classification of aggressivity, it seems unlikely that it can be directly adopted for concrete. At present it is not possible to draw any strict conclusions.

The material specific classification systems (item 5.3) should be directly applicable for the same supplementary materials on the constructions.

5. Methods and data for assessments, modelling and mapping of degradation agents

5.1 Summary

Regarding the requirements for environmental data it is shown that such data and models are available from meteorological offices and the environmental research area, and that these data and the work performed are directly applicable for LIFECON. Also other methods and models, like prEN 13013 and CFD models are available for transforming environmental loads from local to microenvironment on structures. All those issues are more detailed described in the Annexes.

When the degradation factors have been assessed and modelled the LMS’ Environmental Risk Factor (ERF) and Service Life Prediction (SLP) module will contain tools that allow for modelling and mapping also of the corresponding damage –and service life functions. Some examples are shown.

As the IT systems are used for the purpose of exhibiting available degradation data and models those are briefly described first.

5.2 IT based systems available for LMS

5.2.1 ENSIS - Air quality and corrosion cost information systems

Today, surveillance and management of air quality can be facilitated and performed via total information systems. The Air Quality Information System, ENSIS Air, represents the air pollution part of a modern Environmental Surveillance and Information System, ENSIS (Bøhler, 2000). The ENSIS system contains two modules, ENSIS Air and ENSIS CosBen, both of which will be available in the LMS of LIFECON. The combination of on-line data collection, statistical evaluations and numerical modelling enable the user to obtain information, carry out forecasting and future planning of air quality. The system can be used for monitoring and to estimate environmental impacts from planned measures to reduce air pollution.

The ENSIS Air system contains the following modules (see Figure 9)

- On-line monitoring,
- Data handling and quality control,

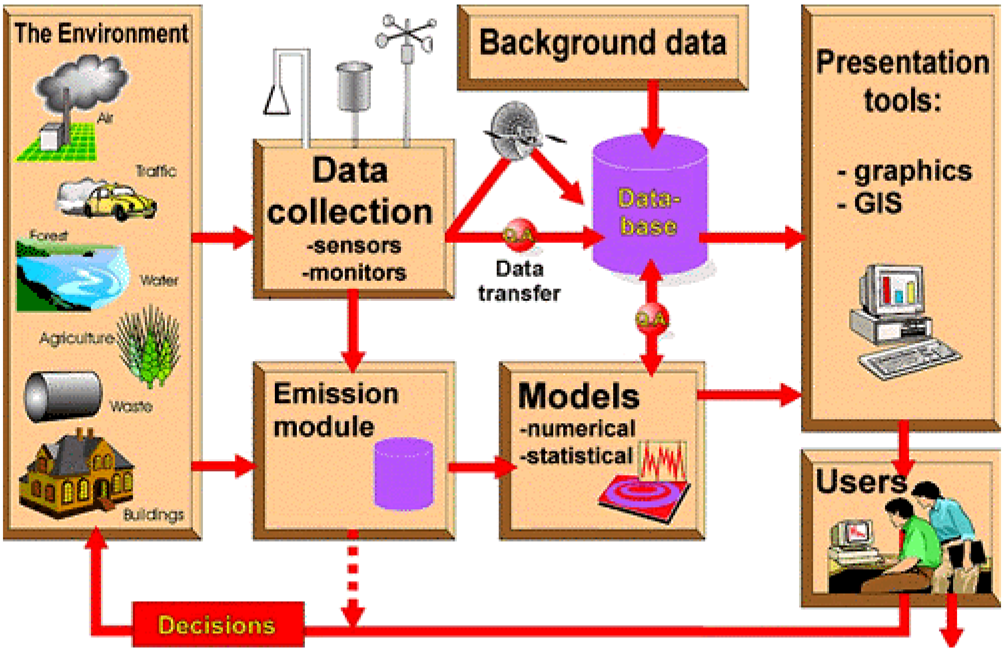


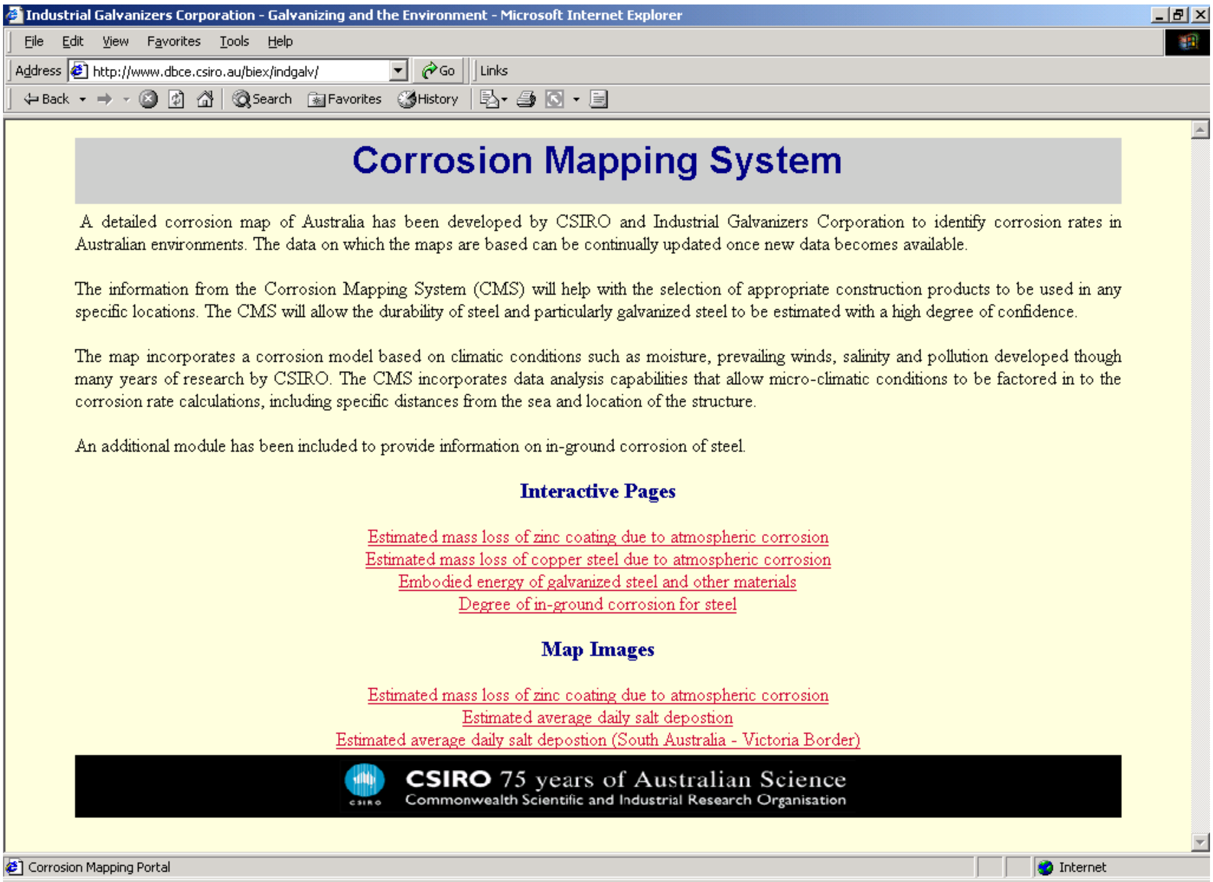
Figure 9 Modules of ENSIS

- Modern data bases,
- Emission inventories,
- Numerical dispersion models
- Generation of wind fields
- Presentations based upon a geographical information system (GIS)
- Exposure models for materials and human health

The exposure module for buildings/materials is called CosBen and is used to do cost benefit analysis for corrosion on buildings based on available damage functions, environmental exposure data and cost functions (Haagenrud et al, 1996). This module is available for the LMS system. Examples are shown in the following.

5.2.2 Australia

Cole (1999) has also used GIS based systems to model and exhibit climatic and pollutant parameters for Australia and South East Asia (CIB, 2000 and Cole, 1999). On contract by the Australian Galvanizers Association he has used this to map the corrosivity and Service life for galvanized coatings in Australia and South East Asia, Figure 10, (http://www.dbce.csiro.au/biex/indgalv/).



Corrosion Mapping System

A detailed corrosion map of Australia has been developed by CSIRO and Industrial Galvanizers Corporation to identify corrosion rates in Australian environments. The data on which the maps are based can be continually updated once new data becomes available.

The information from the Corrosion Mapping System (CMS) will help with the selection of appropriate construction products to be used in any specific locations. The CMS will allow the durability of steel and particularly galvanized steel to be estimated with a high degree of confidence.

The map incorporates a corrosion model based on climatic conditions such as moisture, prevailing winds, salinity and pollution developed though many years of research by CSIRO. The CMS incorporates data analysis capabilities that allow micro-climatic conditions to be factored in to the corrosion rate calculations, including specific distances from the sea and location of the structure.

An additional module has been included to provide information on in-ground corrosion of steel.

Interactive Pages

Estimated mass loss of zinc coating due to atmospheric corrosion
Estimated mass loss of copper steel due to atmospheric corrosion
Embodied energy of galvanized steel and other materials
Degree of in-ground corrosion for steel

Map Images

Estimated mass loss of zinc coating due to atmospheric corrosion
Estimated average daily salt depostion
Estimated average daily salt depostion (South Australia - Victoria Border)

Figure 10 Web-page showing the Corrosion Mapping System of CSIRO

5.2.3 Computational Fluid Dynamics models (CFD)

Computational Fluid Dynamics (CFD) has been used in several studies concerning environmental exposure of building. The wind pattern around buildings is determined by solving Navier-Stokes equations, and the distribution of snow, rain and gaseous components is found using the wind pattern and transport equations. The use of Computational Fluid Dynamics (CFD) gives the possibility to calculate the microclimate around the construction as well as at the surfaces.

This methodology is now extensively used by NBI, which will use it to calculate the micro-environmental pattern around the two chosen objects for NCD (Thiis, 2002). The methodology will be made available for LMS.

Figure 11 shows the wind pattern around city like building environment with a high-rise building.

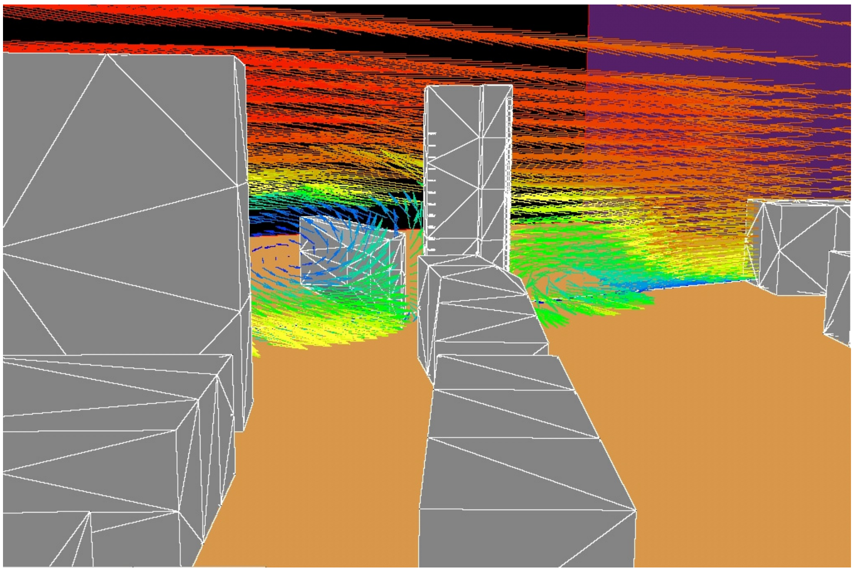


Figure 11 Wind speed around buildings predicted by CFD.

5.3 Sources and geographical levels of data

5.3.1 Introduction

As described in chapter 3.1 the holistic exposure model defined the need for mapping environmental data from macro down to micron level; i.e. on the surface and within the material. In the LIFECON context there is also the need to map data on two separate levels, namely the *network level (from regional to local, i.e. 1 kmx1 km*) and the *specific object level* comprising the micro and the micron level.

In principle, characterisation of degradation agents has to be based on existing data. Measurements are too expensive and time-consuming and can only be performed in specific cases for validation and control purposes (see chap 6.3).

5.3.2 Environmental research frameworks are important for LIFECON

All countries in Europe have extensive meteorological and air pollution monitoring networks, and many have GIS based information and management systems, allowing for the necessary assessment, modelling and mapping from the network down to the local/micro scale on object level. The relevant environmental degradation parameters, climatic and pollutants, can relatively easily be mapped on a network level, down to at least the grid scale of 50x50 km on a European level. In many regions mapping in grid scales of 1x1 km has been achieved. Land transported and wet deposited chloride data are available, however, models for surf- produced chloride have to be implemented in order to map the near sea (< 1 km) influence. Those will be tested out in the Oslo fjord bay case (D4.3c). Chloride from salting also needs special inquiry.

Mapping of environmental parameters and of areas and stock of buildings with increased risk of corrosion, and calculation of cost of corrosion are performed and co-ordinated for Europe within the UN ECE Working group on Effects (WGE) under the CLRTAP, and specifically under its

International co-operative Programmes (ICPs) for Modelling and mapping, and for Materials, respectively (see more on http://www.rivm.nl/cce/).

As is obvious the data and methodologies developed within these environmental research frameworks are directly applicable for the LIFECON tasks, and great synergy could be achieved by a direct link towards these. The concept has many similarities; establishing damage functions, measuring and co-ordinating all existing and relevant environmental data in Europe in order to do proper mapping of degradation parameters, areas -and stock at risk, etc. Its network of co-operating partners would be invaluable data providers for LIFECON, and vice versa much of the results of LIFECON, stock at risk mapping, corrosion costs, etc would constitute important input to these work on improving the corrosion cost mapping for Europe. From the mapping activity in Germany some results of direct applicability to LIFECON (transported sea-salt and H^+) will be shown.

Data shall be shown on maps and the availability of digital maps is an important issue to be sorted out for each region and location.

5.4 Network level-macro, regional and local scale

In the network models used so far (Vesikari-see D4.1) only three environmental parameters are taken into account:

- Temperature, - by dividing Finland into three zones-south, middle and north)
- Moisture, -index 1 corresponds to the amount of external water received by unsheltered concrete on top of a bridge deck and moisture index 0 to the amount of external water under a bridge deck provided with a water membrane
- Chloride, - index- index 1 corresponds to the amount of chloride received by unsheltered concrete on top of a bridge deck with the highest winter maintenance class, and chloride index 0 represents the case when no chloride is spread.

The LIFECON LMS aims for a more refined treatment of the environmental parameters. The limitation is not on the availability of environmental data and models, but the ability to handle more parameters in the prediction models.

5.4.1 Climatic data

All countries have extensive meteorological networks that can provide the necessary meteorological data on all levels, either as point measurements or as models on network level for the area in question. Meteorological data can be shown as maps showing the common meteorological parameters (f.ex average temperature and precipitation), or specifically derived parameters may be generated from the time series of the basic parameter (see D4.3).

5.4.2 Pollutants

The measuring, testing and evaluation of air quality are assuming growing importance in developed countries as elements of a comprehensive clean air policy and geared to sustainable development. A huge bulk of data is therefore generated on the various geographical levels. Point measurements are very expensive, and for a broader assessment of air quality, needed for policy development and assessment, public information etc., measured data needs to be combined with modelling based on emissions inventories, to assess properly the exposure to, and thus the effects of the pollution on public health or on buildings. Such air dispersion models exist, and the results can be mapped and exhibited by modern information technology (see item 5.2) available in LIFECON and LMS. Co-operation with the ICP Modelling and Mapping groups would be very beneficial.

The European Environment Agency (EEA) (www.eea.dk) was established in 1994, with the objective "to provide to the European Community and its Member States with *objective, reliable, and comparable information at a European level enabling the Member States to take the requisite measures to protect the environment, to assess the results of such measures and to ensure that the public is properly informed about the State of the environment (Haagenrud, 1997).*

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

On the *regional scale*, the report revealed that there is extensive monitoring in addition to the EMEP network, and that about 750 sites are in operation totally in Europe. This monitoring is very extensive for S- and N-compounds in air (gases and particles) and deposition, and also for ozone (Haagenrud, 1997).

On the *local/urban scale*, monitoring is carried out at a very large number of sites in Europe, totalling close to 5,000 sites according to the information made available to the Topic Centre (see Figure 12). Most of these sites seem to be general urban background sites, while hot-spot sites (traffic, industry) are less well represented. The compounds of the EU Directives (SO_2, particles, NO_2, ozone, lead) are extensively covered.

These 5,000 local/urban monitoring sites are contained in a large number of networks operated by local, regional or national authorities. We can only assume that operating practices, quality control procedures, data availability and reporting vary considerably from network to network.

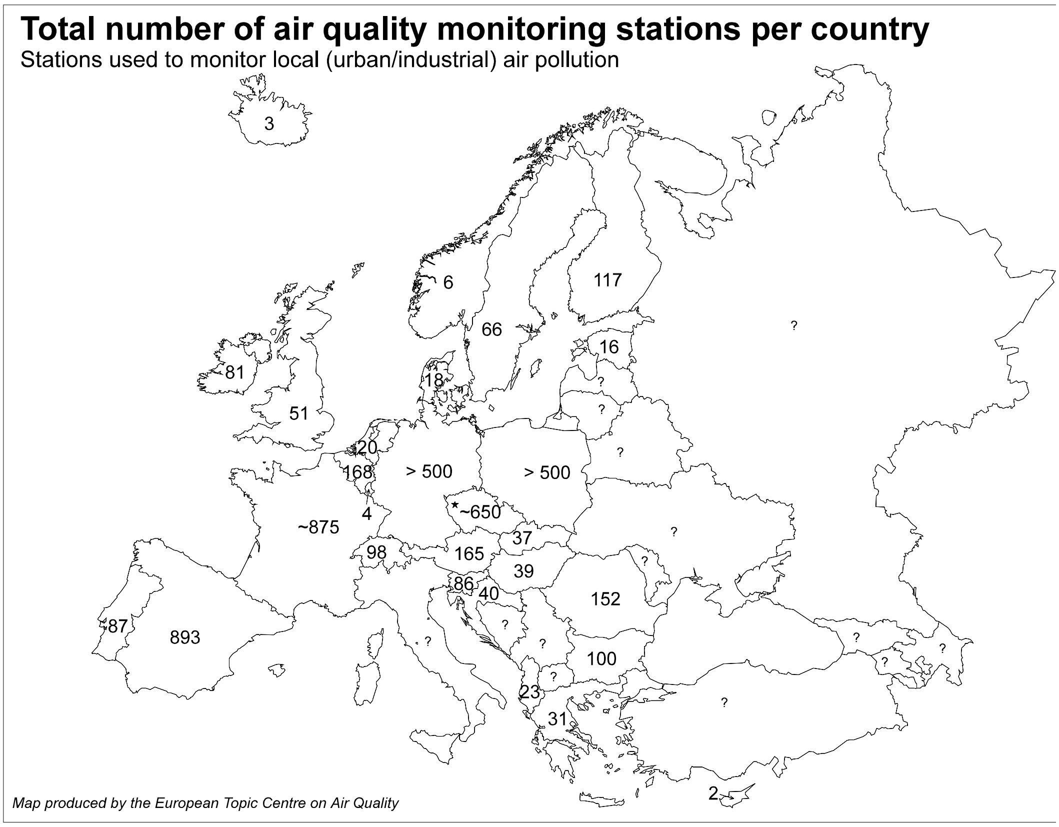


Figure 12 Number of sites per country for the monitoring of urban/local industrial air pollution.

Mapping on network level grids of 50x50 km are possible for whole Europe, while for many regions a resolution down to 1x1 km are possible even today. This will give information of differences in parameters between regions in each country. Regions may be geographical regions or "topographical" regions (coast/inland, mountain/low-lying country, rural/urban).

An extensive collaboration with the ICP Modelling and Mapping groups in each country should be pursued (see http://www.rivm.nl/cce/.)

5.4.3 Chlorides

5.4.3.1 Marine aerosols

Cole (2003) has established the models for production, transport and deposition of marine salts, as well as the integration of these models into GIS based computerized tools, see Figure 13. His models will allow us to calculate the marine aerosol impact in coastal areas of Europe; i.e. from macro down to local level.

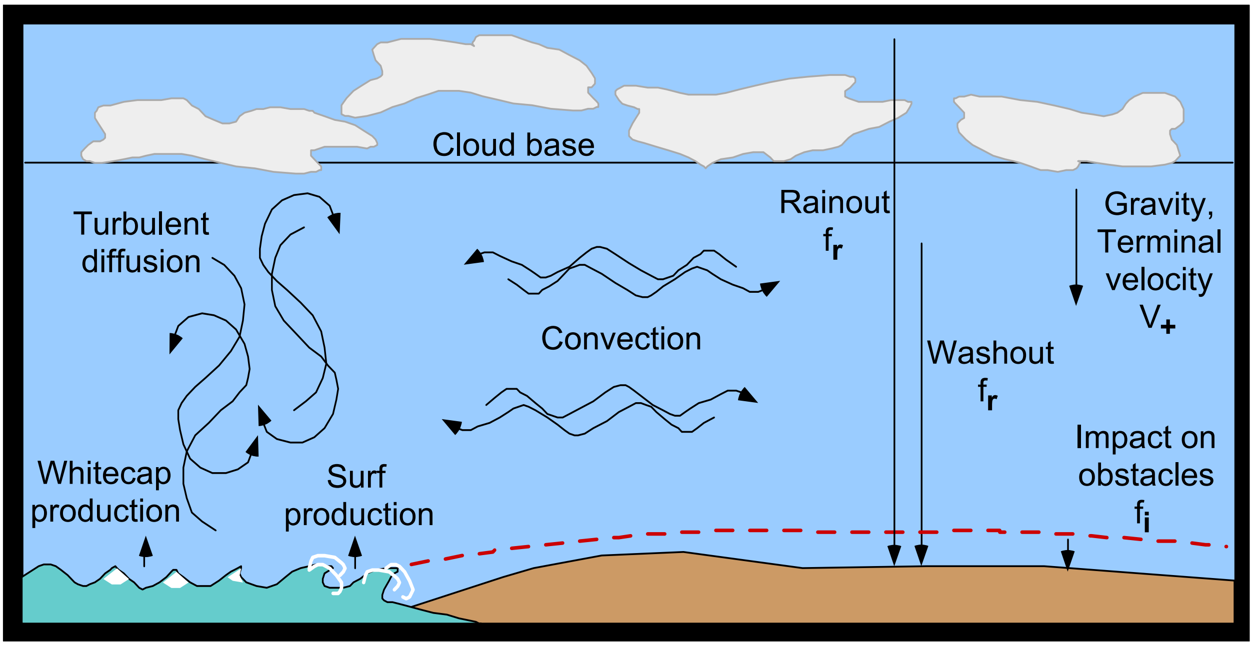
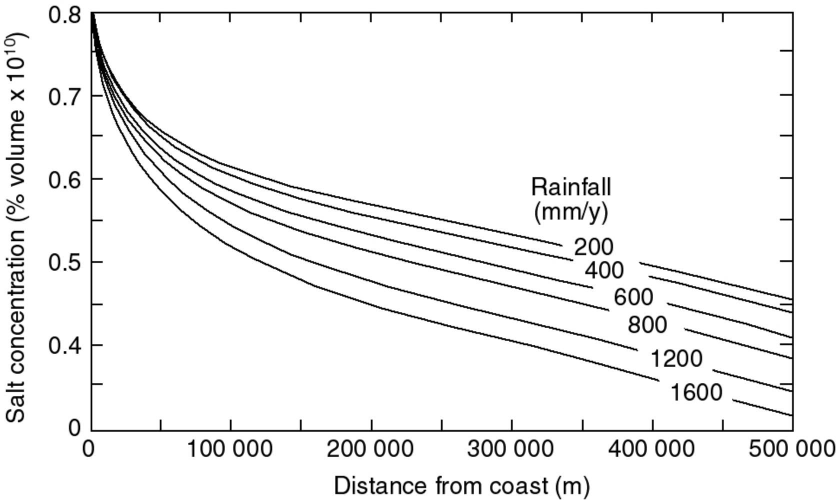
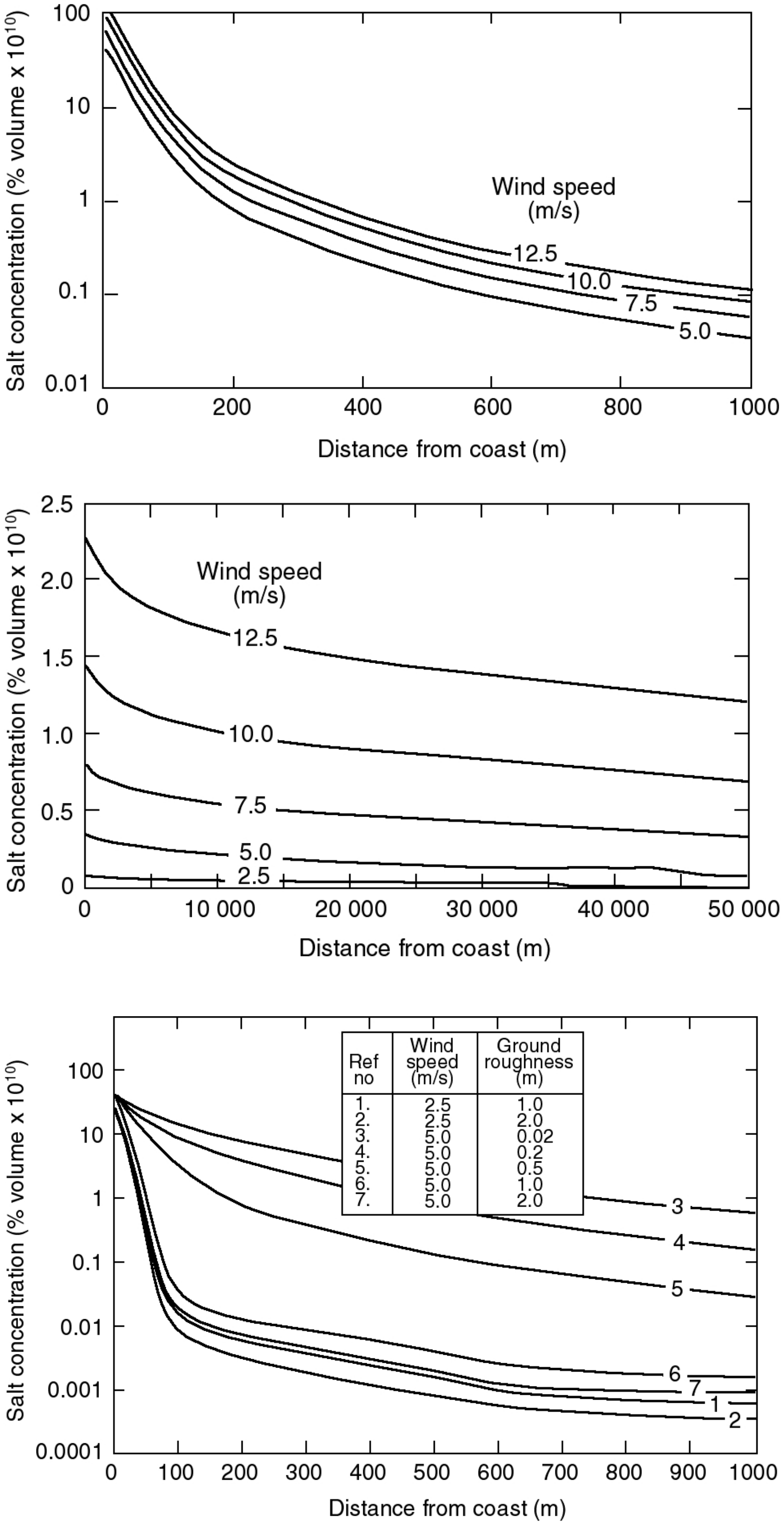


Figure 13 Chloride sea-salt aerosol mass transport model (Cole, 2003)

Some of his conclusions are (Figure 14):

- Salt production by breaking surf is estimated to lead to peak aerosol concentrations up to 40 times higher than salt production by whitecaps on ocean waves.
- The concentration of surf-generated aerosol falls dramatically with distance from the coast so that under typical conditions little aerosol is transported no more than 1 km.
- The concentration of ocean-generated aerosol falls in a more gradual manner so that this aerosol may be transported in excess of 50 km under appropriate conditions.
- The transport of aerosol produced by both surf and ocean white caps is strongly affected by wind speed.
- The transport of surf-generated aerosol is dramatically affected by terrain roughness, whilst that of ocean-generated aerosol is more affected by variations in RH and rainfall.





Ref no	Wind speed (m/s)	Ground roughness (m)
1.	2.5	1.0
2.	2.5	2.0
3.	5.0	0.02
4.	5.0	0.2
5.	5.0	0.5
6.	5.0	1.0
7.	5.0	2.0

Figure 14 Sea salt transport inland as function of aerosol size, wind, terrain roughness, rainfall etc (Cole, 2003)

5.4.3.2 Wet deposition of chlorides from industry and from sea

As shown by the example given for Germany below (item 0) chlorides in precipitation is part of the pollution measurement programmes around Europe, and by calculation is separated in contribution from industry/traffic and sea. For characterisation purposes in LIFECON the chloride contributions left to determine are *the greater aerosols near sea,* and *the emissions from de-icing salts*. The models developed by Cole will be used to characterize and classify the marine exposure to greater aerosols at the chosen objects in the Oslo fjord bay and long the coast, respectively. (D4.3c).

5.4.3.3 Chlorides from de-icing salts

Information shall be sought with the pollution authorities for the selected objects where this is relevant. The formula is given in D4.1.

$$Cr = 1000(-9.56+0.52SF +0.38SL+0.14FD-0.20ID)/w$$

Average amount of de-icing salt for each application incident [g/m²], where:
SF, number of days with snow fall > 0.1 mm [-]
SL number of days with a snow layer > 100 mm [-]
FD, number of days with a average daily temperature > 0° C [-],
ID, number of days with ice on road surface [-]
w, average spread width (street width) [m]

In Germany Lay collected 640 chloride profiles from German road administrations (160 structures), which were analyzed with respect to the most relevant influences. The analysis revealed for the concentration $C_{\Delta x}$:

- a linear decrease with increasing height (h) above street level
- a logarithmic decrease with increasing horizontal distance (a) from the street edge
- no trend with respect to exposure time

These relationships were picked up to derive a function in the form of $C_{\Delta x}$ = f(horizontal, vertical distance to the road):

$$C_{\Delta x,mean}(a,h) = 0.465 - 0.051*\ln(a+1) - \left(0.00065*(a+1)^{-0.187}\right)*h)$$

$C_{\Delta x,mean}(a,h)$	mean chloride concentration in depth Δx	[wt.–%/concrete]
a	horizontal distance to the roadside	[cm]
h	height above road level	[cm]

5.5 Example Germany - mapping air pollution, actual corrosion rates and exceedances

5.5.1 Mapping Critical Loads & Critical Levels in Germany

Germany has done extensive mapping, mostly by the Institute of Navigation, Stuttgart) (http://www.nav.uni-stuttgart.de/German/Forschung/CriticalLoads/englisch.html).

Within the current project national maps of concentration levels and deposition loads are generated. Mapping activities on the national and international level are an instrument for assessing the success and effectiveness of emission reduction measures. The calculation of the maps is based upon measurement network data, additional model estimates and high-resolution land use maps. To manage the complex tasks within mapping Critical Loads & Levels in Germany the efficient use of Geographical Information Systems (GIS) is indispensable. ArcInfo is used to handle the big amount of air pollutant data and to calculate the high-resolution (1x1 km²) output maps on the national scale.

5.5.2 Mapping results for LIFECON

Gauger and Anshelm (2000) state, "Since the start of the ICP Materials material exposure programme in 1987 considerable changes concerning geographic distribution and range or amount of air pollutants over Europe and Germany can be observed". German maps and statistics showing trends in air pollution are presented and discussed. (Annex E)

Main database for mapping air concentration and wet deposition are the routine measurements of the air concentration and wet deposition monitoring networks in Germany. The data of the different species, measured at about 110 to more than 400 measurement points are interpolated using kriging technique to derive air concentration and wet deposition fields respectively.

The mapping of wet deposition loads in Germany as well as the mapping of air concentration fields is based upon monitoring data. A wet deposition database has been set up at Institute of Navigation (INS) by comprehensive data acquisition at the institutions responsible for local, regional and national deposition monitoring programs in Germany. Point measurement data of solute concentration () are interpolated using kriging technique to derive solute concentration fields Figure 15.

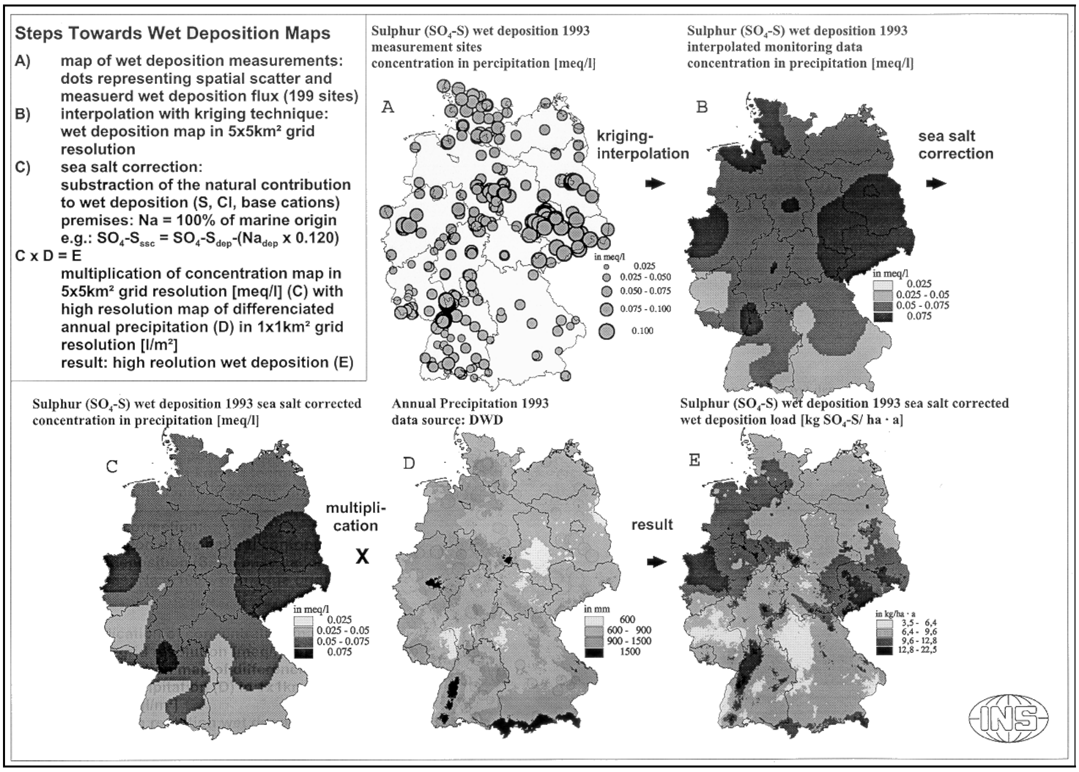


Figure 15 Main procedures of mapping wet deposition loads in Germany

Na wet deposition is used as tracer for sea salt influence, together with a factor, which is the ratio of sodium and the other components in seawater to calculate non marine wet deposition (SO4-$S_{(ssc)}$, Figure 15C). The map of solute concentration fields (in meq/l) then is multiplied with a precipitation map, provided by the German Meteorological Survey (DWD) (Figure 15D), to derive maps of wet deposition loads (in eq/ha·a or kg/ha·a, Figure 15E). The grid resolution of the wet deposition map is 1x1km^2. Annual wet deposition maps presently are calculated for the years 1987 to 1989 and 1993 to 1995.

Wet deposition of protons (H) is used as input for calculating mass loss of unsheltered materials using dose-response functions. The average H wet deposition in Germany declined by about 44% between 1987 and 1995.

Chloride mainly origins from sea pray, which is transported to inland areas by marine air masses. In Figure 16 the annual average wet deposition of chloride (Cl) in the three-year periods 1987-89 and 1993-95 is presented. Cl wet deposition shows a regular gradient from the coastal region of the North Sea (NW) to continental inland Germany (SE). The inland transport distance of marine Cl is connected to the frequency of weather situations with high wind speed, which both leads to higher sea salt emission, and to longer transport distance of marine air masses.

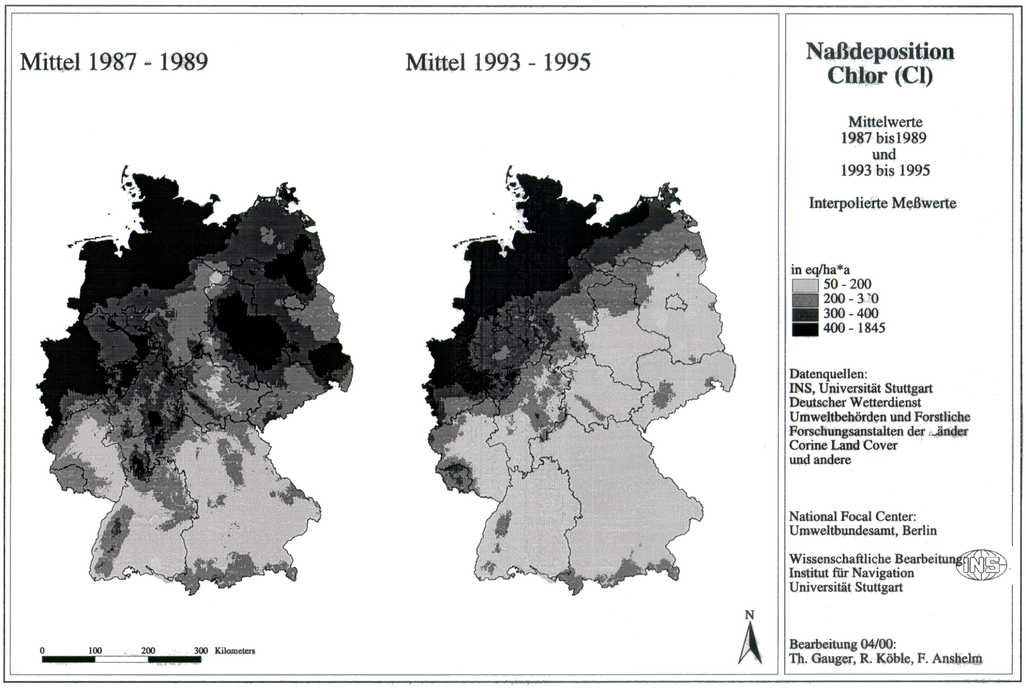


Figure 16 Annual average wet deposition of Cl in the three year periods 1987-89 and 1993-95

The non-sea salt fraction of Cl is assumed to be completely due to anthropogenic hydrogen chloride (HCl) emissions. The ratio between sea salt Cl and total Cl in wet deposition on average rises from 84.6% 1987 to 94.8% 1995, Table 16. This means that the anthropogenic contribution to total Cl wet deposition declined from about 15% 1987 to 5% in 1995, due to HCl emission reduction.

Table 16 Average wet deposition of sea salt chloride

Average wet deposition of sea salt Cl	1987	1988	1989	1993	1994	1995
in eq/ha	265,6	341,8	287,9	242,6	253,3	357,9
in kg/ha	9,42	12,12	10,21	8,60	8,98	9,14
in % of total Cl wet deposition	*84,6 %*	*84,0 %*	*88,6 %*	*94,5 %*	*90,0 %*	*94,8 %*

As seen from those data *what remains to be done is* to calculate the production and transport of surf produced close to the sea (Cole, 2001), while also the contribution of heavy particles from the salting of roads are important. This could also be achieved from pollution authorities.

The trend analysis and the time dependence are very important for LIFECON and the objectives of prediction of durability of concrete structures.

5.6 Object level-atmospheric micro scale

Mapping on object level is the most urgent needs in LIFECON with the selected case studies, while network will be more needed in the planning phase. The available regional exposure data can after appropriate adjustment be used for characterisation of the local and microenvironment at a building or construction.

The microclimate is heavily influenced by the macroclimate. The importance of various factors will of course vary for different types of construction objects and where these objects are used in relation to the orientation of construction and their position on or within the construction.

The prediction of the hazard for a component within the construction envelop is more complex and in general can only be estimated by some type of transfer functions which considers the relevant external parameters and construction design and material characteristics. In order to estimate the environmental conditions for construction surfaces and the internal material conditions an approximation of mass (water, gases) and heat transfer is required.

5.6.1 Climatic data-driving rain from prEn 13013

The moisture content or water availability is important for the corrosion processes. Precipitation is measured at meteorological station, like wise relative or absolute humidity in the air. Time of wetness may be calculated from meteorological data.

Different methods may be used to describe or express the quantity of water at a wall or construction. In addition to methods using the measured data directly, there are standards as the prEN 13013-3 “Calculation of driving rain index for vertical surfaces from hourly wind and rain data.” (CEN, 1997). This is mainly based on the British standard BS 8104:1992 “Code of practice for assessing exposure of walls to wind-driven rain.” (BS 8104:1992).

The standard specifies a procedure for analysing hourly rainfall and wind data derived from meteorological observations so as to provide an estimate of the quantity of water likely to impact on a wall of any given orientation. It takes account of topography, local sheltering and the type of building and wall. It specifies the method of calculation of:

- The annual airfield index, I_A, which influences the moisture content of masonry wall.
- The spell index, I_S, which influences the likelihood of rain penetration through masonry wall.

After calculating the I_S for a period of time the next step is to estimate the actual buildings location and exposure compared to an airfield. That is performed by estimating the values of four different parameters, the roughness coefficient C_R, the topography coefficient C_T, an obstruction factor, O, and a wall factor, W and converting the airfield indices into wall spell indices, I_{WS}, by the formula:

$$I_{WS} = I_S \times C_R \times C_T \times O \times W$$

The prEN has categorised, described, and illustrated the C_R, C_T, O and W factors.
Quantity of available water on the concrete surface will also be determined by the combination of precipitation, wind, temperature and solar radiation. (D4.1).

5.6.2 Pollutants

5.6.2.1 Road network emission and dispersion model

From Haagenrud (1997): The effect of road traffic pollution on urban populations is expected to increase during the next few years. Traffic planners are often in need of practical tools for studying the effect of such measures on the environment. Quite a few air dispersion models exist and can be used for this purpose.

The ENSIS Air and CosBen modules which will be available for LIFECON and included in the LMS, contains the road model *RoadAir*, for quantitative descriptions of air pollution along road networks. RoadAir calculates total emissions, concentrations along each road segment and the air pollution exposure of the population and *buildings* along each road. Calculations can be carried out for road networks, defined by road and traffic data. The model was primarily developed for conditions in Scandinavia, but can easily be adapted to conditions in other parts of the world.

5.6.2.2 Marine aerosols

Cole (1999) has used CFD models to map the chloride aerosols in the microenvironment on walls, see *Figure 17*. NBI will use CFD to calculate the wind pattern around the chosen objects (see D 4.3).

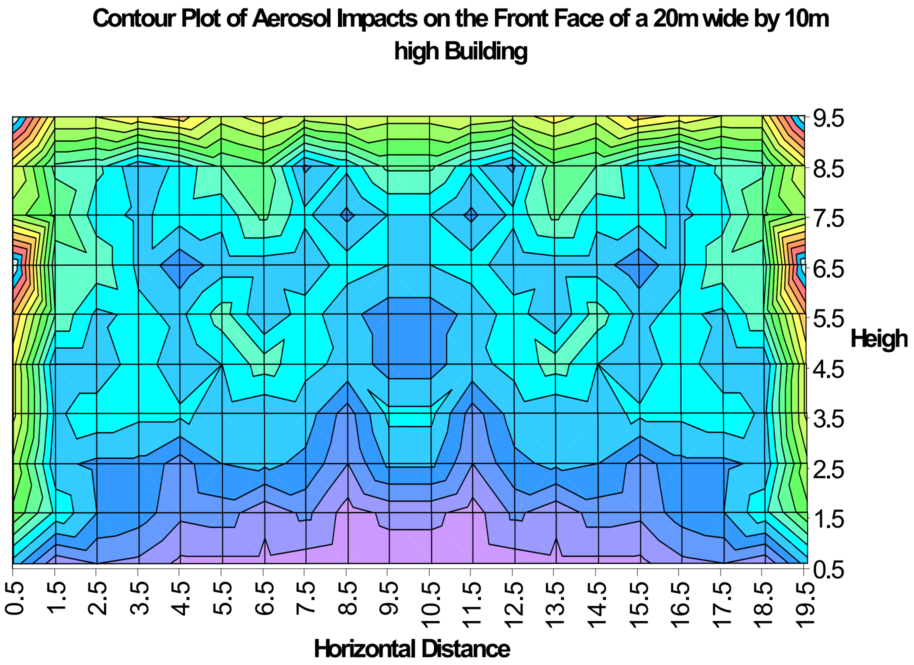
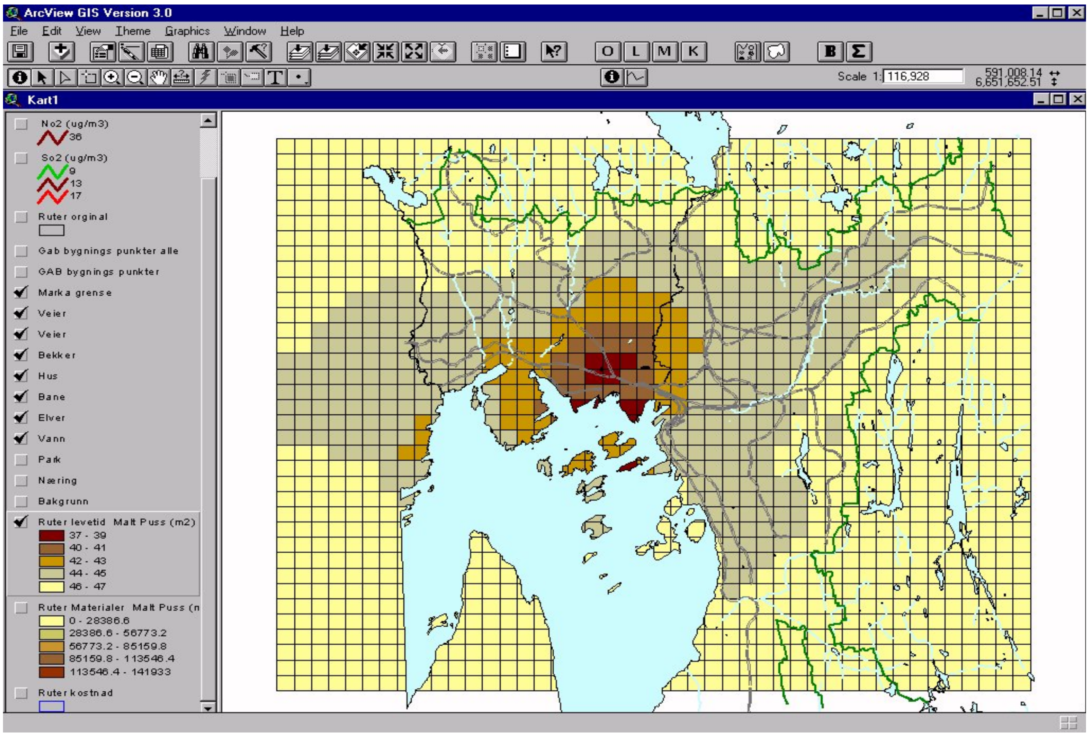


Figure 17 Contour plot of Aerosol impact on wall of high building.

5.7 Modelling and mapping of damage functions and service life

When the degradation factors have been assessed and modelled the LMS ERF and PSL module will contain tools that allows for modelling and mapping also of the corresponding damage –and service life functions.

Already existing are corrosion maps for some supplementary materials, like weathering steel, zinc, aluminium, copper and bronze. An example is shown in Figure 18, shows the map for the service life/maintenance intervals for rendering, respectively Zn-coated steel, in Oslo based on 1994 exposure data.



Scale 1: 116,928
591,008.14 ↔
6,651,652.51 ↕

☐ No2 (ug/m3)
36
☐ So2 (ug/m3)
9
13
17
☐ Ruter orginal
☐ Gab bygnings punkter alle
☐ GAB bygnings punkter
☑ Marka grense
☑ Veier
☑ Veier
☑ Bekker
☑ Hus
☑ Bane
☑ Elver
☑ Vann
☐ Park
☐ Næring
☐ Bakgrunn
☑ Ruter levetid Malt Puss (m2)
37 - 39
40 - 41
42 - 43
44 - 45
46 - 47
☐ Ruter Materialer Malt Puss (n
0 - 28386.6
28386.6 - 56773.2
56773.2 - 85159.8
85159.8 - 113546.4
113546.4 - 141933
☐ Ruter kostnad

Figure 18. The maintenance intervals (lifetime) for rendering in years for Oslo in 1994 given in grids from the CosBen model with grid size 500x500 m.

6. Guidance for characterisation (and subsequent classification) of exposure environment on structures in LIFECON

6.1 Object level

When mapping and determining the category of exposure/degradation on object, the surroundings of the object and the objects components are taken into account. The different components are exposed in different ways and different amounts, due to orientation, sheltering, sun/shadow, distance from "source" for exposure, and more, and all this have to be taken into account.

Below follows a step-wise instruction for characterisation of the environmental parameters onto the surface of the structure, resulting in a protocol for the field assessments of the environmental exposure: **Feil! Fant ikke referansekilden.**.

1. Choose object
2. Divide the structure/construction into components with different expected Categories of Location (due to orientation, sheltering...). Use either the EOTA system (D 4.2 Annexes) or the height classification system, see Table 5.
3. Attain EN 206-1 exposure classes to the various components/parts of the construction
4. Adjust for the effect of sheltering, etc on driving rain and deposition on other agents to the structure by calculation of CR, CT, O and W from 5.6.1.
5. Find climatic information from nearby meteorological stations. Necessary information:
    a. Temperature. Preferably, if available, time series for a long period (>10 years). Main information is average temperature for summer and winter conditions,

    max/min and average monthly temperature. Surface temperature can be calculated from the following equation:

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

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

For the various EN 206-1 classified parts of the structure:

8. Characterisation of RH
9. Characterisation of moisture: Total time with moisture comes from: time with rain + condensation + high RH
10. Characterisation of temperature profiles on construction
11. Characterisation of chloride, either from sea-salt from Cole models/mapping authorities for land transported sea-salt, ref example from Germany, or from deicing salts-formula Cr = 1000(-9.56+0.52SF +0.38SL+0.14FD-0.20ID)/w (Average amount of de-icing salt for each application incident [g/m²]).
12. Characterisation of pollutants like SO_2, O_3, H^+ and CO_2. Contact national (and local) ICP Modelling and Mapping groups concerning already mapped information. Contact points for all European countries are given on web-page http://www.rivm.nl/cce/, see also example from Germany (item 5.7). Find available environmental data from national or local authorities.

Table 17 Protocol for environmental assessment of case studies

Component	**Category of Location EOTA system**			
	1 (horizontal or low slope surfaces (< 20^0)	2 (Steep slope (>20^0)	3 (Vertical)	4 (Underside of horizontal and sloping surface)

Component	**Exposure classes (EN 206-1)**

Environmental parameter characteristic surroundings							
RH (%) summer	RH (%) winter	Days w/rain >2.5mm	Precipitation (mm/y)	Condensation	Av.air temp (summer)	Av.air temp (winter)	Main wind direction

Environmental parameter characteristic components						
Component	Surface T summer	Surface T winter	CR	CT	O	W

6.2 Network level-regional level

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

6.3 Proposal for measurement program for validation of exposure assessment around bridge deck and tunnels

It would be of great importance to try and validate the assessment of exposure environment around concrete road bridges and concrete lined tunnels by conduction a field measurment programme. Two independent studies of, respectively

1. Field measurements around a *bridge deck* to determine the corrosivity in selected areas, the pollution impact and its correlation with meteorological parameters like wind speed, wind direction, turbulence and topographical influence.
2. Modelling the pollution situation with increased CO2 concentrations *in tunnels* based on emission data from the traffic. Based on the model result the increased risk for carbonisation of concrete will be calculated.

7. Conclusions

1. This report provides relevant *systematic* and *requirements* for quantitative classification of environmental loading onto structures, and *overview of existing classification systems*, as well as *sources* of environmental exposure data, and methods for their assessment and modelling on various geographical scales. For most European countries environmental data and models are available from meteorological offices and the environmental research area, and these data and the work performed are directly applicable for LIFECON. The present LMS prediction module, contain such modelling of environmental exposure loads and service life functions for a range of the supplementary materials in concrete structures, such as for example galvanized (and coated) steel.
2. *Instructions/guidelines* for how to characterise the environmental loads on concrete structures on object and network level are given, serving as basis for developing and testing a quantitative classification system for environmental loading.
3. Some systems for quantitative classification of environmental loading related to durability for building materials and components exist. Generic systems try to classify the *generic atmospheric aggressivity*, without specific knowledge of damage functions, but based on overall experience of materials degradation at large (ISO, 2002 and EOTA, 1999). The other option and systematic is material (family) specific and based on knowledge of their damage functions, such as ISO 9223 that are specific for metals. Those are directly applicable to many of the supplementary materials of concrete structures, however, for the very complicated damage functions of concrete they are not applicable.
4. In order to develop the quantitative classification for concrete two strategies have been chosen. Firstly, a more practical approach of validation, where the new European standard -"EN 206-1 Concrete, which contains an agreed qualitative classification system, should be tested out on the chosen objects and compared with detailed environmental characterisation of the same objects, using the available data and methods for environmental characterisation. An EN 206-1 harmonized protocol for the 11 selected objects is therefore also given in chapter 3. Such studies should be undertaken in many countries to develop the needed national annexes for a proper implementaion of EN 206-1 across Europe, see item 2.3. A first sketch of how such as system might look like, based on best available knowledge and experience, is provided in the present report.

   Secondly, a more teoretical classification based upon parametric sensitivity analysis of the complex Duracrete damage functions under various set conditions. In this way the determining factors are singled out and classified. This is performed in D3.2 (Lay, 2003), and shown in context in D4.4.
5. Such environmental classification systematic is needed to enable sound prediction of service lifes and maintenance intervals both on object and network level. This in turn is a necessary prerequisite for change of current reactive practise into a pro-active life- cycle based maintenance management.
6. Mapping of environmental parameters and of areas and stock of buildings with increased risk of corrosion, and calculation of cost of corrosion are performed and co-ordinated for Europe within the UN ECE Working group on Effects (WGE) under its International co-operative Programmes (ICPs) for Modelling and mapping, and for Materials,

respectively. The data and methodologies developed within these environmental research frameworks are directly applicable for the LIFECON tasks, and great synergy could be achieved by a direct link towards these frameworks. An example of such modelling and mapping is shown for Germany.

8. References

Anshelm, F, Gauger, T., Köble, R., (Institute of Navigation, Stuttgart) Mayerhofer, P., Droste-Franke, B., (Institute of Energy Economics and the Rational Use of energy, Stuttgart): Mapping actual corrosion rates and exceedances of acceptable corrosion rates- procedure and results"

British Standards Institution (1992), Code of Practice for assessing exposure of walls to wind-driven rain. *(BS8104:1992).*

CIB report Publication 256, 2000, *GIS and the Built Environment,* Editors. Haagenrud, S. E Rystedt, B, Sjöström, C, Oct 2000, Rotterdam

Cole, I. S., Paterson, D. A. and Ganther, W. D. (2003). A holistic model for atmospheric corrosion-Part 1-Theoretical framework for production, transport and deposition of marine salts *Corrosion Scienc, vol 38, issue 2, 2003*

Cole, I. S., King, G. A., Trinidad, G. S., Chan, W. Y. and Paterson, D. A. (1999). An Australian-wide map of corrosivity: A GIS approach. *In 8th DBMC, Canada.*

European Commite for standardization (2001) EN 206 Concrete-Part 1 –Specification, performance, production and conformity.

European Commite for standardization-CEN (1997) Hygrothermal performance of buildings - Climatic data - Part 3: Calculation of driving rain index for vertical surfaces from hourly wind and rain data (prEN 13013-3).

EU project - Brite Euram BE95-1347- Working report "Environmental actions and response- survey, inspection and measurements (March 1999)

European Organisation for Technical approvals (1999) *Assessments of working life of products.* PT3 Durability (TB97/24/9.3.1)

Fluge, F (2001), Marine chlorides- A probabilistic approach to derive provision for EN 206-1, DURANET, Third Workshop, Tromsø 10th-12th, June 2001

Gauger, T. ; Anshelm, F.(2000) (Institute of Navigation, Stuttgart): Air Pollutants in Germany-Long Term trends in deposition and Air Concentration"

Glomsrød, S., Godal, O., Henriksen, J.F., Haagenrud, S.E. and Skancke, T. (1996) Corrosion costs in Norway. Paper presented at the *UN ECE Convention on Long-Range Transboundary Air Pollution workshop on Economic evaluation of air pollution abatement and damage to buildings including cultural heritage, Stockholm, January 1996.*

Haagenrud, S.E.(1997) Environmental Characterisation including equipment for monitoring. CIB W80/RILEM 140PSL. Subgroup 2 Report. Kjeller (NILU OR 27/97).

Haagenrud, S.E. and Henriksen, J.F. (1996) Degradation of built environment – Review of cost assessment model and dose response functions. In: *7th International Conference on the durability of building materials and components. Stockholm 1996. Proceedings. Ed. by C. Sjöström. London, E & FN Spon. pp. 85-96.*

Haagenrud, S.E., Stordahl.P, Eriksson, B., Riks, E., Krigsvoll, G., and Garofolo, I. (2001) *EU-project ENV4-CT98-0796 MMWood,* Final report, Oslo (NBI).

Haagenrud, S.E., Veit, J., Eriksson, B., Henriksen, J. F., and Krigsvoll, G. (1999) *EU-project ENV4-CT95-0110 Wood-Assess, Final report, Kjeller (NILU).*

International Organisation for Standardisation (1984) Performance standards in buildings – Principles for their preparation and factors to be considered. Geneve (ISO 6241-1984).

International Organisation for Standardisation (2000) Service life planning of buildings and constructed assets-Part 1 –General principles Geneve (ISO 15686-1, 2000).

International Organisation for Standardisation (2000) Service life planning of buildings and constructed assets-Part 1 –General principles Geneve (ISO 15686-2, 2001).

International Organisation for Standardisation (1992) Corrosion of metals and alloys– Corrosivity of atmospheres- Classification. Geneve (ISO 9223:1992).

International Organisation for Standardisation (2002) ISO/WD 15686-4 Buildings – Service Life Data Sets – Part 4 – Service Life prediction data Requirements.

King, G. (1988). A corrosivity survey on a grid of sites ranging from rural to moderately severe marine. *In Corrosion Australasia, Volume 13, Number 1 (February).*

Kucera, V., Henriksen, J. F., Knotkova, D. and Sjöström, C. (1993) Model for calculations of corrosion cost caused by air pollution and its application in three cities. In: Progress in the understanding an dprevention of corrosion, *10th European Corrosion Congress, Barcelona, July 1993. Ed by J. M. Costa and A. D. Mercer. London, Institute of materials. Vol. 1, pp24-32.*

Kucera, V., Gregor, H-D. (2000) Mapping Air Pollution Effects on Materials Including Stock at Risk-*Proceedings of a UN ECE Workshop. SCI Bulletin 108E*

Lay, S. (2003) Models for the Prediction of the Residual Service Life, *Lifecon Deliverable D 3.2, Draft 2*

Moser, K. (1999) Towards the practical evaluation of service life-illustrative application of the probabilistic approach *In 8th DBMC, Vancouver 1999 Edited by M.A.Lacasse and D.J.Vanier, pp1319-29.*

Svenska Betongföreningen (2002) Vägledning för val av exponeringsklass enligt SS-EN 206-1. Betongrapport nr 11.

Scheffer, T.C. (1970) A climate index for estimating potential for decay in wood structures above ground. *Forest products journal, 21*, 10-25.

Sjöström, Ch., Jernberg, P., Caluwaerts, P., Kelly, S., Haagenrud, S., Chevalier, J.L. (2002) Implementation of the European Construction Products Directive via the ISO 15686 standards, *9th Conference of Durability of Building Materials and Components, Brisbane 2002*

Tidblad, J, Kucera, V. and Mikhailov, A.A. (1998) Statistical analysis of 4-year materials exposure and acceptable deterioration and pollution levels. Convention on long-range transboundary air pollution. Prepared by the main research centre, Swedish Corrosion Institute, Stockholm. (*UN ECE ICP on effects on materials including historic and cultural monuments, Report No. 30).*

Tomiita, T. (1993) *Service life prediction system of polymeric materials exposed outdoors.* Personal communication.

van Mook, Fabien, J. R. (1999) Full-scale measurements and numerical simulations of driving rain on a building, *Proc. 10th International Conference on Wind Engineering, Copenhagen, denmark, pp 1145-1152*