LIFECON DELIVERABLE D 5.3

Methodology and data for calculation of LCE (Life Cycle Ecology) in repair planning

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Lifecon Deliverables

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

Keywords

Life Cycle Ecology (LCE), Life Cycle Assessment (LCA), concrete structures, repair methods, rehabilitation, preventive maintenance, patch repair, hydrophobic surface treatment.

Abstract

In many countries, there is a growing amount of deteriorating concrete structures that not only affect the productivity of the society, but it also has a great impact on resources, environment and human safety. The poor and uncontrolled durability with maintenance and rehabilitation of all these concrete structures are consuming much energy and resources and are producing a heavy environmental burden and large quantities of waste. Therefore, concrete durability is not only a question of technical performance and economy, but also a question of impact to the environment.

In the present paper, the framework and methodology for quantifying the environmental burden of various materials and systems for maintenance and rehabilitation of concrete structures is outlined. This includes materials and energy consumption, waste generation and emission to the environment as well as human- and eco toxicity.

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1 Introduction

Over recent years, there has been an increasing concern with how human activities affect the loss of biodiversity, the thinning of stratospheric ozone, climate changes and the reduction of natural resources. The term Sustainable Development (SD) came into use by the World Commission on Environment and Development (WCED, 1987), where the Brundtland Commision was responsible for the most frequently cited definition of Sustainable Development:

"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Both on the basis of weight, volume and economy, the construction industry is the largest consumer of materials in our society. Thus, approximately 40 % of all materials used are related to the construction activities [1]. From a production point of view, several of these materials have a great impact on both the local and global environment. This is particularly true for concrete as one of the most dominating construction materials. Therefore, an increased environmental consciousness in the form of a better utilization of concrete as a construction material and the creation of a better harmony and balance with our natural environment represent an increasing challenge to the construction industry, as expressed by the Lofoten Declaration of 1998 [2].

In addition to the large consumption of natural resources for concrete production, the production of portland cement is based on a very energy consuming and polluting industrial process. Thus, the production of each ton portland cement releases approximately one ton of carbon dioxide in addition to a number of other polluting constituents to the atmosphere. The production of portland cement worldwide constitues approximately 5 % of the total global emission of CO_2.

During recent years, deterioration of reinforced concrete structures has emerged as one of the most demanding challenges facing the construction industry [3]. Public agencies are already spending a significant portion of their annual construction budget on repair and rehabilitation.

In the years to come, repair and rehabilitation of concrete structures will be the subject of strict requirements both with regard to environmental impacts and to economical constraints. It is very important, therefore, also to take environmental effects into consideration during design and construction, as well as in the selection of various measures for rehabilitation and maintenance of concrete structures.

The objective of the present report is to present a framework and methodology for quantifying the environmental impact of various methods and systems for rehabilitation and maintenace of concrete structures. This includes materials and energy consumption, waste generation, emission to the environment and human- and eco toxicity.

2 Framework for Life Cycle Ecology (LCE)

According to ISO 14040:1997 [4], Life Cycle Ecology (LCE) or Life Cycle Assessment (LCA) is a technique for assessing the environmental aspects and potential impacts associated with a product, by

- compiling an inventory of relevant inputs and outputs of a product system;
- evaluating the potential environmental impacts associated with these inputs and outputs;
- interpreting the results of the inventory analysis and impacts assessment phases in relation to the objective of the study.

LCE should ideally include assessment of environmental impacts caused by all human activities throughout the whole life cycle of a structure. This is, however, a very difficult process since the relationship between the external environment and the category endpoint can be very complex. Normally, the Life Cycle Ecology (LCE), will stop at the step before category endpoint, showing only the impact categories, which is fairly easy to do, and then interpret the results from the various category indicators. The concept of category endpoints is shown in Figure 1.

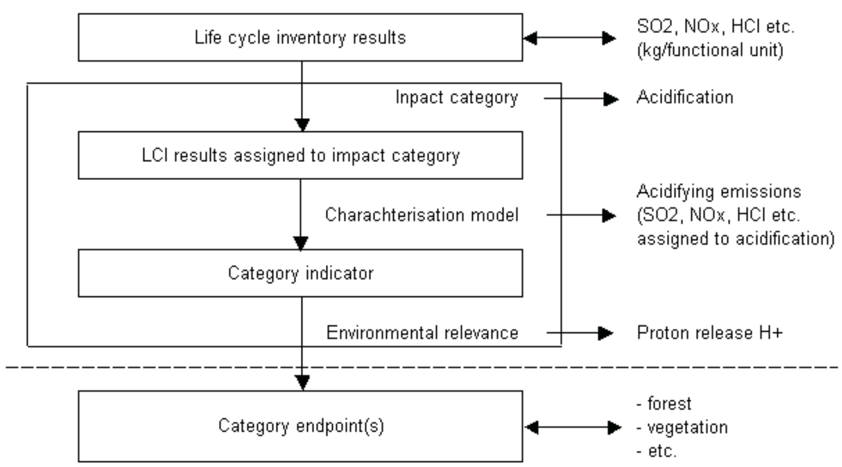

Figure 1. Concept of category indicators [4].

The methodological framework for the assessment of environmental impacts from rehabilitation and maintenance of concrete structures is shown in Figure 2. Figure 2 is based on the ISO-standards 14040 - 14043 [4-7].

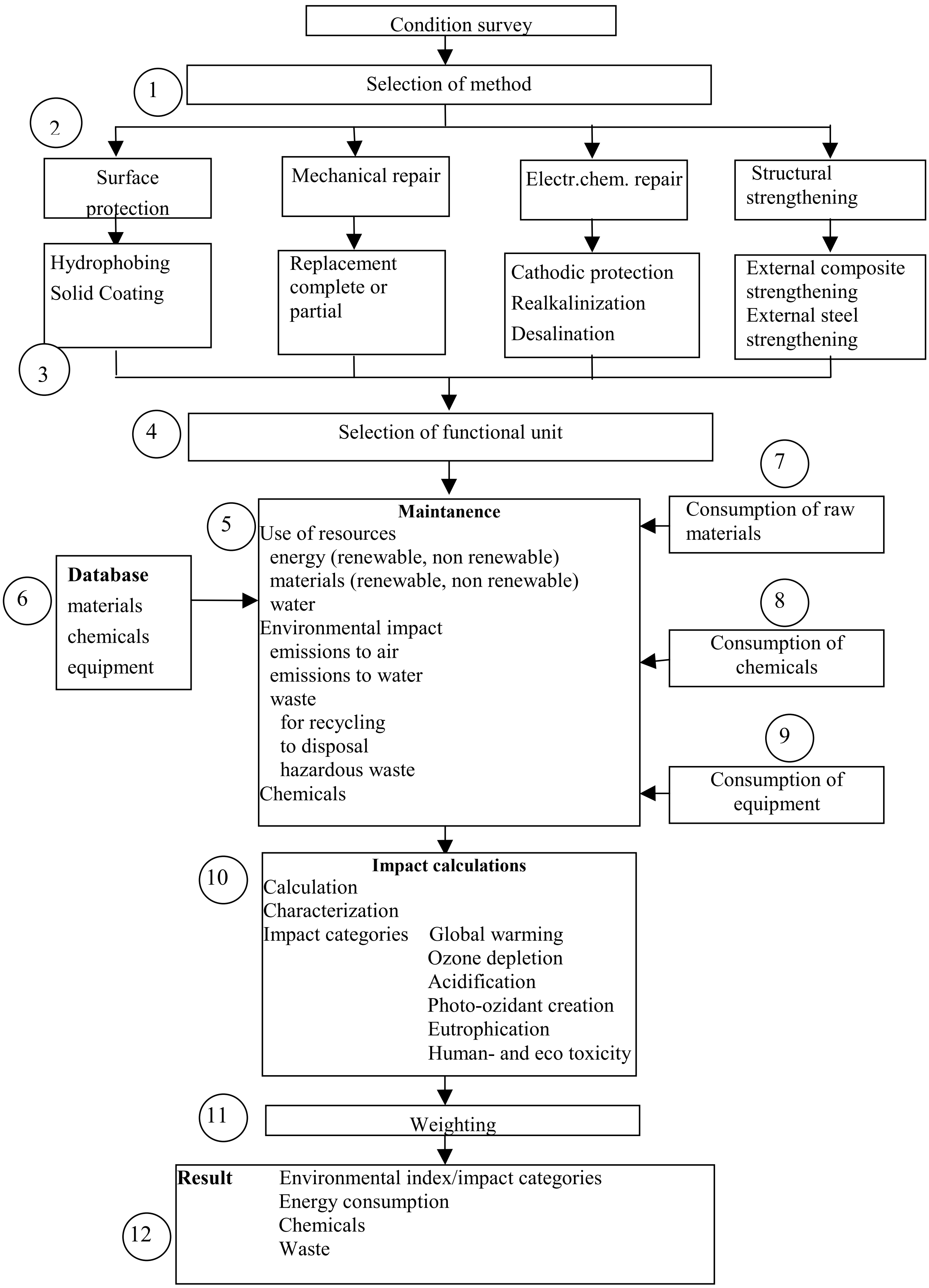

Figure 2. Methodological framework for assessment of environmental impacts from rehabilitation and maintenance of concrete structures.

From the condition survey of a concrete structure, the method of maintenance (**1) (2)** and type of maintenance (**3**) are first selected. The selections depend on type and extent of damage and type of external environmental conditions as well as type of equipment and materials to be used for the repair.

The next step in the process is to determine the functional unit (**4**). The functional unit is the reference unit used in a life cycle study [6]. All emission, energy and flow of materials occurring during the repair process are related to this unit. The functional unit shall be measurable and will depend on the goal and scope of the analysis. The goal of the Life Cycle Ecology (LCE) shall unambiguously state the intended application and indicate to whom the results will be communicated. Thus, the functional unit for a paint system may be defined as the unit surface (m^2) protected for a specified time period.

The maintenance/life cycle inventory (LCI) phase (**5**) will consist of:

1. Quantifying the amount of all raw materials (**7**), chemicals (**8**) and equipment (**9**), which are necessary to fulfil the maintenance function. This quantification gives the reference flow [7], for which all inputs and outputs are referred to and are closely connected to the functional unit.

2. Providing environmental data (**6**) of consumed raw materials (**7**), chemicals (**8**) and equipment (**9)** from the suppliers (specific data) or from databases (generic data) or from a life cycle inventory (LCI) carried out at supplier level. All materials used are recommended to have an environmental declaration with scope “Cradle to port”. The environmental declaration shall include use of resources such as energy (renewable, non renewable), materials (renewable, non renewable), water and waste as well as emissions to air and water.

3. Quantifying and classifying the waste from the process as recycling, disposal or hazardous waste.

The calculations to impact categories (**10**) should be carried out as shown in Figure 1. The impact categories will be: Global warming, Ozone depletion, Acidification, Photo-oxidant creation, Eutrophication and Human- and Eco toxicity. All calculated effects should be potential effects.

Classification is assignment of LCI results to impact categories. Classification and characterization should be carried out according to ISO 14042, using effect factors from IPCC * in the Montreal protocol, Heijungs [8] (Appendix 1). Emission of a specific gas may be assigned to more than one category. An example is the emissions of $NO_{x,}$ which will be assigned to the category of both eutrophication and acidification. The final result (**12**) may be displayed as impact categories or weighted (**11**) to an environmental index.

Weighting is the process of converting indicator results of different impact categories by using numerical factors based on value-choices and is an optional element in ISO 14042 [5]. Thus, factors from value-choices may be based on political targets (Kyoto-protocol) or on other preferences. Interpretation of the results should be based on ISO 14043 [7] and shall identify, qualify, evaluate and present the findings of significant issues.

3 Case studies

3.1 General

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

A major difficulty in the analysis of commercial products is to obtain specific data. This was also the case for the present surface protection system, where the supplier only released relative information and was reluctant to release specific data on energi inputs, raw materials inputs and other physical inputs.

However, by means of the relative data received from the supplier in combination with some other general information available, a backwards calculation was carried out. In this way, results for the various impact categories could be calculated, the results of which are demonstrated in the following.

For both case studies, some common assumptions for the calculation of environmental impacts were made:

- Transport distance forth and back : 60 km
- Materials and equipment are transported by truck.
- Fuel consumption (diesel): 0,2 kg per ton-km
- Same functional unit (1 m^2 of repaired or protected concrete surface for a period of 10 years)

Quantification of the waste generated, and assessment of human- and eco toxicity from the processes were omitted due to lack of relevant data.

The environmental profile of one kg of diesel is demonstrated in Table 1.

Table 1. Environmental profile of diesel [11].

Use of energy	**Global warming** CO_2 eq.	**Acidification** SO_2 eq.	**Eutrophication** PO_4 eq.	**Photo-oxidant formation** Ethene eq.
43,2 MJ/kg	3150 g/kg	2,8 g/kg	50,0 g/kg	10,0 g/kg

3.2 Patch repair

The analysis was based on the following assumptions:

- Surface area repaired: 30 m^2
- Rebound of shotcrete: 25 %
- Power supply on the construction site is based on diesel engines

It was further assumed that the concrete cover was removed to an average depth of 50 mm. The assumed average thickness of the shotcrete layer was 50 mm.

The various steps of the process included:

- Removal of concrete cover to an average depth of 50 mm by high pressure (1000 bar) hydro jetting
- Cleaning of the reinforcing bars by sand blasting
- Protective coating of the reinforcement
- Application of the shotcrete layer.
- Curing measures of the shotcrete surface

The mixture used for the shotcrete is given in Table2.

Table 2. Concrete mixture for the shotcrete.

v/b	0,43
Cement	500 kg/m^3
Admixtures	1,0 kg/m^3
Aggregate	1500 kg/m^3

The environmental profile of one cubic meter of concrete with a composistion as given in Table 2 is presented in Table 3.

Table 3. Use of energy and environmental impacts of 1 m^3 of concrete.

Impact category				
Use of energy MJ/m^3	**Global warming CO_2 eq/m^3**	**Acidification SO_2 eq/m^3**	**Eutrophication PO_4 eq/m^3**	**Photo-oxidant formation Ethene eq/m^3**
2795	405 kg	1,59 kg	0,234 kg	0,191 kg

Use of energy and environmental impacts of the patch repair are presented in Table 4.

Table 4. Energy and ecological impact of the patch repair.

Process	**Impact category**				
	Use of energy (MJ/m^2)	**Global warming (kg CO_2 eq/m^2)**	**Acidification (g SO_2 eq/m^2)**	**Eutrophication (g PO_4 eq/m^2)**	**Photo-oxidant formation (g Ethene eq/m^2)**
Hydro jetting	677	84	75	1330	266
Cleaning of reinforcement	296	22	4	350	70
Protective coating on reinforcement	35	1,4	19	2,4	3
Application of shotcrete	59	4,4	19	70	14
Transportation	127	10	8	150	30
Sum	1194	122	125	1902	383

3.3 Hydrophobic surface protection

3.3.1 General

For a hydrophobic surface protection, silane-based systems are often used, where the treament includes the following mechanisms:

- After application to the concrete surface, the silanes are sucked into the pore system of the concrete by capillary suction.
- In the pore system, chemical reactions take place, which lead to the formation of a very thin film of a silicon resin chemically bound to the surface of the pore walls. As a result, the concrete surface becomes hydrophobic.
- Surface treatments based on silanes only slightly reduce the water vapour permeability.

For the efficiency and durability of the hydrophobic treatment, the penetration depth and content of active substances in the concrete are decisive parameters. For a good treatment, a minimum penetration depth of 5 mm or more is desirable.

Concentrated or diluted silanes which are commercially available in three forms, e.g. liquid, creem and gel, are normally applied to the concrete surface by spraying. For the liquid silane, the contact time between the liquid and the concrete surface is typically in the range of a few minutes, and the penetration depth is mostly in the range of 1 to 2 mm. For the creem and the gel type, a longer contact time and a deeper penetration depth are normally obtained. For the hydrophobic system analyzed in the present case, a silane gel was selected, where the supplyer claims that a penetration depth of 8 mm or more may be achieved.

3.3.2 Silane chemistry

Silanes are silicon-organic compounds with silicon as the sentral atom, bound to four organic groups. The standard silane used for treatment of building materials consists of three ethoxy groups (OR) and one non-reactive, non-polar hydrocarbon group (R*) wich is an alkyl group.

Two commercial types of silanes are normally used for hydrophobic treatment of concrete structures. The difference between the two silanes is the lenghth of the carbon chain of the non-reactive alkyl group (R*) . For iso-butyl triethoxysilane, the alkyl group (R*) consists of four carbon atoms, while for the iso-octyl triethoxysilane it is composed of eight carbon atoms.

As a concequence of the specific structure of the silanes, differences both in chemical reactivity (e.g. the rate of hydrolysis) and physical behaviour (e.g. volatility) can be observed, that strongly affects both the chemical reaction and the rate of transport of the silanes into the concrete [8,9]. The iso-butyl triethoxysilane is much more volatile than the iso-octyl triethoxysilane.

The non-reactive alkyl group is oriented towards the solid surface of the capillaries leading to the hydrophobic effect.

3.3.3 Environmental impacts of the hydrophobic treatment

The analysis was based on the following assumptions:

- Type of coating: Iso-octyl triethoxysilane mixed with a mineral thickener.
- Surface area treated : 150 m^2

The various steps of the hydrophobic treatment included:

a) Surface preparation.
All surfaces treated were cleaned with hot water (60 – 90 °C) at high pressure (160 bar).

b) Application of the hydrophobic agent.
A high pressure sprayer was used to apply the hydrophobic agent in a thickness of more than 0,25 mm. In the present analysis, it was assumed that only 45 % of the hydrophobic agent from the high pressure sprayer reached the concrete surface. It was further assumed that the amount of agent applied was appoximately 500 g/m^2, while the emission to air was approximately 600 g/m^2. The iso-octyl triethoxysilane is volatile and ethanol is released to the atmosphere.

c) Emissions of ethanol during film setting.
After the application to the concrete surface, the water repellent agents penetrate into the concrete by capillary suction. Inside the concrete, a chemical reaction takes place forming chemically reactive silanols and ethanol which evaporates to the atmosphere.

In the next step of reaction, the silanoles polymerize into a thin film of silicon resin which is fixed to the pore walls by chemical bonds. It was assumed that the emission of ethanol from 1000 g iso-octyltriethoxysilane was 500 g.

d) Long term degradation processes.
Long term degradation processes include emissions of CH_4, CO_2, SiO_2 and water. It was assumed that 500 g of iso-octyltriethoxy silane lead to the emission of 101 g CH_4 and 50 g CO_2.

e) Service life of surface treatments.
The service life of a silane-based surface treatment may range from 7 to 20 years. For the present analysis, it was assumed that the surface treatment would have a service life of 10 years, which is in accordance with Sweedish regulations for highway bridges.

As can be seen from Table 5, it turns out that the major part of the environmental impacts of the surface treatment arises from the production of the hydrophobic agent.

Use of energy and environmental impacts are demonstrated in Table 5, where transportation of materials and equipment are included in the relevant impact categories.

Table 5. Energy consumption and environmental impacts of the hydrophobic surface protection.

Process	**Impact category**				
	Use of energy (MJ/m^2)	**Global warming (g CO_2 eq/m^2)**	**Acidification (g SO_2 eq/m^2)**	**Eutrophi-cation (g PO_4 eq/m^2)**	**Photo-oxidant formation (g Ethene eq/m^2)**
Production of hydrophobic agent	47	295	0,5	6	2
Surface preparation	17	13	0,4	7	1
Transportation and surface treatment	12	80	0,1	2	66
Long-term degradation		2171			1
Sum	76	2559	1	15	70

3.4 Comparison of the two cases

By comparing the two cases selected for analysis, it can be seen from Table 6 that the ecological impacts from the patch repair strongly exceeds that of the hydrophobic surface protection. The results demonstrate that the hydrophobic surface treatment can be repeated more than five times before the environmental impact in the form of photo-oxidant formation approaches that of the patch repair by shotcreting.

Table 6. Comparison between patch repair and hydrophobic surface treatment.

Method	**Impact category**				
	Use of energy (MJ/m^2)	**Global warming** (kg CO_2 eq/m^2)	**Acidifi-cation** (g SO_2 eq/m^2)	**Eutrophi-cation** (g SO_2 eq/m^2)	**Photo-oxidant formation** (g Ethene eq/m^2)
Hydrophobic treatment	76	2,6	1	15	70
Patch repair	1194	122	125	1902	383

4 Concluding remarks

Assessment of impact on the environment caused by human activities throughout the life cycle of a structure may be very complex and difficult. Over recent years, however, a methodological framework for assessment of Life Cycle Ecology (LCE) or Life Cycle Assessments (LCA) has been established through a number of international standards and guidelines.

In order to carry out the present assessment of LCE, a number of assumptions had to be made. The results clearly demonstrate, however, that from an ecological point of view, it appears to be a very good strategy to carry out preventive maintenance of a concrete structure before a stage is reached where patch repairs may be necessary.

5 Proposal for further development

In order to facilitate future assessment and analysis of LCE, an international data base should be established, where also the material suppliers should contribute with all relevant environmental information about their products.

6 References

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Appendix

Effect factors.

Global warming	(100 years)
Source: IPCC 1995	g CO_2 eq. /g
Emission to air	
C_2F_6	9200
C_3F_8	7000
C_4F_{10}	7000
$C5F_{12}$	7500
C_6F_{14}	7400
$C\text{-}C_4F_8$	8700
CF_4	6500
CFC-11	2100
CFC-113	3600
CFC-114	7000
CFC-115	7000
CFC-12	7100
CFC-13	13000
CH_2Cl_2	9
CH_4	21
$CHCl_3$	4
CO_2	1
CO	2
HALON-1211	4900
HCFC-123	50
HCFC-124	430
HCFC-141b	370
HCFC142b	1700
HCFC-22	1400
HFC-125	2800
HFC-134	1000
HFC-134a	1300
HFC-143	300
HFC-143a	3800
HFC152a	140
HFC-227ea	2900
HFC-23	11700
HFC-236fa	6300
HFC-245ca	560
HFC-32	650
HFC-41	150
HFC-43-10mee	1300
N_2O	310
SF_6	23900

Acidification	
Source: Heijungs	g SO_2 eq,/g
Emission to air	
HCl	0,88
HF	1,6
NH_3	1,88
NO	1,07
NO_2	0,7
NOx (as NO_2)	0,7
HNO_3	0,51
H_3PO_4	0,98
H_2S	1,88
SO_2	1

Ozone depletion	
Source: Montreal Protocol	
Emission to air	g CFC11 eq,/g
CCl_4	1,1
CFC-11	1
CFC-113	0,8
CFC-114	1
CFC-115	0,6
CFC-12	1
CFC-13	1
CH_3CCl_3	0,1
$CHCl_3$	0,12
HALON-1201	1,4
HALON-1202	1,25
HALON-1211	3
HALON-1301	10
HCFC-123	0,006
HCFC-124	0,04
HCFC-141b	0,11
HCFC142b	0,065
HCFC-22	0,055
Other CFC	1

Eutrophication

Source: Heijungs

Emission to air	g PO_4 eq,/g
N_2O	0,13
NH_3	0,35
NO	0,2
NO_2	0,13
NO_x (as NO_2)	0,13

Discharge to water	g PO_4 eq,/g
Ammoniacal N	0,33
BOD	0,11
COD	0,022
Nitrate	0,1
Orthophosphate	1
Total Nitrogen	0,42
Phosphorous	3,06

Formation of photo-oxidants

Source: Heijungs

Emission to air	g ethene eq/g
124trimethylbenzene	1,2
22dimethylpropane	0,398
2methylhexane	0,492
2methylpentane	0,524
3methylhexane	0,492
3methylpentane	0,431
4methylpentan2one	0,326
Acetone	0,178
Acetylene	0,168
Aromatic Hydrocarbons	0,761
Benzene	0,189
But2ene	0,992
Butan2one	0,326
Butane	0,41
Butanols	0,196
Butylacetate	0,323
CCl_4	0,021
CFC-11	0,021
CFC-113	0,021
CFC-114	0,021
CFC-115	0,021
CFC-12	0,021

Formation of photo-oxidants

Source: Heijungs

Emission to air	g ethene eq/g
HFC-143a	0,021
HFC152a	0,021
HFC-227ea	0,021
HFC-23	0,021
HFC-236fa	0,021
HFC-245ca	0,021
HFC-32	0,021
HFC-41	0,021
HFC-43-10mee	0,021
Isobutane	0,315
Isopentane	0,296
Methylheptanes	0,469
m-ethyltoluene	0,794
m-xylene	0,993
NMVOC	0,416
Octane	0,493
Other CFC	0,021
Other HCFC	0,021
Other paraffins	0,761
Other unknown VOC	0,337
Other VOC	0,337
o-xylene	0,666

CFC-13	0,021	PCB's	0,021
CFC-50$_2$	0,021	Pent2ene	0,93
CH_2Cl_2	0,021	Pentane	0,408
CH_3CCl_3	0,021	Pentane isomers	0,296
CH_4	0,007	p-ethyltoluene	0,725
$CHCl_3$	0,001	Propan1ol	0,196
Ethane	0,082	Propan2ol	0,196
Ethanol	0,268	Propane	0,42
Ethene	1	Propylene	1,03
Ethylacetate	0,218	p-xylene	0,888
Ethylbenzene	0,593	Aliphatic Hydrocarbons	0,398
Formaldehyde	0,421	Tetrachloroethene	0,005
Glycols	0,196	Toluene	0,563
HALON-1201	0,021	Trichloroethene	0,066
HALON-1202	0,021	White spirit	0,761
HALON-1211	0,021	Xylenes	0,888
HALON-1301	0,021		
HCFC-123	0,021		
HCFC-124	0,021		
HCFC-141b	0,021		
HCFC142b	0,021		
HCFC-22	0,021		
Heptane	0,529		
Hexane	0,421		
HFC-125	0,021		
HFC-134	0,021		
HFC-134a	0,021		
HFC-143	0,021		