LIFECON DELIVERABLE D 5.1

Qualitative and quantitative description and classification of RAMS (Reliability, Availability, Maintainability, Safety) characteristics for different categories of repair materials and systems

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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

Repair methods, materials, RAMS, QFD, decision making.

Abstract

This final deliverable contains the completed RAMS classifications for different repair methods and systems. This final report starts with the explanation of the first principles from which the results have been derived. The principles are used to determine the qualitative RAMS characteristics by using them to perform classifications on four different structures, all well documented by extensive surveys. Finally, the qualitative RAMS descriptions are transmuted into quantitative data by redefining the RAMS parameters. The quantitative data are then analysed by the use of Quality Function of Deployment, taking the general Lifecon requirements into account, such as economy, pollution, human conditions, etc.

Survey data from relevant structures have been used to create a real life basis for the classification of RAMS.

Short descriptions of the four structures are given below:

The first structure is a concrete girder bridge situated in Gävle city, Sweden. Gävle is situated on the coast of the Baltic sea. The main type of damage is splitting and cracking of the concrete, caused by corrosion of the reinforcement. The damage is mostly a consequence of carbonation of the concrete.

The second structure is a wharf at Ormsund, which is located in the East of Norway. It is owned by Norway's largest municipal port authorities. The main cause of damage is the detrimental processes of chloride ingress and reinforcement corrosion.

The third structure is a large public building complex situated in the city centre of Oslo, Norway. The main cause of damage are detrimental processes such as carbonation and frost attack, as well as singularities such as execution errors.

The fourth structure is a subway tunnel system situated below the city centre of Oslo, Norway. The structure, which was constructed during the mid 1970s, had a problem ridden youth, which lead to extensive damage to the structure itself, and to its surroundings due to water leakages. The water leaking into the tunnel system through alum shale bedrock contained substances corrosive to concrete and reinforcement steel. The water leakages also resulted in both ground heave and subsidence, giving severe problems to surrounding buildings. The RAMS classifications are based on a rehabilitation report which evaluates the success of the rehabilitation result.

An innovative result is the incorporation of the change in RAMS with change in the type of structure and its accessibility. The qualitative and quantitative RAMS descriptions system, combined with the QFD, form a basis from which decision making tools can be developed.

List of Contents

List of terms, definitions and symbols

Terms:

QFD *Quality Function Deployment*

The RAMS definitions are:

Reliability: **The ability to reduce maintenance to a minimum during service life.**

Availability: The ease of supply of methods, systems, materials, or qualified personnel.

Maintainability: The ease with which the combination of all technical and associated administrative actions during the service life can retain a repair and /or upgrade in a state in which it can perform its required functions.

Safety: The health and accident risks that can be directly connected to methods, systems, products, and their end results.

1 Introduction

Existing standards and norms describe condition assessment works, rehabilitation methods, and suitable repair materials, but they do not offer a complete decision making tool, nor do they include the environmental and human aspects found in today's legislation. At present, repair strategies are developed by the owners, using in-house decision making techniques. A decision making tool, which integrates lifetime considerations, environmental aspects, total costs, all balanced against the actual available resources, is clearly needed. This need can be met by the making of an open ended system, which can be tailored to meet the end user's needs. Such a tool can be based on a decision making process, which best can be illustrated by a flow diagram, such as shown in diagram 1. The flow diagram shows the re-iterative process of finding the best maintenance strategy within the budgeted resources. The work tasks which are implemented in the flow diagram boxes numbered 2 and 4, and from 6 to 12, were necessary to meet the work objectives, which were to provide information and documentation on RAMS of repair and retrofitting products and techniques. For practical purposes, these were limited to:

1. Surface protection materials and techniques
2. Mechanical repair materials and techniques
3. Electrochemical repair materials and techniques

This report does not stand on its own, as it is a part of the Lifecon LMS. It is recommended that this report is read and used in conjunction with the D5.2 report on LCE, and the D5.3 report on LCC. The RAMS classification system, which produces numerical data, can be used in its present form to serve as a basis for the creation of decision making tools.

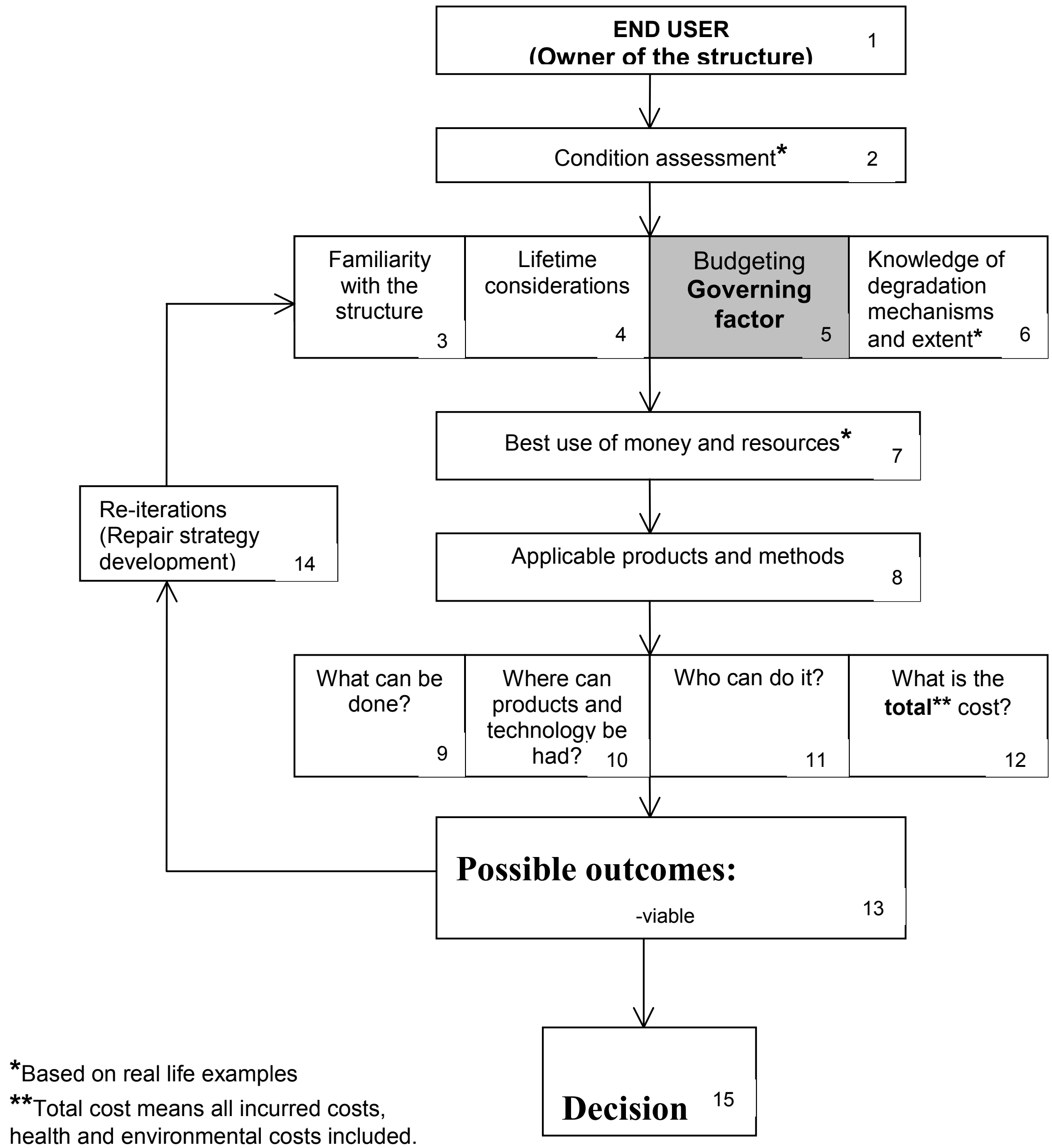

Diagram 1: The re-iterative decision making process

2 The D5.1 work

2.1 Underlying thoughts

The work tasks were complex and it was easy to loose sight of the main objectives. The tasks could seem overwhelming if boundaries were not drawn. It is important to remember that the collection of data for every product used throughout Europe, and to address all damage mechanisms, and all possible residual lifetime considerations that can occur, was impossible within the given resources. The work resources were used to cover the most common of these, and to create suitable input to aid in the development of IT tools. Our challenge was to create an *open-ended* system, including as many damage mechanisms, products, methods, and health and environmental aspects as we possibly could. The system, being open- ended, allow new modules to be attached when needed, thus easily expanding the compass of the tools.

It was decided to limit the number of damage mechanisms to be included to chloride induced corrosion, carbonation induced corrosion, AAR, sulphate attack, frost attack, and water leakage. It was also decided to limit the types of structures to be nominated for the purpose of RAMS classifications to four, namely bridges, tunnels, quays, and public buildings.

2.2 The work plan - a description of the flow diagram

The work plan is illustrated in the form of a flow diagram as shown overleaf.

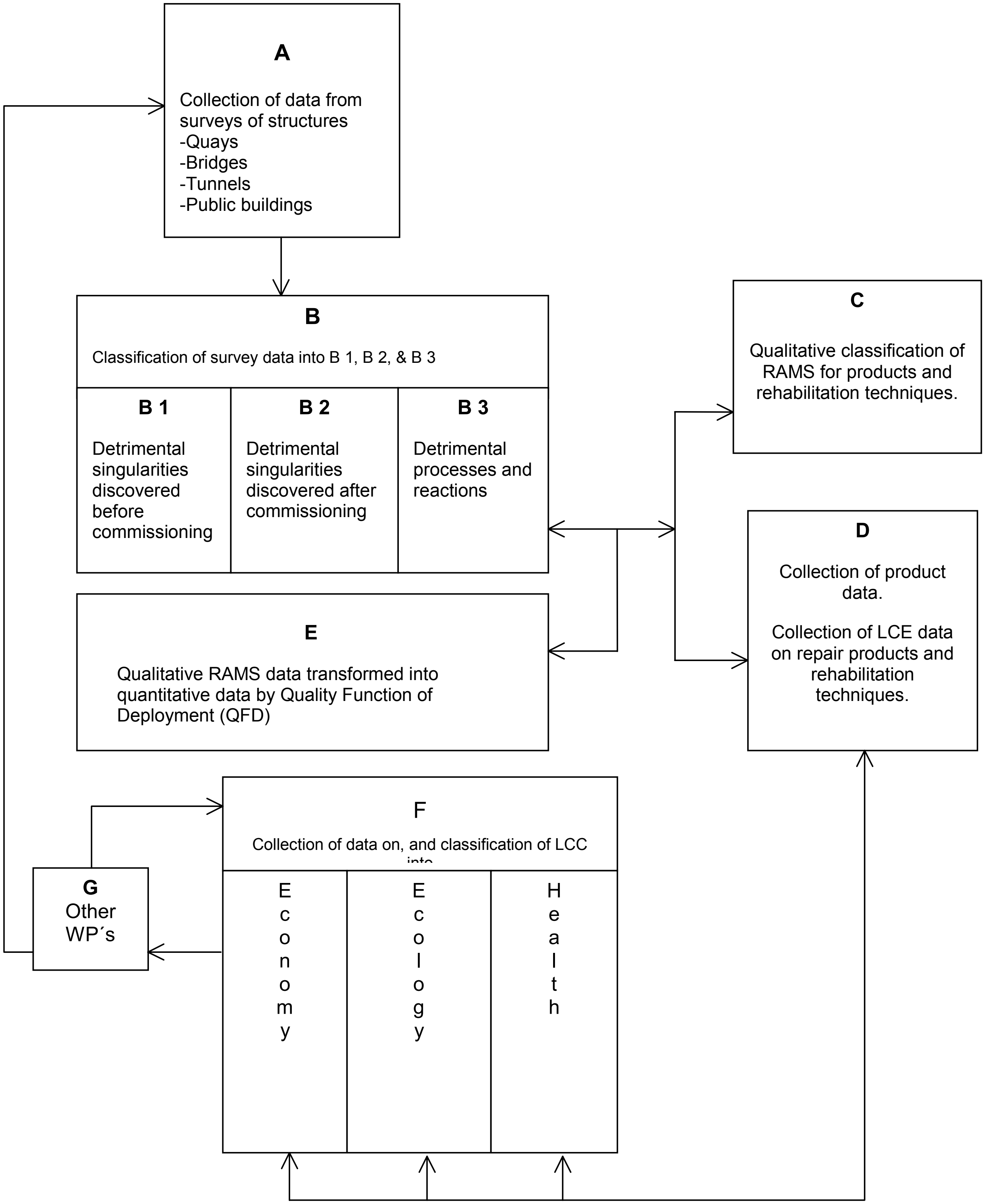

Diagram 2: The work plan flow diagram

The real life examples collected from the four structures, was used to reduce RAMS characteristics as an input to life cycle analysis, and for the examination of both materials and systems after application to these structures. The work plan diagram shows the work process stage-wise, where each stage is represented by boxes labelled from A to G. The boxes A, B, C, E, and F are all relevant to the creation of the RAMS characteristics.

Box A

Box A represents real life data collected from the four structures in mention.

Box B in relation to Box C

A description of the categories follows:

B1: Before commissioning, a survey is normally done to discover flaws made during construction or repair. Commissioning a structure before flaws are remedied may cause critical conditions. An example of such a flaw is severe cracking of concrete slabs, which can lead to rapid chloride ingress and accelerated carbonatisation along cracks.

B2: After commissioning, critical conditions can cause reductions of service life, if not remedied. An example of such a condition is fire damage causing accelerated carbonatisation and chloride ingress.

B3: Detrimental processes and reactions are relatively slow, relatively distributed processes which do not require immediate remediation. An example is carbonation of concrete, where the remediation should be done before reinforcement corrosion is initiated, or becomes severe. Processes of this nature are amenable to mathematical modelling.

These three categories are used for classifying the types of damage given from the surveys of the four structures listed in box A. The results from this classification are used for deriving the qualitative RAMS characteristics which are represented in Box C.

Box D

Ideally, this box should contain LCC and LCE data on products and rehabilitation techniques used and employed in the rehabilitation of the four structures given in box A. As it was not possible to find well documented rehabilitation works performed on such structures, the data in box D is substituted with data from rehabilitation techniques and products of known performance.

Box C, D and F in relation to Box E

Box E represents the QFD method for the transmution of qualitative data into quantitative data. The qualitative RAMS data represented by Box C is ranked by a numbering system which is fed into the QFD system together with the LCC and LCE data from Boxes D and F. The result is quantitative RAMS characteristics related to technical performance, LCC, and LCE.

Box G

Box G represent the survey work and comments to be made by other WP`s.

3 Presentations of the selected structures

3.1 Bäck Bridge in Gävle City, Sweden

3.1.1 Description

The object is a concrete girder bridge with ordinary reinforcement. The total span of the bridge is 48.8 m and the main span is 20.2 m. The frame members are fixed in the abutment. There is no insulation between road pavement and the supporting concrete for protection from moisture and chlorides. The road consists of two layers: 250 mm bituminous concrete and 25 mm asphalt.

The structure concrete density is 2300 kg/m^3 and the content of cement is 250 kg/m^3. According to the specification of the structure, the concrete quality corresponds to Btg 300/350 (σ_{cc}=30/35 MPa) depending on component. In 1994 the compressive strength (according to SS13 72 30), chloride ingress and carbonation depth were investigated with the following results:

Compressive strength of the concrete in beams: 31-39 MPa.

Compressive strength of the concrete in plate-deck: 41-52 MPa.

Chloride content in the upper- and under side of the plate deck: 0.04-1.13 % of the cement weight.

Chloride content in the bottom side of the beam: 0.02-0.04 % of the cement weight.

Depth of carbonation on the beams: 23-33 mm.

Drawings are shown overleaf in figures 1 to 3.

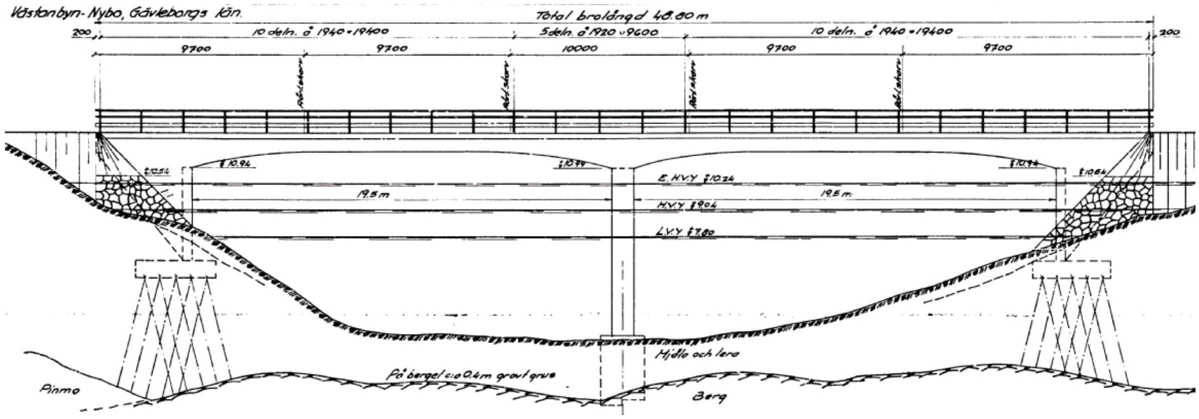

Figure 1: Elevation

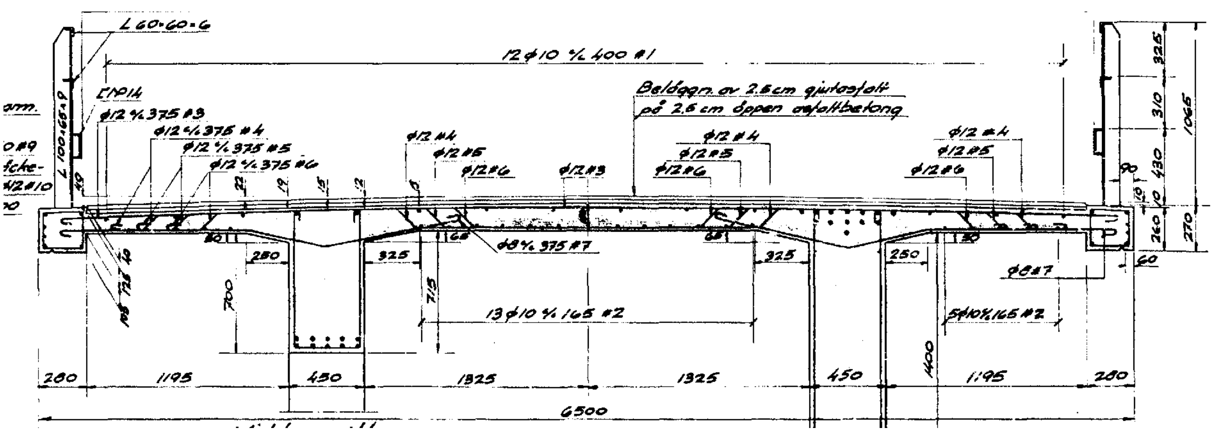

Figure 2: Cross section of the plate deck

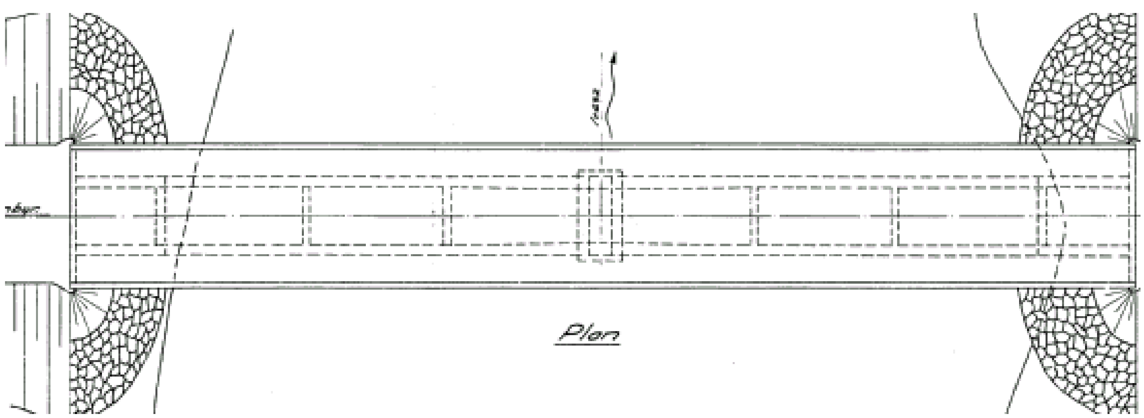

Figure 3: Bridge Plan

3.1.2 Damage

Edge beam:
Splitting and cracking of the concrete are probably caused by corrosion of the reinforcement. The damage is probably a consequence of chloride ingress in the concrete. The concrete cover is missing in much of the beam area. About 25 percent of the reinforcement is not active.

Photo 1: Corrosion of the reinforcement

Photo 2: Cracks in the edge beam
Beams:
Many cracks caused by bending and shearing stress. In parts, the stirrup reinforcement is visible.

Plate deck:
Many cracks and spalls in the concrete. The surface is covered by lime deposits in patches because of calcareous leaching from the concrete. Repairs to cracks have failed in many parts of the plate deck.

Photo 3: Cracks and leaching

Pier:
Decomposition in parts near the water line.

Baluster:
Many of the balusters are corroded, particularly of connections to the plate deck.

3.2 Ormsund wharf, Norway

The wharf, which is located in the East of Norway, is owned by one of Norway's largest municipal port authorities. The wharf has a total length of 272 meter and consists of two parts, each part built in 1977 and 1986. The newest part was investigated in this survey. The length of the newest part is 99.5 metres, and its width is varying from 16 to 53 metres.

The structural system consists of 27 sections, each of them consisting of a deck slab supported by 2 secondary beams, one at the front and one at the rear, and 2 main beams supported by from 3 to 9 reinforced concrete pillars.

The heights above mean seawater to:

-the top of the wharf deck is 2.2 meter

-the bottom of the slab is 1.7 meter

-to the bottom of secondary beams is 0.95 meter

The difference between high water at Autumnal equinox and the average water level at this location is 0.3 metre. The location of the sections and the different beams are described in accordance with the system used in the original drawings as shown in figure 4.

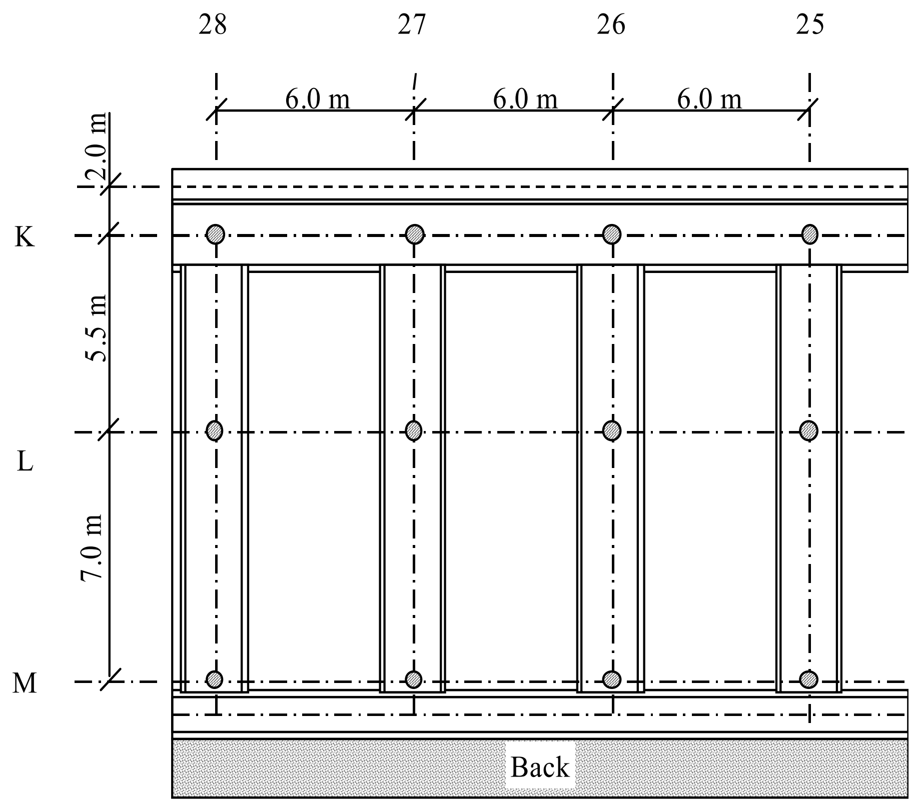

Figure 4: Structural layout

The deck slab is 500 mm in thickness, and the main reinforcement is 20 mm in diameter. The beams were designed with a trapezoidal shape, with bottom width 120 cm, top width 160 cm, and 75 cm in height. The beams are reinforced with 20-25 mm main reinforcement. The diameter of the pillars varies from 60 to 80 cm, and their reinforcement varies from 30-32 mm in diameter.

The original structural analyses showed that the wharf was designed for an evenly distributed live load of 50 kN/m^2 and concentrated wheel loads of 700 kN/m^2. The wharf was designed for cranes with 1000 kN axle loads.

Annual visual inspections have been carried out on this wharf since 1990.

The wharf has not had maintenance since it was built in 1977.

3.3 The Congress Centre, Folkets Hus in Oslo City, Norway

3.3.1 Description

The Congress Centre Folkets Hus A/L is a 10 storey public building complex situated in the centre of Oslo city. The complex was built in three stages as follows, with facades follows:

Stage 1:	Pre war to 1960s	Parts of the façade facing Henrik Ibsens gate
Stage 2:	1960s	Part of the façade facing Henrik Ibsens gate The whole façade facing Torggata Part of the façade facing Youngs gate
Stage 3:	1970s	Part of the façade facing Youngs gate and Møllergata

The pre-war building is mainly of steel and masonry, except from the top 3 floors, which are of reinforced concrete and light concrete building blocks. The steel and masonry parts of this building will not be used for the classification of damage categories.

The rest of the complex, stages 2 & 3, are of reinforced concrete.

The complex serves as a congress centre and as office premises.

3.3.2 The structure's usefulness for classification purposes

During the summer 2000, Millab Consult a.s. conducted an extensive survey of the structure, which included carbonation tests, chloride tests, reinforcement cover measurements, damage mapping, relative humidity measurements, and removal of spalled concrete.

The concrete surfaces exposed to the atmosphere have never been repaired, painted, or coated. It is therefore appropriate to use this object for performing RAMS classifications on repair systems and materials which can be employed for repair and maintenance work.

On the walls and eaves of storeys 8 & 9 there are spalled concrete due to carbonation and reinforcement corrosion. The render on the eaves and walls is coming off. Some walls are covered with gas concrete blocks, for used as insulating material. The blocks are loose, and need fixing to the substrate. The concrete cover of the reinforcement varies between 10 and 30 mm. Phenolphthalein tests showed that the concrete was carbonated to an average depth of 25 mm. In some areas as much as 35 mm of carbonation have been found. Taking into account that the concrete is about 35 years old, the time needed for further carbonation is considerable. Nevertheless, it is necessary to bring the current reinforcement corrosion under control.

The top storey is built in light concrete blocks. No particular problems were found here.

The concrete does not contain chloride concentrations above levels considered harmful to reinforcement surrounded by sound or carbonated concrete.

3.3.3 Building stage 2

The façade concrete exposed to the atmosphere consists of columns, beams and soffits. The concrete is frequently spalled, which is caused by reinforcement corrosion due to carbonation. The most serious and frequently occurring damage is in the upper third of the façade columns between the concrete floors, where the reinforcement cover varies from 0 to 30 mm. The low cover is due to misplaced reinforcement during construction, see figure 5.

Beams and soffits have frequent spalls caused by carbonation.

The concrete cover of the reinforcement varies between 0 and 100 mm. Phenolphthalein tests showed that the concrete was carbonated to an average depth of 25 mm. In some areas, as much as 45 mm carbonation have been found. Taking into account that the concrete is about 35 years old, the time needed for further carbonation is considerable. Nevertheless, it is necessary to bring the current reinforcement corrosion under control.

The concrete does not contain chloride concentrations above levels considered harmful to reinforcement surrounded by sound or carbonated concrete.

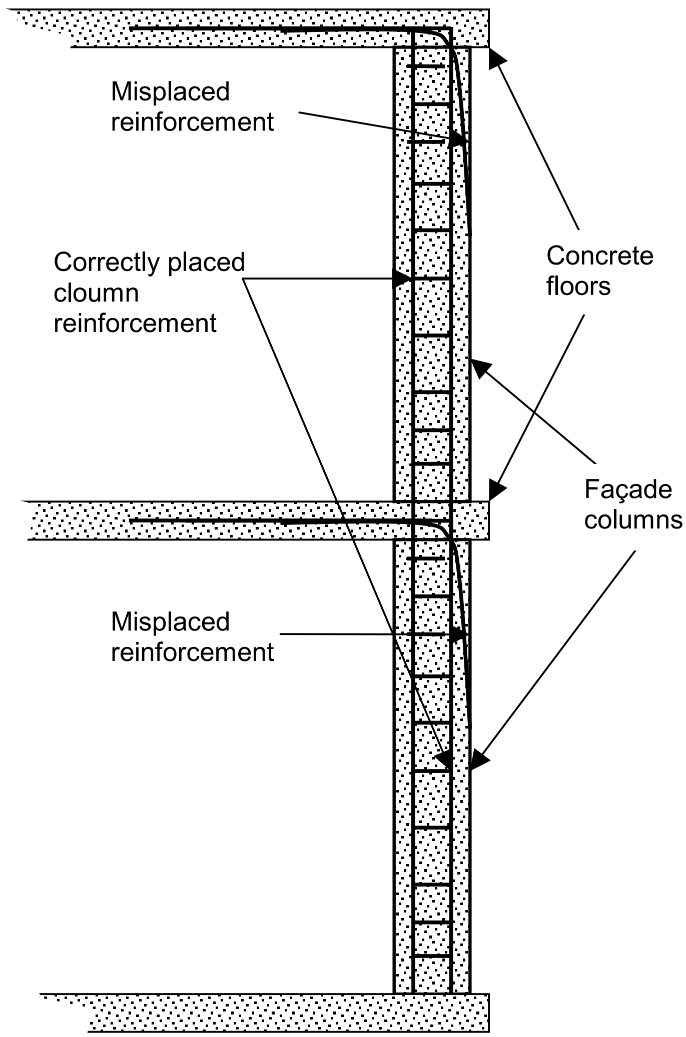

Figure 5: Principle sketch showing concrete floors and misplaced reinforcement in façade columns.

3.3.4 Building stage 3

The façade concrete exposed to the atmosphere consists of columns, beams and soffits. Spalled concrete does occur, but only in areas where the reinforcement cover is less than 15 mm. The damage frequency is low. Misplaced reinforcement as shown in figure 5 does not occur on this part of the structure.

The concrete cover of the reinforcement varies between 5 and 70 mm. Phenolphthalein tests showed that the concrete was carbonated to an average depth of 12 mm. In some areas, as much as 20 mm of carbonation has been found. Taking into account that the concrete is about 25 years old, the time needed for further carbonation is considerable. Nevertheless, it is necessary to bring the current reinforcement corrosion under control. The concrete does not contain chloride concentrations above levels considered harmful to reinforcement surrounded by sound and carbonated concrete.

3.4 Parliament Station, Oslo City, Norway

3.4.1 Description

Parliament Station with its connecting tunnels and facilities form the major part of A/S Oslo Sporveier`s (Oslo Tramways) sub-way system below Oslo. The station is also Oslo's main atomic shelter, and in time of war is meant to house and protect people.

A prerequisite of the tunnels was that they should be watertight in order not to drain the neighbouring ground in the central parts of Oslo. Bedrock in the area is chiefly so called alum shale, which upon weathering caused by lowering the water table, can produce corrosive and aggressive sulphatic solutions as well as giving rise to ground heave.

In the station's area of influence, the loose deposits consist of soft marine clays, which, should leakages occur in the tunnels, would be subject to increases in effective stress, which in turn would result in the settlement of buildings. In addition, the tunnels were to be dry out of consideration to employees, the public, and the technical installations.

In 1978, one year after its opening, the station was already plagued by troublesome leakages in practically all areas and at all levels. These became gradually worse, and as their compass increased, damage to technical equipment and installations became apparent. In 1980, a large piece of the concrete fell from the vault arch in one of the train tunnels. This lead to a survey, which uncovered conditions so alarming that the station was closed in 1983 for extensive repairs.

About alum shale

The alum shale matrix contains finely divided sulphide minerals. It is generally known that the sulphide minerals are the main cause of the chemical reactions occurring in alum shale. When the ground water table is lowered, oxygen is introduced to the alum shale matrix, causing oxidisation of the sulphide minerals. The process releases iron sulphates, which can decompose ordinary Portland concrete, and sulphuric acid, which can deteriorate concrete and cause reinforcement corrosion.

In addition to releasing harmful substances, alum shale swells upon weathering, creating swelling pressures up to 200 t/m^2, and causing heave of up to 30 cm depending on thickness.

The construction

In principle, the tunnels were constructed by first casting a 20-30 cm thick layer of un-reinforced blind concrete directly against the raw blasted rock surface. The function of this concrete was to stabilise the rock surface during the construction period, and to form a base for the gluing of 1 to 3 layers of watertightening membrane. This membrane was an approximately 2 mm thick glass fibre reinforced, asphaltic material.

The structural concrete, which was to have a thickness of between 35 to 100 cm, was then cast against the membrane on the walls and ceilings using jackable, hinged formwork. This concrete is cross reinforced on the atmospheric side of walls and vaults. The cement used was a Norwegian produced sulphate resistant cement.

3.4.2 Errors made during construction

Today, there is some uncertainty as to how the rebars were placed in the formwork prior to casting, but they appear to have been partly pushed in from the open end of the formwork, partly placed on the formwork before jacking it into place, and partly tied to metal framework bolted onto blind concrete and to rock. Whichever the case, it is obvious that the installation of the steel led to innumerable punctures in the membrane, and to correspondingly innumerable leakages.

A general characteristic of the concrete is its high porosity and poor workability. This was due to stiff concrete consistency, and to the fact that all vibrating had to be done through the formwork, which absorbed almost all vibration energy. In many sections, the lack of vibration is almost total, which lead to the formation of cavities, honeycombs, pores, segregation, channels along the reinforcement, cracks, etc. In addition, yielding of the shuttering during casting operation resulted in extensive delaminations.

The casting joints had not been tightened by waterstops or in any other way.

3.4.3 Construction flaws leading to damage to the structure and its surroundings

1. Water from the surrounding rock has leaked through innumerable punctures in the membrane, thus lowering the water table and initiating alum shale oxidation.

2. Alum shale decay as a direct consequence of the leakages and lowering of the water table caused ground heave and subsidence, which gave numerous problems in cellars and foundations in the surrounding area.

3. Water from the surrounding shale has pressed against the membrane, and torn it off its substrate where unsupported in cavities.

4. The water has then leaked between the concrete layers and found its way to the many leakage points along rebar channels, cracks, and other paths in the structural concrete.

<u>Carbonation of concrete</u>

The concrete cover of the reinforcement varies between 0 and 12 cm. Phenolphthalein tests showed that the concrete was carbonated to an average depth of 3 cm. In some areas, as much as 10 to 15 cm carbonation has been found. Taken into account that the concrete was only 6 to 8 years old, that the depth of carbonation was 3 cm, and that the average cover thickness of the reinforcement is approx. 5 cm, the prediction could be made that all the concrete would be carbonated to the first layer of reinforcement in approx. 10 to 12 years.

Due to the extreme carbonation depths that were found, a laboratory investigation was initiated to examine whether sulphate resistant cement carbonates faster that ordinary Portland cement. It was found that the carbonation rate in sulphate resistant cement is 3-4 times faster than in ordinary Portland cement.

Reinforcement corrosion

Just about all the observed cases of corrosion damage on reinforcement steel can be ascribed to alum shale water in channels along the reinforcement.

Sulphuric acid attack on sulphate resistant concrete

Alum shale water containing sulphuric acid exited in cast joints and through other leakage points, disintegrating the concrete.

Sulphate and sulphuric acid attack on ordinary concrete

Structural parts of ordinary concrete were exposed to alum shale water containing sulphates and sulphuric acid causing swelling and disintegration.

Technical installations

Electrical installations, ventilation and heating equipment, ticket offices, shops, plumbing fixtures, etc. were subject to damage caused by leakages of corrosive alum shale water.

3.4.4 Employed rehabilitation techniques

Concrete repair

Some of the delaminated areas in the tunnel vault arches were deemed too weak to withstand the weights and pressure loads associated with cement grout injection. In these areas, delaminated concrete was chiselled off, and the cavities repaired by wet spraying of concrete.

Injection of cement grout combined with chemical grout

As described earlier, there were more or less continuous gaps and cavities between the structural concrete and the membrane in the tunnels and the vault. As the gaps and cavities acted as water distribution

reservoirs, and also resulted in considerably reduced bearing capacity due to lack of support behind the vault construction, they had to be filled as completely as possible.

Gaps and cavities were filled by cement grout injection. A stable cement grout containing 20 parts per weight of cement and 1 of silica fume, with w/c approx. 0,6 was used. The maximum allowed injection pressure was 10 bar.

Small gaps formed between the injected grout and the cavity walls due to water separation in the grout. These gaps were filled by injecting a low viscosity silicate grout (Siprogel), which on setting gave a stable gel.

Watertightening membrane

On coating the free concrete surface with an impervious adhering membrane, transport of water will stop completely, and the concrete will gradually become saturated. Polyurethane coating applied in the most common used thickness of 1.2 mm, will, for all practical purposes, be watertight, diffusion proof to atmospheric gasses including water vapour, diffusion proof to chlorides, and will be able to bridge across cracks which open from 0 to 1 mm.

The water and gas pressure which can be resisted is limited by the tensile strength of the concrete surface. For lesser concrete qualities, i.e. up to C35, it is not difficult to obtain tensile strengths of up to 2-3 MPa. Compared to commonly encountered water pressures, which rarely exceed 20-30 m, even 1 MPa (100 m water column) should be a safe adhesion value in most cases.

Prior to applying the coating, the surfaces were prepared by high pressure jetting, sandblasting, scabbing, or flame cleaning. After cleaning was completed, the surfaces were brushed and vacuumed.

To control problems connected with water leakages remaining after injection works in order to create optimal conditions for the application of the coating, it was necessary to either drain or inject the largest leakages to allow preparation of the working area, at least locally or in part.

Application of the polyurethane coating was performed by brush, roller, and spray gun.

Saturation of the concrete

Coating the concrete stops the carbonation process, both because the coating itself is diffusion proof, and because it allows complete saturation of the concrete. The extremely low diffusivity of the coating limits the access of oxygen, and thereby contributes to slowing the corrosion process.

Passive realkalisation

On sealing the concrete surface, the access to carbon dioxide is cut off, and the concrete saturates with water. When the concrete is completely saturated, all water transport stops. What now happens is that alkaline agents in the concrete behind the reinforcement and the carbonated zone dissolve and diffuse into the carbonated zone and raise the pH to protective levels.

4 The RAMS classification process

4.1 Bäck Bridge in Gävle City, Sweden

The first step is to systemise the damage into a protocol as shown below.

Table 1: The damage protocol on Bäck Bridge in Gävle

Structural part	Conditions	Degradation mechanisms and/or causes	Consequences
Edge beam	Delaminations, cracks, and spalls in the concrete caused by corrosion of the reinforcement. The concrete cover is spalled in many parts of the beam area.	Chloride ingress Reinforcement corrosion	About 25 percent of the reinforcement is inactive. Structural damage
Main beams	Extensive cracking, spalling, and delamination. The stirrup reinforcement is visible. Thin concrete cover	Bending stress Shearing stress. Heavy load	Structural damage Hazards to pedestrian and car traffic. No danger of collapse if the axle load from traffic is restricted
Plate deck Insulation	Extensive delaminating and cracking. Lime leaching. Failure of earlier repairs Bending crack near the abutment Thin concrete cover	No bridge membrane Chloride contamination Water leaching Sensitive to frost attack Sensitive to reinforcement corrosion Heavy load	Structural damage No danger of collapse if the axle load from traffic is restricted
Abutment front wall	Bending crack Spalls in water line	Displacement in foundation Frost damage	Structural damage

Table 1 continued: The damage protocol on Bäck Bridge in Gävle

Structural part	Conditions	Degradation mechanisms and/or causes	Consequences
Pier, the central column.	Abrasion damage and leaching in the parts near the water line Spalls in the concrete near the water line	Mechanical damage from ice formation. Frost attack	Concrete degradation.
Railings	Corroded railings, particularly at the transition to the deck surface. Deformed railings Cracks in railings	Corrosion caused by chloride attack Steel corrosion in gaps between steel and asphalt and on steel surrounded by carbonated and/or chloride contaminated concrete. Traffic collision damage	Hazards to pedestrian and car traffic

The second step is to classify the damage according to Box B in the work plan flow shown in diagram 2.

Table 2: Classification of damage, Bäck Bridge in Gävle

Condition	Cause	Classification	Reason for classification	Employed rehabilitation techniques and options on rehabilitation techniques
Main beams				
The concrete cover is missing in many parts of the beam area. The stirrup reinforcement is visible	Reinforcement corrosion	**B3**	Detrimental process	Mechanical repair and wet spray concrete or dry spray mortaring Electrochemical repair
Extensive delaminations, spalling, and cracks.	Chloride contamination	**B3**	Detrimental process	Electrochemical desalination Cathodic protection
	Missing bridge membrane	**B2**	Singularity Poor maintenance	Application of bridge membrane
	Carbonation	**B3**	Detrimental process	Electrochemical realkalisation
	Bending and shear stresses from overload	**B3**	Detrimental process	External reinforcement
	Compressive strength of the concrete in beams 31-39 MPa. Too strong or too low?	**B2**	Singularity	External reinforcement

Table 2 continued: Classification of damage, Bäck Bridge in Gävle

Condition	Cause	Classification	Reason for classification	Employed rehabilitation techniques and options on rehabilitation techniques
Deck				
Extensive delaminations, spalling, and cracking. Lime leaching from the concrete. Failed earlier repairs.	Frost attack No bridge membrane Water leaching	**B3**	Detrimental process	Application of bridge membrane Mechanical repair and wet spray concrete or dry spray mortaring
Bending crack near the abutment	Overload from heavy traffic.	**B2**	Detrimental singularities	External reinforcement
Thin concrete cover	Reinforcement corrosion	**B3**	Detrimental process	Mechanical repair and wet spray concrete or dry spray mortaring Cathodic protection
	Carbonation	**B3**	Detrimental process	Electrochemical realkalisation
	Chloride contamination	**B2**	Singularity Poor maintenance	Electrochemical desalination and/or realkalisation
	Missing expansion joints, or defective bearing	**B2 and/or B3**	Detrimental process, poor maintenance and/or singularity	Installation of expansion joints, or repair of bearing

Table 2 continued: Classification of damage, Bäck Bridge in Gävle

Condition	Cause	Classification	Reason for classification	Employed rehabilitation techniques and options on rehabilitation techniques
Pier and front wall				
Decomposition in the parts near the water line	Probably abrasive mechanical damage from ice.	**B3**	Detrimental process	Mechanical repair and wet spray concrete or dry spray mortaring.
Spalls in the concrete near the water line	Frost damage	**B3**	Detrimental process	Application of polyurethane slip coating
Bending crack	Displacement in foundation	**B3**	Detrimental process	Replacing the foundation
Railings				
Corroded railings, particularly at the transition to the deck surface.	Corrosion caused by chloride attack Steel corrosion in gaps between steel and asphalt and on steel surrounded by carbonated and/or chloride contaminated concrete.	**B3**	Detrimental process	Mechanical repair, or change the balusters
Deformed railings	Traffic collisions	**B2**	Singularity	Mechanical repair
Crack in railings	Traffic collisions	**B2**	Singularity	Mechanical repair, or change the railings

Table 2 continued: Classification of damage, Bäck Bridge in Gävle

Condition	Cause	Classification	Reason for classification	Employed rehabilitation techniques and options on rehabilitation techniques
Edge beam				
Delaminations, cracks, and spalls in the concrete caused by corrosion of the reinforcement The concrete cover is spalled in many parts of the beam area.	Chloride ingress of concrete Reinforcement corrosion	**B3**	Detrimental process	Mechanical repair

The third step is to qualitatively describe the suggested repair methods and materials according to the RAMS categories. The RAMS definitions on which these qualitative descriptions based on are given below.

<u>RAMS definitions</u>

Reliability: The ability to reduce maintenance to a minimum during service life.

Availability: The ease of supply of methods, systems, materials, or qualified personnel.

Maintainability: The ease with which the combination of all technical and associated administrative actions during the service life can retain a repair and /or upgrade in a state in which it can perform its required functions.

Safety: The health and accident risks that can be directly connected to the methods, systems, products, and their end results.

The classification of materials and products is integrated into the Reliability, Availability, Maintainability, and Safety considerations made in this qualitative phase.

Table 3: Classification of RAMS

Index No.	Methods, systems, and materials	Reliability	Availability	Maintainability	Safety
1	Electrochemical desalination	Near perfect	Good	Poor to good	Very good
2	Electrochemical realkalisation	Near perfect	Good	Poor to good	Very good
3	Mechanical repair method	Good	Excellent	Poor to good	Good
4	Cathodic protection	Poor to very good	Poor to very good	Poor to very good	Poor to very good
5	Concrete spraying, wet method	Very good	Excellent	Poor to good	Good
6	Concrete spraying, dry method	Very good	Good?	Good	Good
7	Application of bridge membrane	Good to excellent	Very good?	Poor	Good
8	External reinforcement	Poor to very good	Poor to very good?	Poor to very good	Poor to very good

Reasoning

The reasoning behind the RAMS descriptions is given below. The index numbers corresponds to the index numbers in table 3.

Index number 1: Electrochemical desalination

Reliability: Near perfect

To date, about 500 000 square metres of reinforced concrete have been desalinated world-wide with no reports of re-occurring reinforcement corrosion. The achieved corrosion protection of the reinforcement steel is practically maintenance free, if chloride re-contamination is prevented.

Availability: Good

Works can be executed in Sweden by Norwegian contractors.

Maintainability: Poor to good

Should recontamination of chlorides occur, re-treatment may be necessary.

Safety: Very good

The desalination process reduces the extent of heavy labour and potential hazards associated with mechanical repair works. In comparison to mechanical repair and some cathodic protection systems, the desalination process offers reduced noise emissions, which during refurbishment improves human health conditions. It is also lenient on the surroundings.

Index number 2: Electrochemical realkalisation

Reliability: Near perfect

To this day, about 1 500 000 square metres of reinforced concrete have been realkalised world-wide with no reports of re-occurring reinforcement corrosion.

Availability: Good

No license exists in Sweden, but successful works have been performed in Sweden. Norwegian contractors can offer desalination works performed in Sweden.

Maintainability: Poor to good

The need for maintenance has not yet appeared, although re-treatment is possible.

Safety: Very good

The realkalisation process reduces the extent of heavy labour and potential hazards associated with mechanical repair works. In comparison to mechanical repair and some cathodic protection systems, the realkalisation process offers reduced noise emissions, which during refurbishment improves human health conditions. It is also lenient on the surroundings.

Index number 3: Mechanical repair

Reliability: Good

It is known that mechanical repair can give rise to incipient anodes and the creation of macro-cells which induces reinforcement corrosion. Its reliability depends on the extent of removal of carbonated concrete surrounding the reinforcement, which in many cases is insufficient.

Availability: Excellent

Numerous contractors can offer mechanical repair works performed in Sweden.

Maintainability: Good to very good

Re-occurring corrosion is a frequent problem, which requires maintenance. The maintenance itself is relatively easily performed.

Safety: Good

Mechanical repair works is labour intensive, and employs chiselling tools harmful to human health. Water jetting tools relieve the worker of harmful chiselling stresses, but increases risks of serious injury. The noise emissions from mechanical repair works are high.

Index number 4: Cathodic protection

Reliability: Poor to very good

Cathodic protection systems which are correctly designed and installed, can offer reliable corrosion protection.

Availability: Poor to very good

Available on the Swedish market

Maintainability: Poor to good

Malfunction may require reinstallation or repair of system elements.

Safety: Very good

Cathodic protection reduces the extent of heavy labour and potential hazards associated with mechanical repair works. Installation require drilling which give rise to relatively high noise emissions.

Index number 5: Wet sprayed concrete

Reliability: Very good

Few problems are associated with wet sprayed concrete, which is deemed a well functioning replacement for the original concrete.

Availability: Excellent

Numerous contractors can offer wet sprayed concrete.

Maintainability: Poor to good

Repair is easy to perform in itself, but involves access to the structural parts.

Safety: Good

Wet spraying involves relatively laborious operations, which can be considered as detrimental to human health. Noise and dust emissions are acceptably low. The end result is normally very safe.

Index number 6: Dry sprayed mortar

Reliability: Very good

Few problems are associated with dry sprayed mortar, which is deemed a well functioning replacement for the original concrete.

Availability: Poor

Availability is limited in Sweden.

Maintainability: Good

Repair is easy to perform, but involves access to the structure.

Safety: Good

The dry spraying process involves relatively laborious operations which can be considered as detrimental to human health. Noise and dust emissions are acceptably low. The end result is normally very safe.

Index number 7: Bridge membrane

Reliability: Good to excellent

The method is proven to be very reliable in Norway, where bituminous membranes are most commonly used.

Availability: Very good

Availability unknown in Sweden.

Maintainability: Poor

Repair is easy to perform in itself, but is likely to involve removal of the tarmac.

Safety: Good

Surface preparation involves the use of abrasive equipment driven by compressed air, which causes high dust and noise emissions. The coating works itself does not involve heavy labour, or dust and noise emissions.

Index number 8: External reinforcement

Reliability: Good very good

Many methods and techniques are considered reliable.

Availability: Good

Maintainability: Poor to very good

Depends on the type of reinforcement.

Safety: Good to very good

Depends on the type of reinforcement.

Steps 1 to 3 are repeated for the next three structures in sections 4.2 to 4.4.

4.2 The Ormsund wharf situated at the East coast of Norway

Table 4: The damage protocol on Ormsund wharf situated at the East coast of Norway

Structural part	Conditions	Degradation mechanisms and/or causes	Consequences
Deck slab	Visual inspection showed that there was, no spalling, delamination, cracking, nor symptoms of corrosion. The concrete cover average is 35 mm Depth of carbonation average is 1.7 mm Average estimated depths of chloride concentration ≥0.4 % of cement is >25 mm.	Chloride penetration	Reinforcement corrosion Concrete spalling
Beams	A large portion of the beams suffered from reinforcement corrosion, extensive delamination and spalling Depth of carbonation is very low and varies from 1 to 3 mm. Average estimated depth of chloride concentration ≥ 0.4 % of cement average is 8.9 cm.	Combination of poor casting and chloride induced corrosion Chloride penetration No chloride impermeable membrane	Reinforcement corrosion Structural damage
Pillars	The pillars are of concrete filled steel pipes and were not investigated.		

Table 5: Classification of damage on Ormsund wharf situated at the East coast of Norway.

Condition	Cause	Classification	Reason for classification	Employed rehabilitation techniques and options on rehabilitation techniques
Deck slab Visual inspections showed that there was no spalling, delamination or cracking, nor symptoms of corrosion. The concrete cover average is 35 mm Depth of carbonation average is 1.7 mm Average estimated depth of chloride concentration ≥0.4 % of cement average is > 25 mm.	Chloride penetration.	**B3**	Detrimental process	Continued inspections Cathodic protection Electrochemical desalination Establishing a chloride impermeable membrane Hydrophobation of part of the concrete cover

Table 5 continued: Classification of damage on Ormsund wharf situated at the East coast of Norway.

Condition	Cause	Classification	Reason for classification	Employed rehabilitation techniques and options on rehabilitation techniques
Beams				
A large portion of the beams suffer from reinforcement corrosion, extensive delamination and spalling Depth of carbonation is low and varies from 1 to 3 mm.	Combination of poor casting and chloride induced corrosion	**B1/B3**	Detrimental singularity Detrimental process	Mechanical repair and wet spray concrete or dry spray mortaring.
Average estimated depths with chloride concentration of ≥0.4 % of cement average is 8.9 cm.	Chloride penetration.	**B3**	Detrimental process	Continued inspections. Cathodic protection Electrochemical desalination Establishing a chloride impermeable membrane Hydrophobation of part of the concrete cover

RAMS definitions

Reliability: The ability to reduce maintenance to a minimum during service life.

Availability: The ease of supply of the methods, systems, materials, or qualified personnel.

Maintainability: The ease with which the combination of all technical and associated administrative actions during the service life can retain a repair and /or upgrade in a state in which it can perform its required functions.

Safety: The health and accident risks that can be directly connected to methods, systems, products, and their end results.

The classification of materials and products is integrated into the Reliability, Availability, Maintainability, and Safety considerations made in this qualitative phase.

Table 6: The qualitative classification of RAMS on the Ormsund wharf situated at the East coast of Norway.

Index No.	**Methods, systems, and materials**	**Reliability**	**Availability**	**Maintainability**	**Safety**
1	Electrochemical desalination	Very good	Very good	Good	Very good
2	Mechanical repair method	Poor	Excellent	Good to very good	Good
3	Cathodic protection Ceramic rod anodes	Very good	Good	Poor	Very good
4	Concrete spraying, wet method	Very good	Excellent	Good	Good
5	Concrete spraying, dry method	Very good	Very good	Good	Good
6	Application chloride impermeable membrane – polyurethane	Excellent	Poor to good	Poor to good	Good
7	Application of hydrophing agent on the concrete surfaces with silanes or siloxanes	Good?	Poor to good	Poor to very good?	Very good

Reasoning

Index number 1: Electrochemical desalination

Reliability: Very good

To this day, about 500 000 square metres of reinforced concrete have been desalinated world-wide with no reports of re-occurring reinforcement corrosion. The achieved corrosion protection of the reinforcement steel is practically maintenance free, if chloride re-contamination is prevented.

Availability: Very good

Several contractors can offer desalination works on the Norwegian market.

Maintainability: Good

Should recontamination of chlorides occur, re-treatment may be necessary.

Safety: Very good

The desalination process reduces the extent of heavy labour and potential hazards associated with mechanical repair works. In comparison to mechanical repair and some cathodic protection systems, the desalination process offers reduced noise emissions, which during refurbishment improves human health conditions. It is also lenient on the surroundings.

Index number 2: Mechanical repair

Reliability: Poor

It is known that mechanical repair can give rise to incipient anodes and the creation of macro cells which induces reinforcement corrosion. Its reliability depends on the extent of removal of chloride infected concrete surrounding the reinforcement, which in many cases is insufficient.

Availability: Excellent

Numerous contractors can offer mechanical repair works performed in Norway.

Maintainability: Good to very good

Re-occurring corrosion is frequent, requiring maintenance. The maintenance itself is relatively easy.

Safety: Good

Mechanical repair work is labour intensive, and employs chiselling tools harmful to human health. Water jetting tools relieves the worker of harmful chiselling, but increases risks of serious injury. The noise emissions from mechanical repair works are high.

Index number 3: Cathodic protection – ceramic rod anodes

Reliability: Very good

This cathodic protection system, if correctly designed and installed, can offer reliable corrosion protection.

Availability: Good

The system is available in Norway, but is not widely known.

Maintainability: Poor to good

Malfunction may require reinstallation or repair of system elements.

Safety: Very good

Cathodic protection reduces the extent of heavy labour and potential hazards associated with mechanical repair works. This installation process requires drilling which gives rise to relatively high noise emissions.

Index number 4: Wet sprayed concrete

Reliability: Very good

Few problems are associated with wet sprayed concrete, which is deemed a well functioning replacement for the original concrete.

Availability: Excellent

Numerous contractors can offer wet sprayed concrete.

Maintainability: Poor to good

Repair is easy to perform in itself, but involves access to the structural parts.

Safety: Good

Wet spraying involves relatively laborious operations, which can be considered as detrimental to human health. Noise and dust emissions are acceptably low. The end result is normally very safe.

Index number 5: Dry sprayed mortar

Reliability: Very good

Few problems are associated with dry sprayed mortar, which is deemed a well functioning replacement for the original concrete.

Availability: Very good

Many contractors can perform dry sprayed mortar in Norway.

Maintainability: Good

Repair is easy to perform in itself, but involves access to the structure.

Safety: Good

The dry spraying process involves relatively laborious operations, which can be considered as detrimental to human health. Noise and dust emissions are acceptably low. The end result is normally very safe.

Index number 6: Chloride impermeable coating - polyurethane

Reliability: Excellent

Polyurethane coatings are known as very reliable, and they are perhaps the only practical coating that are known to be chloride impermeable.

Availability: Poor to good

A few contractors can offer proper application of polyurethane coatings in Norway.

Maintainability: Poor to good

Repair involves several operations, which includes removal of damaged coating, reactivation of existing undamaged coating with solvents, and application of new coating.

Safety: Good

Surface preparation involves use of abrasive equipment driven by compressed air which causes high dust and noise emissions. The coating work itself does not involve heavy labour, or dust and noise emissions.

Index number 7: Hydrophobing – silanes or siloxanes

Reliability: Good

Not much experience exists.

Availability: Poor

A few contractors can offer application of hydrophobing agents in Norway.

Maintainability: Poor to very good

Re-treatment will be necessary in time.

Safety: Very good

Hydrophobing is not very labour intensive and does not involve hazardous operations.

4.3 The Congress Centre Folkets Hus A/L situated in the centre of Oslo City in Norway

Table 7: The damage protocol on the Congress Centre Folkets Hus A/L situated in the centre of Oslo city in Norway.

Structural part	Condition	Degradation mechanisms and causes	Consequences
Eves, stage 1, 8 storey	Spalling concrete	Carbonated concrete Reinforcement corrosion	Loose concrete - hazard to pedestrian and car traffic.
Walls, stage 1, 9 storey	Spalling concrete and render	Carbonated concrete Reinforcement corrosion	Loose concrete - hazard to pedestrian and car traffic.
Walls, stage 1, 10 storey	Loose blocks of gas concrete	Error during execution Carbonated concrete Reinforcement corrosion	Loose concrete - hazard to pedestrian and car traffic.
Eves, stage 1, 9 storey	Disintegration of render and concrete	Frost damage	Loose concrete - hazard to pedestrian and car traffic.

Table 7 continued: The damage protocol on the Congress Centre Folkets Hus A/L situated in the centre of Oslo city in Norway.

Structural part	Condition	Degradation mechanisms and causes	Consequences
Columns, stage 2, storeys 2 to 10	Concrete spalls weighing from 0.1 kg up to 20 kg.	Systematic low concrete cover on the upper third of columns between concrete floors. Carbonated concrete Reinforcement corrosion	Structural damage Loose concrete - hazard to pedestrian and car traffic.
Eves, stage 2, storeys 8 and 10	Spalling concrete	Generally low concrete cover Carbonated concrete Reinforcement corrosion	Long term degradation of eves Spalling concrete will in time represent a hazard to pedestrian and car traffic.
Joint between stage 1 and stage 2, storeys 1 to 8	Deterioration of cellulose based joint filling	Age Poor joint filling material Absorption of humidity into concrete and joint Frost damage	Concrete degradation
Wall and circumferencial beam, stage 2, between storeys 1 and 2	Concrete spalls weighing up to 1 kg	Generally low concrete cover Carbonated concrete Reinforcement corrosion	Loose concrete - hazard to pedestrians.
Joint between stage 2 and stage 3, storey 2	Spalling concrete at joint	Reinforcement corrosion Absorption of humidity into concrete and joint Frost damage	Loose concrete - hazard to pedestrians. Concrete degradation
Corner column, stage 3, storeys 2 - 10	Spalling concrete	Low concrete cover Carbonated concrete Reinforcement corrosion	Long term degradation of eves Loose concrete - hazard to pedestrians
Eves, stage 2, storeys 8 and 10	Spalling concrete	Generally low concrete cover Carbonated concrete Reinforcement corrosion	Long term degradation of eves Loose concrete - hazard to pedestrian and car traffic

Table 8: The classification of damage on the Congress Centre Folkets Hus A/L situated in the centre of Oslo city in Norway.

Condition	Cause	Classification	Reason for classification	Options on rehabilitation techniques
Spalling concrete on eves, stage 1, 8 storey	Carbonation of concrete Rebar corrosion	**B3**	Detrimental process	Electrochemical passivation of reinforcement, or mechanical repair combined with coatings, or cathodic protection, or removal and substitution with other materials.
Spalling concrete and render on walls on the 9. storey, stage 1	Carbonation of concrete Rebar corrosion	**B3**	Detrimental process	Electrochemical passivation of reinforcement and/ or mechanical repair combined with coatings, or cathodic protection and removal and substitution of render
Loose blocks of gas concrete on walls on the 10. storey, stage 1	Error during execution	**B2**	Singularity discovered after commissioning	Removal of loose blocks and substitution of new blocks or alternative materials, or fixing loose blocks to substrate using ties.
Disintegrating concrete and render on eves, stage 1, 8 storey	Frost damage	**B3**	Detrimental process	Removal of frost damaged concrete and render combined with replacement of repair mortar and render. Protective coating.
Spalling concrete in façade columns stage 2	Execution error Low concrete cover Carbonation of concrete Rebar corrosion	**B2 & B3**	Detrimental process Singularity: Error during construction	Mechanical repair combined with electrochemical passivation of reinforcement. Theoretical option of protective coatings.

Table 8 continued: The classification of damage on the Congress Centre Folkets Hus A/L situated in the centre of Oslo city in Norway.

Condition	Cause	Classification	Reason for classification	Options on rehabilitation techniques
Spalling concrete on eves, stage 2, 8. and 10. storey	Low concrete cover Carbonation of concrete Rebar corrosion	**B3**	Detrimental process	Mechanical repair combined with electrochemical passivation of reinforcement. Theoretical option of protective coatings.
Deterioration of joint material between stage 1 and 2	Age combined with poor joint filling material	**B3**	Detrimental process	Removal of the accessible part of existing joint material with substitution of new joint material.
Spalling concrete on wall and circumferencial beam, stage 2	Low concrete cover combined with carbonation of concrete	**B3**	Detrimental process	Mechanical repair combined with electrochemical passivation of reinforcement.
Spalling concrete at joint between stage 2 and 3	Rebar corrosion caused by execution error and frost damage	**B3**	Detrimental process	Mechanical repair combined with electrochemical passivation of reinforcement.
Corner column stage 3	Low concrete cover combined with carbonation of concrete	**B3**	Detrimental process	Mechanical repair combined with electrochemical passivation of reinforcement. Theoretical option of protective coatings.

Table 9: The qualitative classification of RAMS for the Congress Centre Folkets Hus A/L situated in the city centre of Oslo in Norway.

Index No.	Methods, systems, and materials	Reliability	Availability	Maintainability	Safety
1	Norcure realkalisation	Excellent	Good	Good to very good	Very good
2	Mechanical repair	Medium to poor	Very Good	Good	Medium
3	Cathodic protection, category 1: Embedded rod anodes	Very good	Good	Poor to good	Very good
4	Cathodic protection, category 2: Embedded mesh	Medium	Very good	Easy to poor	Good
5	Cathodic protection, category 3: Embedded ribbon	Very good to medium	Very good	Easy to poor	Good
6	Cathodic protection, category 4: Conductive coating	Poor	Medium to poor	Poor	Very good
7	Paints and coatings, category 1: Organic paints and coatings, CO_2 barriers	Poor	Excellent	Poor	Good to very good
8	Protective paints and coatings, category 2: Organic paints and coatings	Medium	Good	Medium to poor	Medium
9	Protective paints and coatings, category 2: Cementitious paints and coatings containing polymer admixtures and enhancers	Poor	Good	Medium to poor	Good
10	Aesthetic coatings Cementitious paints and coatings	Good	Good	Good	Good

<u>Definitions</u>

Reliability: The ability to reduce maintenance to a minimum during service life.

Availability: The ease of supply of the methods, systems, materials, or qualified personnel.

Maintainability: The ease with which the combination of all technical and associated administrative actions during the service life can retain a repair and /or upgrade in a state in which it can perform its required functions.

Safety: The health and accident risks that can be directly connected to methods, systems, products, and their end results.

The classification of materials and products is integrated into the Reliability, Availability, Maintainability, and Safety considerations made in this qualitative phase.

<u>Reasoning</u>

Index number 1: Realkalisation

Reliability: Near perfect

To this day, about 1.5 million square meters of reinforced concrete have been realkalised with no reports of re-occurring reinforcement corrosion.

Availability: Very good

Four licensed contractors can offer Realkalisation works performed in the Oslo region

Maintainability: Very good to excellent

The achieved corrosion protection of the reinforcement steel is practically maintenance free.

Safety: Very good

The realkalisation process reduces the extent of heavy labour and potential hazards associated with mechanical repair works. In comparison to mechanical repair and some cathodic protection systems, the realkalisation process offers reduced noise emissions, which during refurbishment improves human health conditions for the building users.

Index number 2: Mechanical repair

Reliability: Good

It is known that mechanical repair can give rise to incipient anodes and the creation of macro cells which induce reinforcement corrosion. Its reliability depends on the extent of removal of carbonated concrete surrounding the reinforcement, which removal in many cases is insufficient.

Availability: Excellent

Numerous contractors can offer mechanical repair works performed in the Oslo region

Maintainability: Good to very good

Re-occurring corrosion is frequent, requiring maintenance. The maintenance itself is relatively easy.

Safety: Very good

Mechanical repair works is labour intensive, and employs chiselling tools harmful to human health. Water jetting tools relieves the worker of harmful chiselling stresses, but increases risks of serious injury. The noise emissions from mechanical repair works are high.

Index number 3: Cathodic protection – embedded rod anodes

Reliability: Very good

If correctly designed, this cathodic protection system can offer reliable corrosion protection.

Availability: Good

Four contractors can offer this type of cathodic protection works in the Oslo region

Maintainability: Very good

The system is not maintenance free, but has a trouble free service life expectancy of 10 to 20 years. Troubleshooting is in principle easy to perform. Malfunction may require reinstallation or repair of system elements.

Safety: Very good

Cathodic protection reduces the extent of heavy labour and potential hazards associated with mechanical repair works. This installation process requires drilling which give rise to relatively high noise emissions.

Index number 4: Cathodic protection – embedded mesh anode

Reliability: Medium

If correctly designed, this cathodic protection system can offer reliable corrosion protection. The installation process is difficult, which can give rise to flaws and reductions in service life.

Availability: Poor

A few contractors can offer this type of cathodic protection works in the Oslo region.

Maintainability: Poor

The system is not maintenance free, but has a trouble free service life expectancy of 10 years or more. Trouble shooting is difficult to perform. Malfunction may require the removal and reinstallation of large parts of the system.

Safety: Medium

The installation process does not involves high noise emissions, but does not use hazardous equipment. Dust emissions can be high.

Index number 5: Cathodic protection – embedded ribbon or wire

Reliability: Very good

If correctly designed, this cathodic protection system can offer reliable corrosion protection.

Availability: Poor

Few contractors can offer this type of cathodic protection works in the Oslo region

Maintainability: Good to very good

The system is not maintenance free, but should have a trouble free service life of 10 years or more. Trouble shooting is in principle easy to perform. Malfunction may require reinstallation or repair of system elements

Safety: Very good

The installation process does involve relatively high dust and noise emissions, and may involve the use of hazardous equipment.

Index number 6: Cathodic protection – conductive coating

Reliability: Poor

It is doubtful that organic based conductive coatings can deliver sufficient current densities to passivate the reinforcement steel. In addition, the coating itself is subjected to wear and tear from weather, and incompatibility with the substrate, which can reduce its design life.

Availability: Poor

Only one contractor can offer this type of cathodic protection works in the Oslo region

Maintainability: Poor to good

The system is not maintenance free, but has a trouble free service life expectancy up to 10 years. Failed coating needs removal and renewal. Troubleshooting is difficult to perform.

Safety: Very good

The installation process does not involve high noise or dust emissions, nor the use of hazardous equipment.

Index number 7: Protective paints and coatings – organic based CO2 barriers

Reliability: Poor

Achieved film thickness is difficult to control during application due the substrates ability to absorb paint, which lead to large film thickness. Thus, laboratory tests performed on even film thickness are often misleading. Large film thickness can cause H_2O inpermeability, causing water to condense in the substrate material. This may in turn lead to frost damage and the deterioration of paint and substrate. This is especially the case on application to rendered concrete surfaces.

Some organic paints are incompatible with concrete substrates due to their different thermal expansion coefficient to that of concrete, particularly in winter..

Availability: Very good

Numerous suppliers and contractors can offer products and their application in the Oslo region.

Maintainability: Poor

Failure is common. Removal is required before repainting.

Safety: Good

Some products contain solvents that can be harmful on inhalation. Some products contain harmful substances. Many products are considered safe.

Index number 8: Protective paints and coatings – Cementitious CO2 barriers

Reliability: Excellent

Cementitious paints and coatings are applied onto pre-wetted substrates, causing the substrates to absorb paint reasonably uniformly. This contributes to a controlled paint thickness, with predictable permeability parameters. Cementitious paints and coatings are without question compatible with concrete substrates, provided their performance is not based on additives such as polymeric modifiers.

Availability: Poor to good

Several suppliers and contractors can offer such products and their applications in the Oslo region

Maintainability: Very good

Flaking paint seldom occurs. Discoloration may require repainting. Re-painting can be performed without removing old paint.

Safety: Excellent

Pure cementitious products do not contain solvents or substances that are harmful on inhalation. Only ordinary precautions for the handling of cementitious products are necessary.

Index number 9: Protective paints and coatings – Cementitious products based on polymeric modifiers

Reliability: Good

Cementitious paints and coatings based on polymeric modification can be applied onto pre-wetted substrates, causing the substrates to absorb paint reasonably uniformly. This contributes to a controlled paint thickness, with predictable permeability parameters. In some cases, priming is used in stead of pre-wetting for sealing the pore system, thus controlling the film thickness, as well as forming a bond between the concrete substrate and the coating.

Polymeric conditioned paint and coatings are less stable than pure cementitious products. It is known that they can decompose in UV-light, and that some polymers decompose in contact with highly alkaline substances present in green concrete, and realkalised concrete.

Some polymerically modfied paint and coatings forms high water vapour resistance film, which may cause water vapour condensation problems.

Availability: Very good

Numerous suppliers and contractors can offer products and their applications in the Oslo region

Maintainability: Poor

Failure is common. Removal is required before repainting.

Safety: Good to very good

Cementitious polymer based products do not contain solvents or substances that are harmful on inhalation, although some primers do. Polymeric modifying substances are considered as safe. Only ordinary precautions for the handling of cementitious products are necessary.

4.4 Parliament Station situated in the centre of Oslo in Norway

Table 10: Classification of damage on the Parliament Station situated in the city centre of Oslo in Norway

Structural part	Conditions	Degradation mechanisms and/or causes	Consequences
Original watertightening membrane between blind concrete and structural concrete in tunnels and culverts	Perforated membrane caused ground water leakage into the structural complex Cavities between the blind concrete and the structural concrete caused the membrane to be torn off due to the water pressure on the membrane	Lowering of the ground water level lead to oxidation of alum shale bedrock. Release of sulphates and sulphuric acid from oxidised alum shale.	Swelling of alum shale bedrock caused structural damage to surrounding buildings. Lowering of the water table caused surface subsidence. Reinforcement corrosion Sulphuric acid attack on sulphate resistant concrete Sulphate attack on ordinary concrete Electrical problems Stoppage of drain pipes Closure of public toilets Public discomfort Reduced serviceability & final closure
Reinforced structural concrete in tunnels and the vault	Cavities, high porosity, honeycombing, cracks, and delaminations. Channels below and along the reinforcement steel.	Insufficiently compacted concrete Yielding formwork during casting	Multiple water passages throughout the structure

Table 10 continued: Classification of damage on the Parliament Station situated in the city centre of Oslo in Norway.

Structural part	Condition	Degradation mechanisms and causes	Consequences
Structural concrete in tunnels and the vault	Spalled concrete, some pieces weighing up to 300 kg	Rapid carbonation of concrete due to high porosity and due to high $C0_2$ levels, increased pressure caused by pumping action from trains, as well as the rapid carbonation rate of sulphate resistant concrete.	Reinforcement corrosion Structural damage Hazards to pedestrian and rail traffic
	Disintegrated concrete	Sulphuric acid attack	Disintegration of the sulphate resistant concrete at leakage points. Reinforcement corrosion
Non-structural concrete	Disintegration of concrete	Sulphate and sulphuric acid attack	Damage to secondary concrete features

Table 11: The classification of damage on the Parliament Station situated in the centre of Oslo city in Norway.

Condition	Cause	Classification	Reason	Employed rehabilitation techniques
Perforated membrane caused ground water leakage into the structural complex	Errors during execution	**B2**	Detrimental singularities discovered after commissioning	Injection works Surface application of watertight membrane
Cavities between the blind concrete and the structural concrete caused the membrane to be torn off due to water pressure on the membrane.	Errors during execution	**B2**	Detrimental singularities discovered after commissioning	Injection works Application of watertight membrane

Table 11 continued: The classification of damage on the Parliament Station situated in the centre of Oslo city in Norway

Condition	Cause	Classification	Short form reason for classification	Options Rehabilitation technique
Cavities, high porosity, honeycombing, cracks, and delaminations. Channels below and along the reinforcement steel.	Errors during execution	**B2**	Detrimental singularities discovered after commissioning	Injection works Mechanical repair Removed concrete replaced by wet sprayed concrete
Spalled concrete, some pieces weighing up to 300 kg	Carbonation of concrete Sulphuric acid attack on reinforcement	**B2 & B3**	Detrimental singularities discovered after commissioning Detrimental reaction	Mechanical repair Removed concrete replaced by wet sprayed concrete Sealing the concrete surface with a watertight and diffusion proof membrane, allowing passive realkalisation and saturation of the concrete to occur.
Disintegrated sulphate resistant concrete	Execution errors Sulphuric acid attack	**B2 & B3**	Detrimental singularities discovered after commissioning Detrimental reactions	Injection works Application of watertight membrane
Disintegration of ordinary (not sulphate resistant) concrete	Execution errors Sulphuric acid and sulphate attack	**B2 & B3**	Detrimental singularities discovered after commissioning Detrimental reactions	Injection works Application of watertight membrane Mechanical repair

<u>RAMS definitions</u>

Reliability: The ability to reduce maintenance to a minimum during service life.

Availability: The ease of supply of the methods, systems, materials, or qualified personnel.

Maintainability: The ease with which the combination of all technical and associated administrative actions during the service life can retain a repair and /or upgrade in a state in which it can perform its required functions.

Safety: The health and accident risks that can be directly connected to methods, systems, products, and their end results.

The classification of materials and products is integrated into the Reliability, Availability, Maintainability, and Safety considerations made in this qualitative phase.

Table 12: The qualitative classification of RAMS on the Parliament Station situated in Oslo city centre in Norway.

Index No.	Methods, systems, and materials	Reliability	Availability	Maintainability	Safety
1	Mechanical repair method	Very good	Very good	Extremely poor to good	Good
2	Concrete spraying, wet method	Very good	Very Good	Extremely poor to good	Good
3	Cement grout injection	Very good	Very good	Extremely poor to difficult	Very good
4	Silicate grout injection	Very good	Very good	Difficult	Good
5	Sealing by application of watertightening diffusion proof polyurethane coating	Excellent	Limited	Extremely poor to good	Good

<u>Reasoning</u>

The classification of materials and products are integrated into the Reliability, Availability, Maintainability, and Safety considerations made in this qualitative phase.

Index number 1: Mechanical repair

Reliability: Very good

In this case, mechanical repair should be seen as a part of the rehabilitation technique, and not as a remedial measure in itself. As the concrete became saturated and was passively realkalised, the steel reinforcement was uniformly passivated. The risk of creating incipient anodes is therefore slight.

Availability: Excellent

Numerous contractors can offer mechanical repair works performed in the Oslo region

Maintainability: Extremely poor to good

Repair is easy to perform in itself, but may involve puncturing the watertightening membrane, which would need patching. In addition, repair is likely to involve removal of technical or architectural fixtures, and may reduce the stations serviceability towards the public.

Safety: Good

Mechanical repair works is labour intensive, and employs chiselling stresses harmful to human health. Water jetting tools relieves the worker of harmful chiselling tools, but increases risks of serious injury. The noise emissions from mechanical repair works are high.

Index number 2: Wet sprayed concrete

Reliability: Very good

Few problems are associated with wet sprayed concrete, which is deemed a well functioning replacement for the original concrete.

Availability: Excellent

Numerous contractors can offer mechanical wet sprayed concrete in the Oslo region

Maintainability: Extremely poor to good

Repair is easy to perform in itself, but is likely to involve removal of technical or architectural fixtures, and may reduce the stations serviceability towards the public.

Safety: Good

The wet spraying process involves relatively laborious operations, which can be considered as detrimental to human health. Noise and dust emissions are acceptably low. The end result is normally very safe.

Index number 3: Cement grout injection

Reliability: Very good

Successful injections are normally stable and trouble free.

Availability: Very good

Numerous contractors can offer cement grout injection works in the Oslo region

Maintainability: Difficult

The injection process is inherently difficult, and repairs even more so.

Safety: Very good

Cement grout injection involves heavy labour, much the same type of operation as wet spraying but little exposure to harmful chemicals. Noise emissions can be relatively high. The end result is normally very safe.

Index number 4: Silicate grout injection

Reliability: Good

Successful injections are normally stable and trouble free.

Availability: Good

Several contractors can offer silicate grout injection works in the Oslo region

Maintainability: Extremely poor to difficult

The injection process is inherently difficult, and repairs even more so.

Safety: Good

Silicate grout injection does not involve heavy labour, and limited exposure to harmful chemicals. Noise emissions can be relatively high. The end result is normally very safe.

Index number 5: Polyurethane watertightening diffusion proof coating

Reliability: Excellent

To this day, near 16 years after the rehabilitation works were finished, no new water leakages, reinforcement corrosion, ground heave, or surface subsidence have been reported.

Availability: Limited

Only one or two suppliers, contractors, and consultants can offer appropriate products and their application and services in the Oslo region

Maintainability: Extremely poor to easy

Repair is easy to perform in itself, but is likely to involve removal of technical or architectural fixtures, and may reduce the stations serviceability towards the public.

Safety: Good

Surface preparation involves use of abrasive equipment driven by compressed air, which causes high dust and noise emissions. The coating works itself does not involve heavy labour, nor dust and noise emissions. Polyurethane work is regarded by some to be harmful. However, no known cases of health problems have ever been reported in connection with the MDI type of polyurethane used in Norway, France, Denmark, and Switzerland for coating works. The end result is considered very safe.

5 Transforming the qualitative RAMS descriptions into quantitative characteristics

Before the qualitative RAMS description can be transformed into quantitative figures, a revised set of the RAMS characteristics is needed. The characteristics are given in the following, and they are used to transform the qualitative data listed in table 9. These qualitative data are used to illustrate how all RAMS descriptions, including the remaining three cases, may be transmuted into quantitative values.

Table 9 repeated: The qualitative classification of RAMS on the Congress Centre Folkets Hus A/L situated in the city centre of Oslo in Norway.

Index No.	**Methods, systems, and materials**	**Reliability**	**Availability**	**Maintainability**	**Safety**
1	Realkalisation	Excellent	Good	Good to very good	Very good
2	Mechanical repair	Medium to poor	Very Good	Good	Medium
3	Cathodic protection, category 1: Embedded rod anodes	Very good	Good	Poor to good	Very good
4	Cathodic protection, category 2: Embedded mesh	Medium	Very good	Easy to poor	Good
5	Cathodic protection, category 3: Embedded ribbon	Very good to medium	Very good	Easy to poor	Good
6	Cathodic protection, category 4: Conductive coating	Poor	Medium to poor	Poor	Very good
7	Paints and coatings, category 1: Solvent and resin free organic paints and coatings, CO_2 barriers	Poor	Excellent	Poor	Good to very good
8	Protective paints and coatings, category 2: Solvent and resin free organic paints and coatings	Medium	Good	Medium to poor	Medium
9	Protective paints and coatings, category 2: Cementitious paints and coatings containing polymer ad-mixtures and enhancers	Poor	Good	Medium to poor	Good
10	Aesthetic coatings Cementitious paints and coatings	Good	Good	Good	Good

5.1 The *Reliability* characteristic for quantitative classification

The characteristic is defined as the elapsed time in years before a maintenance action is needed.

1 year = 1 point

.

.25 years = 25 points

.

.and so on

Thereupon the ***Reliability*** column in table 9 becomes:

Index No.	Methods, systems, and materials	Reliability	Availability	Maintainability	Safety
1	Realkalisation	**25**	Good	Good to very good	Very good
2	Mechanical repair	**5**	Very Good	Good	Medium
3	Cathodic protection, category 1: Embedded rod anodes	**20**	Good	Poor to good	Very good
4	Cathodic protection, category 2: Embedded mesh	**10**	Very good	Easy to poor	Good
5	Cathodic protection, category 3: Embedded ribbon	**10**	Very good	Easy to poor	Good
6	Cathodic protection, category 4: Conductive coating	**6**	Medium to poor	Poor	Very good
7	Paints and coatings, category 1: Solvent and resin free organic paints and coatings, CO_2 barriers	**5**	Excellent	Poor	Good to very good
8	Protective paints and coatings, category 2: Solvent and resin free organic paints and coatings	**5**	Good	Medium to poor	Medium
9	Protective paints and coatings, category 2: Cementitious paints and coatings containing polymer ad-mixtures and enhancers	**7**	Good	Medium to poor	Good
10	Aesthetic coatings Cementitious paints and coatings	**20**	Good	Good	Good

5.2 The *Availability* characteristic for quantitative classification

The criterion is defined as the normal lead time in weeks, from firm order until delivery, of goods, services, or materials.

1 week = 1 point

.

.25 weeks = 25 points

.

.and so on

Thereupon the ***Availability*** column in table 9 becomes:

Index No.	**Methods, systems, and materials**	Reliability	**Availability**	Maintainability	Safety
1	Realkalisation	25	**4**	Good to very good	Very good
2	Mechanical repair	5	**2**	Good	Medium
3	Cathodic protection, category 1: Embedded ceramic rod anodes	20	**12**	Poor to good	Very good
4	Cathodic protection, category 2: Embedded mesh	10	**8**	Easy to poor	Good
5	Cathodic protection, category 3: Embedded ribbon	10	**8**	Easy to poor	Good
6	Cathodic protection, category 4: Conductive coating	6	**4**	Poor	Very good
7	Paints and coatings, category 1: Solvent and resin free organic paints and coatings, CO_2 barriers	5	**0.5**	Poor	Good to very good
8	Protective paints and coatings, category 2: Solvent and resin free organic paints and coatings	5	**0.5**	Medium to poor	Medium
9	Protective paints and coatings, category 2: Cementitious paints and coatings containing polymer ad-mixtures and enhancers	7	**0.5**	Medium to poor	Good
10	Aesthetic coatings Cementitious paints and coatings	20	**1**	Good	Good

5.3 The *Maintainability* characteristic for quantitative classification

Scale from 0 to 4 where

0 represents Excellent
1 represents very good
2 represents good
3 represents fair
4 represents poor

The characteristic 0 applies if there is

- No special procedures
- No need for highly specialised equipment
- No need for highly trained personnel
- No need for specialised materials

1 point is added for each of the following:

- Special procedures is needed
- Highly specialised equipment is needed
- Highly trained personnel is needed
- Highly specialised materials

Thereupon the ***Maintainability*** column in table 9 becomes:

Index No.	**Methods, systems, and materials**	Reliability	Availability	**Maintainability**	Safety
1	Realkalisation	25	4	**1** (Scaffolding)	Very good
2	Mechanical repair	5	2	**1** (Scaffolding)	Medium
3	Cathodic protection, category 1: Embedded ceramic rod anodes	20	12	**3** (Highly trained personnel) (Scaffolding) (Highly specialised equipment)	Very good
4	Cathodic protection, category 2: Embedded mesh	10	8	**3** (Highly trained personnel) (Scaffolding) (Highly specialised equipment)	Good
5	Cathodic protection, category 3: Embedded ribbon	10	8	**3** (Highly trained personnel) (Scaffolding) (Highly specialised equipment)	Good
6	Cathodic protection, category 4: Conductive coating	6	4	**3** (Highly trained personnel) (Scaffolding) (Highly specialised equipment)	Very good
7	Paints and coatings, category 1: Solvent and resin free organic paints and coatings, CO_2 barriers	5	0.5	**1** (Scaffolding)	Good to very good
8	Protective paints and coatings, category 2: Solvent and resin free organic paints and coatings	5	0.5	**1** (Scaffolding)	Medium
9	Protective paints and coatings, category 2: Cementitious paints and coatings containing polymer ad-mixtures and enhancers	7	0.5	**1** (Scaffolding)	Good
10	Aesthetic coatings Cementitious paints and coatings	20	1	**1** (Scaffolding)	Good

5.4 The *Safety* characteristic for quantitative classification

The characteristic is defined on a scale of 0 to 4

0 represents Excellent
1 represents very good
2 represents good
3 represents fair
4 represents poor

The characteristic 0 applies if there is

- No special procedures
- No need for highly specialised equipment
- No need for highly trained personnel
- No need for specialised materials

1 point is added for each of the following:

- Special procedures is needed
- Highly specialised equipment is needed
- Highly trained personnel is needed
- Highly specialised materials are needed

Thereupon the ***Safety*** column in table 9 becomes:

Index No.	**Methods, systems, and materials**	Reliability	Availability	Maintainability	**Safety**
1	Realkalisation	25	4	1	**1** (Protective clothing)
2	Mechanical repair	5	2	1	**2** (Protective clothing) (Special procedures)
3	Cathodic protection, category 1: Embedded ceramic rod anodes	20	12	3	**1** (Protective clothing)
4	Cathodic protection, category 2: Embedded mesh	10	8	3	**1** (Protective clothing)
5	Cathodic protection, category 3: Embedded ribbon	10	8	3	**1** (Protective clothing)
6	Cathodic protection, category 4: Conductive coating	6	4	3	**1** (Protective clothing)
7	Paints and coatings, category 1: Solvent and resin free organic paints and coatings, CO_2 barriers	5	0.5	1	**1** (Protective clothing)
8	Protective paints and coatings, category 2: Solvent and resin free organic paints and coatings	5	0.5	1	**1** (Protective clothing)

9	Protective paints and coatings, category 2: Cementitious paints and coatings containing polymer ad-mixtures and enhancers	7	0.5	1	**1** (Protective clothing)
10	Aesthetic coatings Cementitious paints and coatings	20	1	1	**1** (Protective clothing)

The RAMS characteristics are now represented by quantitative data which can be manipulated by the Quantitative Function Deployment, QFD method.

6 Reliability, Availability, Maintainability and Safety (RAMS) Assessment with the Quality Function Deployment (QFD) Method

6.1 Background

The QFD method has been applied to quantitative and classified RAMS information based on the content of the Lifecon deliverable D2.3 "Methods for optimisation and decision making in lifetime management of structures, Part II: Quality function deployment (QFD)" [1], and the chapters 3-5 of this deliverable D5.1.

6.2 Use in Lifecon LMS

The combination method of RAMS and QFD consists basically of 3 phases shown in Figure 6. QFD has been applied to maintenance and repair planning where QFD is serving as a quantitative method and RAMS as a qualitative method. Part 1 deals with the analysis of the object to be repaired, while the Part 2 deals with the selection between repair alternatives. Part 3 deals with sensitivity analysis.

The purpose has been to offer an adjutant decision making tool, which takes into account LIFECON basic requirements for human conditions, economy, culture and ecology, when considering best choices between different repair methods, systems and materials.

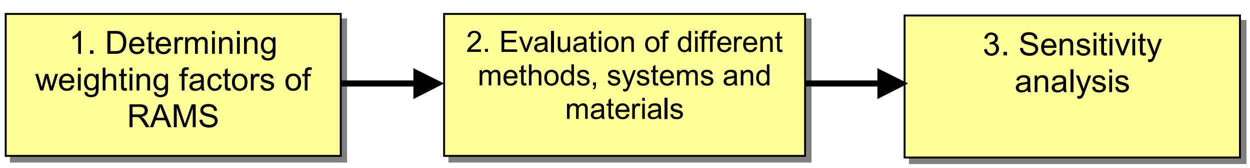

Figure 6. 3 phases of the combination method.

6.3 Principles of combination of Quality Function Deployment (QFD) and Reliability, Availability, Maintainability and Safety -analysis system (RAMS)

The objective of integrated lifetime repair planning methodology is to optimise and guarantee the life cycle pertaining to human conditions, economy, cultural compatibility and ecology and moderate it with technical performance parameters. It is thus possible to control and optimise human conditions, the monetary economy and the ecology while taking social aspects into account.

Here, QFD has been applied to maintenance and repair planning where QFD is serving as a quantitative method and RAMS as a qualitative method.

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

Fundamental objectives in the combination of QFD and RAMS are:

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

The QFD method entails building a matrix first between generic Lifecon requirements and RAMS properties (Part 1) and secondly between different repair alternatives and RAMS (Part 2). Weighting factors of generic Lifecon requirements and RAMS as well as correlations between generic Lifecon requirements, RAMS, and classification between alternative repair methods and RAMS are identified and determined numerically.

Part 1 deals with the analysis of the object to be repaired, while the Part 2 deals with the selection between repair alternatives. The QFD method has been applied to both steps.

QFD provides an empty matrix (House of Quality) to be filled, firstly in Part 1 (Table 13) with generic Lifecon requirements vertical along the left hand side. Performance properties (RAMS) horizontal along the top. The connecting texts are to be filled with numbers describing the relationship between each repair alternative and the corresponding RAMS. The importance measures of RAMS properties (weight factors) appear at the bottom of the matrix, as estimated correlations and weighting factors of requirements.

Proceeding in the filling of the table in Part 1 is free. It is important to fill every box in the matrix. Weights of generic Lifecon requirements can be filled either before defining correlation values or after.

Table 14 in part 2 provides an empty matrix to be filled with alternative repair methods or products in the rows along the left hand side column. Performance properties (RAMS) are listed in the boxes along the top portion. The connecting boxes are to be filled with numbers describing the relationship (classifications) between each repair alternative and the RAMS property. The importance measures (weight factors of RAMS determined in Part 1) are at the bottom, and the boxes in the right hand side contains the evaluation of competing alternatives.

Proceeding in the Part 2 after listing repair alternatives is also free. Amount of listed repair alternatives can change case by case. Like in Part 1 it is important to give value in every box.

Part 3 deals sensitivity analysis. Sensitivity analysis tests the robustness of an optimal solution and increases understanding and qualification of the system. It gives information about relationship between input and output variables. Sensitivity analysis measures the impact on project outcomes of changing one or more key input values about which there is uncertainty. For example, a pessimistic and optimistic value might be chosen for an uncertain variable. Then an analysis could be performed to see how the outcome changes as each of the chosen values is considered in turn, with other things held the same.

Sensitivity analysis can be done by using actual cases as is the case here. Sensitivity analysis method used in this connection can be classified as Scenario Analysis. This method one assumes scenarios (e.g. certain combinations of possible values of uncertain parameter) and solves the problem for each. By solving the problem repeatedly for different scenarios and studying the solutions obtained, the manager observes sensitivities and heuristically decides on an approximate, which is subjective.

In this connection uncertain parameters are weighting factors of RAMS and RAMS classifications. Solutions (ranking order of repair alternatives) using different scenarios (combinations of 2 different weighting factors of RAMS properties and 2 different RAMS classification values) have been presented. Additionally standard deviations of different scenarios have been presented.

Table 13: Part 1 in the combination of QFD and RAMS.

Notation: RAMS = Reliability, Availability, Maintainability, Safety, QFD = Quality Function Deployment

Combination of QFD and RAMS
Part 1
Determinig of weighting factors of RAMS on the basis of generic Lifecon requirements

	Generic LIFECON Requirements	**RAMS** **Reliability**: the elapsed time in years before a maintenance action is needed	**Availability**: as the normal lead time in weeks, from firm order until delivery, of goods, services or materials	**Maintainability**	**Safety**	Weights of Requirements (p)
		Correlation (Ci)				
HUMAN CONDITIONS	**Functionality and usability** (functionality of spaces, accessibility, flexibility in use, maintainability, refurbishment...)					
	Health (internal air quality, hygro-thermal and acoustical performance, quality of drinking water...)					
	Safety (functionality of spaces, accessibility, safety and reliability in use...)					
	Comfort (functionality of spaces, internal air quality, accessibility, maintainability, hygro-thermal and acoustical performance, operability...)					
ECONOMY	**Investment economy** (an investor's view of the lifetime economy of her/his investment, including income/cost/investment ratios, which mean the general profitability of the investment)					
	Building costs (construction costs)					
	Life cycle costs (operation costs, maintenance costs, repair costs, restoration costs, rehabilitation costs, renewal costs, service life, changes of structures and building services...)					
CULTURE	**Building traditions** (non energetic and energetic resources economy, recycling of wastes of materials, components and modules, reuse of components and modules...)					
	Life style (functioning of spaces, flexibility in use, non energetic and energetic resources economy...)					
	Business culture					
	Aesthetics (accessibility, service life, hygro-thermal performance...)					
	Architectural styles and trends (functionality of spaces, accessibility, reuse of components and modules...)					
	Image (recycling of wastes of materials, components and modules, reuse of components and modules...)					
ECOLOGY	**Raw materials resources economy** (service life, changes of structures and building services, recycling of wastes of materials, ability for selective mantling, reuse of components and modules...)					
	Energy resources economy (service life, hygro-thermal performance, energetic resources economy, recycling of wastes of materials, reuse of components and modules...)					
	Environmental burdens economy (service life, energetic resources economy, production of pollutants into air, water and soil, recycling of wastes of materials, reuse of components and modules, hazardous wastes...)					
	Loss of biodiversity (service life, non energetic and energetic resources economy, production of pollutants into air, soil and water, hazardous wastes...)					
	Waste economy (recycling of wastes of materials, reuse of components and modules, recycling of dismantling materials...)					
		=SUMMA(E12*$	=SUMMA(F12*$I$12	=SUI	=SUI	=SUMM
	Weight Wi	**=E30/$I$30**	**=F30/$I$30**	**=G3(**	**=H30**	=SUMM
	***Priority class Npi**: 0= Not important, 1= Important, 2= High, 3= Very high*					

Estimate correlations between RAMS and generic LIFECON requirements
(scale: 0= no correlation,
1= possible correlation,
3= moderate correlation or
9= strong correlation)

Definition of weights of generic Lifecon requirements:
1= no requirements
2= only general recommendations of owner, user and society have to be met
3= minimum requirements of owner, user and society
4=clearly defined more than minimum requirements of owner, user and society
5=high requirements of owner, user and society

Formulaes in boxes refer to the formulaes used in xls-sheets.

Explanations can be found in the conncetion of Table 3.

Table 14. Part 2 in the combination of QFD and RAMS

Combination of QFD and RAMS
Part 2: Evaluation of different methods, systems and materials

CASE:

No.	METHODS, SYSTEMS AND MATERIALS / RAMS	Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N
		Pi					
1						=D12*D	
2						=D13*D	
3						=D14*D	
4						=D15*D	
etc...						=D16*D	
	Weighting factor W_i = 0...1	=PART1!E	=PART1!F	=PART1!G	=PART1!H	=SUMMA(	

Reliability: P_i = 1...5
1= 1...5 years 2= 6...10 years
3= 11...15 years 4= 16... 20 years
5= 21...25 years

Availability: Pi = 1...5
1= 21...25 weeks 2= 16...20 weeks
3= 11...15 weeks 4= 6...10 weeks
5= 1...5 weeks

Weighting factors calculated in Part 1 are transferred here.

The formulaes in the boxes refer to the formulaes used in xls-sheets.

The formulaes in the boxes refer to the formulaes used in xls-sheets.

$P = \sum (W_i \times P_i)$

Maintainability and Safety: Pi = 1...5
1= Poor (all of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
2= Fair (three of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
3= Good (two of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
4= Very good (one of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
5= Excellent (no special procedures, no need for highly specialiced equipment or highly trained personnel or specialised materials)

6.4 Part 1: Determining weighting factors of RAMS on the basis of generic Lifecon requirements

The weighting factors of the generic requirements have to be defined separately case by case. While it is not usually possible to use estimations with exact calculations, values have to be given on the basis of expertise knowledge, client questionnaires, long-term experience and expectations on the future trends. In the examples presented here, relative scale from 1 to 5 has been used. It is also possible to use other scales. In the examples presented here basic requirements of lifetime quality has been used. These can be specified closer for example using guidelines given in D2.3 [1].

In the first example (Table 15), general mean values of correlations and weights of requirements estimated by some Lifecon project participants have been used. Weighting factors presented here are meant only as a general guide.

In the example, Lifecon requirements of human conditions and economy have stronger correlation with properties of RAMS than the requirements of culture and ecology. When looking at each requirement individually, safety and life cycle costs have the highest correlations with RAMS properties, and the requirements of image, business culture and life style the lowest. RAMS property of Reliability has a higher correlation for generic Lifecon requirements, and Safety lower.

Requirements of human conditions have higher weights and requirements of culture lower. When analysing individual weights, health and safety have the highest weights and life style and image the lowest.

As a result of this, the final order of weighting factors of RAMS from highest to lowest is Reliability>Maintainability>Safety>Availability. The weighting factor of Reliability is clearly high compared to other properties, while the weights of other properties are quite near each other. This means that priority class of Reliability is classified as 3 (very high) and other RAMS properties are classified as priority class 2 (high).

Table 15: The determination of weighting factors of RAMS on the basis of Lifecon´s basic generic guideline requirements.

Example 1: Determining of weighting factors of RAMS on the basis of Lifecon basic requirements: generic guidelines

No.		Generic LIFECON Requirements / RAMS	Reliability	Availability	Maintainability	Safety	Weights of Requirements(p) 2)
			Correlation Ci 1)				
1	HUMAN CONDITIONS	Functionality and usability	6	1	6	4	4
2		Health	5	3	3	7	5
3		Safety	7	3	4	8	5
4		Comfort	3	1	3	3	3
5	ECONOMY	Investment economy	5	4	4	2	4
6		Building costs	3	3	1	1	4
7		Life cycle costs	7	3	5	4	4
8	CULTURE	Building traditions	3	3	2	1	3
9		Life style	1	0	1	3	1
10		Business culture	1	1	1	2	2
11		Aesthetics	3	2	2	1	3
12		Architectural styles and trends	3	3	3	1	2
13		Image	1	0	1	1	1
14	ECOLOGY	Raw materials resources economy	5	6	2	1	3
15		Energy resources economy	4	4	4	1	3
16		Environmental burdens economy	4	3	3	1	3
17		Loss of biodiversity	4	1	1	1	3
18		Waste economy	3	2	2	1	3
		$\Sigma (c_i \times p)$	*233,1*	*141,0*	*168,6*	*150,8*	*693,5* ← $\Sigma[\Sigma(cxp)]$
		Weights and priorities of RAMS $w_i = \Sigma(cxp) / \Sigma[\Sigma(cxp)]$					
		Weight W_i	**0,34**	**0,20**	**0,24**	**0,22**	*1,00* ← $\Sigma w_i = 1$
		Priority class N_{pi} 3)	3	2	2	2	0

1) Correlations between RAMS and generic LIFECON requirements
0= no correlation,
1= possible correlation,
3= moderate correlation or
9= strong correlation

2) Weights of requirements
1= less important to 5= very important

3)
0= Not important
1= Important
2= High
3= Very high

Phase 2/ Part 1. Definition of weights of generic Lifecon requirements
1= no requirements
2= only general recommendations of owner, user and society have to be met
3= minimum requirements of owner, user and society
4=clearly defined more than minimum requirements of owner, user and society
5=high requirements of owner, user and society

When defining correlations and weighting factors of Lifecon requirements and RAMS, definitions of the properties should be clear. Some definitions, which have required closer definition, are presented below. Closer definitions of some other requirements can be found in other Lifecon Deliverables (e.g. D2.1 and D2.3) [1,2].

Definitions of RAMS properties	
Reliability	The elapsed time in years before a maintenance action is needed
Availability	As the normal lead time in weeks, from firm order until delivery, of goods, services or materials
Maintainability and Safety	Need of special procedures, highly specialised equipment, highly trained personnel or highly specialised materials

Definitions of some Lifecon requirements	
Health	All kinds of effects on health during the manufacturing of materials, operation and use of an object, repair, demolition, reuse and recycling. Typical health aspects are for example the poisonous or otherwise unhealthy emissions from materials, or allergic reactions from materials.
Safety	Safety of structures in use, and the working safety, during the manufacturing, operation and use of an object, repair, demolition, reuse and recycling.
Investment economy	An investor's view of into the lifetime economy of his/her investment, including income/cost/investment ratios, which mean the general profitability of the investment.

In the following 4 examples (Tables 16 to 19), weighting factors have been estimated individually case by case:

In these cases, differences between weights of RAMS are minor; only the weighting factor of reliability gets a slightly different value in case 3 (Table 18). Correlations in different cases are the same (estimated by same person), only some changes to weights of requirements (aesthetics, architectural styles and trends and loss of biodiversity) have been made. Compared to weights in example 1 (Table 15. Generic guidelines), the order of weights are the same, but the weight of availability has been estimated as 0 (not important) in cases 1-4, while in the generic guidelines it is in category 2 (high).

Table 16: The determination of weighting factors on Folkets Hus, Oslo, Norway

Determinig of weighting factors of RAMS on the basis of Lifecon basic requirements.
CASE 1: Folkets Hus, Oslo, Norway

No.		Generic LIFECON Requirements / RAMS	Reliability	Availability	Maintainability	Safety	Weights of Requirements
			Correlation Ci				
1	HUMAN CONDITIONS	Functionality and usability	9	0	9	9	5
2		Health	9	0	9	9	5
3		Safety	9	0	9	9	5
4		Comfort	3	0	3	3	4
5	ECONOMY	Investment economy	3	1	3	3	4
6		Building costs	3	3	3	3	4
7		Life cycle costs	9	0	3	1	5
8	CULTURE	Building traditions	1	0	1	3	4
9		Life style	1	0	0	0	3
10		Business culture	0	0	1	1	2
11		Aesthetics	3	0	3	0	5
12		Architectural styles and trends	3	0	1	1	4
13		Image	1	0	0	0	1
14	ECOLOGY	Raw materials resources economy	3	3	3	0	3
15		Energy resources economy	1	1	3	0	2
16		Environmental burdens economy	3	0	3	0	4
17		Loss of biodiversity	1	0	1	0	4
18		Waste economy	3	0	3	1	4
			290,00	*27,00*	*254,00*	*198,00*	*769,00*
		Weight Wi	**0,38**	**0,04**	**0,33**	**0,26**	*1,00*
		Priority class Npi (1)	3	0	3	2	0

Table 17: The determination of weighting factors on Bäck Bron in Gävle, Sweden

Determinig of weighting factors of RAMS on the basis of Lifecon basic requirements.
CASE 2: Baeckbron Gaevle, Sweden

No.		**Generic LIFECON Requirements** / **RAMS**	**Reliability**	**Availability**	**Maintainability**	**Safety**	Weights of Requirements
			Correlation Ci				
1	HUMAN CONDITIONS	Functionality and usability	9	0	9	9	5
2		Health	9	0	9	9	5
3		Safety	9	0	9	9	5
4		Comfort	3	0	3	3	4
5	ECONOMY	Investment economy	3	1	3	3	4
6		Building costs	3	3	3	3	4
7		Life cycle costs	9	0	3	1	5
8	CULTURE	Building traditions	1	0	1	3	4
9		Life style	1	0	0	0	3
10		Business culture	0	0	1	1	2
11		Aesthetics	3	0	3	0	4
12		Architectural styles and trends	3	0	1	1	4
13		Image	1	0	0	0	1
14	ECOLOGY	Raw materials resources economy	3	3	3	0	3
15		Energy resources economy	1	1	3	0	2
16		Environmental burdens economy	3	0	3	0	4
17		Loss of biodiversity	1	0	1	0	4
18		Waste economy	3	0	3	1	4
			267,00	*27,00*	*251,00*	*198,00*	*763,00*
		Weight Wi	**0,38**	**0,04**	**0,33**	**0,26**	*1,00*
		Priority class Npi (1)	3	0	3	2	0

Table 18: The determination of weighting factors on Ormsund Wharf, east coast of Norway

Determinig of weighting factors of RAMS on the basis of Lifecon basic requirements.
CASE 3: The wharf of Ormsund, Norway

No.		RAMS / Generic LIFECON Requirements	Reliability	Availability	Maintainability	Safety	Weights of Requirements
			Correlation Ci				
1	HUMAN CONDITIONS	Functionality and usability	9	0	9	9	5
2		Health	9	0	9	9	5
3		Safety	9	0	9	9	5
4		Comfort	3	0	3	3	4
5	ECONOMY	Investment economy	3	1	3	3	4
6		Building costs	3	3	3	3	4
7		Life cycle costs	9	0	3	1	5
8	CULTURE	Building traditions	1	0	1	3	4
9		Life style	1	0	0	0	3
10		Business culture	0	0	1	1	2
11		Aesthetics	3	0	3	0	4
12		Architectural styles and trends	3	0	1	1	1
13		Image	1	0	0	0	1
14	ECOLOGY	Raw materials resources economy	3	3	3	0	3
15		Energy resources economy	1	1	3	0	2
16		Environmental burdens economy	3	0	3	0	4
17		Loss of biodiversity	1	0	1	0	5
18		Waste economy	3	0	3	1	4
			279,00	27,00	249,00	195,00	750,00
		Weight Wi	**0,37**	**0,04**	**0,33**	**0,26**	*1,00*
		Priority class Npi (1)	3	0	3	2	0

Table 19: The determination of weighting factors on Parliament Station, Oslo, Norway

	Determinig of weighting factors of RAMS on the basis of Lifecon basic requirements. CASE 4:Parliament Station Oslo, Norway	**RAMS**	**Reliability**	**Availability**	**Maintainability**	**Safety**	Weights of Requirements
No.		**Generic LIFECON Requirements**	*Correlation Ci*				
1	HUMAN CONDITIONS	Functionality and usability	9	0	9	9	5
2		Health	9	0	9	9	5
3		Safety	9	0	9	9	5
4		Comfort	3	0	3	3	4
5	ECONOMY	Investment economy	3	1	3	3	4
6		Building costs	3	3	3	3	4
7		Life cycle costs	9	0	3	1	5
8	CULTURE	Building traditions	1	0	1	3	4
9		Life style	1	0	0	0	3
10		Business culture	0	0	1	1	2
11		Aesthetics	3	0	3	0	4
12		Architectural styles and trends	3	0	1	1	3
13		Image	1	0	0	0	1
14	ECOLOGY	Raw materials resources economy	3	3	3	0	3
15		Energy resources economy	1	1	3	0	2
16		Environmental burdens economy	3	0	3	0	4
17		Loss of biodiversity	1	0	1	0	5
18		Waste economy	3	0	3	1	4
			285,00	*27,00*	*251,00*	*197,00*	*760,00*
		Weight Wi	**0,38**	**0,04**	**0,33**	**0,26**	*1,00*
		Priority class Npi (1)	3	0	3	2	0

6.5 Part 2: Evaluation of different methods, systems and materials

In the Part 2, the combination of QFD and RAMS has been presented with four cases using individual weighting factors Wi from Part 1 (Tables 20 to 23).

When there have been several possible RAMS classification values, mean values have been used.

In the case 1 (Table 20), Folkets Hus, Norcure realkalisation (1) has been ranked as the best choice, aesthetic coatings (10) next best and cathodic protection methods (4-6) and mechanical repair (2) as the worst choice.

In the case 2 (Table 21), Baeckbron Gävle, Electrochemical desalination (1) and realkalisation (6) have been ranked as the best choices and cathodic protection (4) has been ranked lowest.

In the case 3 (Table 22), the wharf of Ormsund, electrochemical desalination (1) has been ranked as the best alternative and mechanical repair method (2) the lowest.

In case 4 (Table 23), Parliament Station, Polyurethane (6) has been ranked highest and silicate grout injection (4) the lowest.

Table 20: Ranking orders, case 1, Folket Hus in Oslo, Norway

CASE 1: Folkets Hus, Oslo, Norway

No.	RAMS / METHODS, SYSTEMS AND MATERIALS	Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N
1	Norcure realkalisation	5	5	4	4	4,5	1
2	Mechanical repair	1	5	4	3	2,7	7
3	Cathodic protection, category 1:embedded ceramic rod anodes	4	3	2	4	3,3	6
4	Cathodic protection, category 2: embedded mesh	2	4	2	4	2,6	9
5	Cathodic protection, category 3: embedded ribbon	2	4	2	4	2,6	9
6	Cathodic protection, category 4: conductive coating	2	5	2	4	2,7	8
7	Paints and coatings, category 1: organic paints and coatings, CO_2 barriers	1	5	4	4	2,9	4
8	Protective paints and coatings, category 1: organic paints and coatings	1	5	4	4	2,9	5
9	Protective paints and coatings, cat. 2:cementitious paints and coatings cont. polymer admixtures and enhancers	2	5	4	4	3,3	3
10	Aesthetic coatings: cementitious paints and coatings	4	5	4	4	4,1	2
	Weighting factor W_i = 0…1	0,38	0,04	0,33	0,26		

Estimated Priority Numbers P_i **Reliability**
(the elapsed time in years before a maintenance action is needed)
P_i = 1…5
1= 1…5 years
2= 6…10 years
3= 11…15 years
4= 16… 20 years
5= 21…25 years

Estimated Priority Numbers Pi **Availability**
(as the normal lead time in weeks, from firm order until delivery, of goods, services or materials)
Pi = 1…5
1= 21…25 weeks
2= 16…20 weeks
3= 11…15 weeks
4= 6…10 weeks
5= 1…5 weeks

Estimated Priority Numbers Pi **Maintainability and Safety**
Pi = 1…5
1= Poor (all of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
2= Fair (three of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
3= Good (two of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
4= Very good (one of the following is required: special procedures, highly specialised equipment, highly trained personnel or highly specialised materials)
5= Excellent (no special procedures, no need for highly specialiced equipment or highly trained personnel or specialised materials)

Table 21: Ranking orders, case 2, Bäck Bron in Gävle. Sweden

CASE 2: Baeckbron Gaevle, Sweden	RAMS	Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N
No.	METHODS, SYSTEMS AND MATERIALS						
1	Electrochemical desalination	5	3	2	4	3,7	1
2	Elecktrochemical realkalisation	5	3	2	4	3,7	1
3	Mechanical repair method	3	5	2	3	2,7	5
4	Cathodic protection	2,5	2,5	2,5	2	2,4	7
5	Concrete spraying, wet method	4	5	2	3	3,1	3
6	Concrete spraying, dry method	4	3	3	3	3,4	2
7	Application of bridge membrane	4	4	1	3	2,8	4
8	External reinforcement	2,5	2,5	2,5	2,5	2,5	6
	Weighting factor W_i = 0…1	0,38	0,04	0,33	0,26	1	

Table 22: Ranking orders, case 3, the wharf of Ormsund at the east coast of Norway

CASE 3: The wharf of Ormsund, Norway	RAMS	Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N
No.	METHODS, SYSTEMS AND MATERIALS						
1	Electrochemical desalination	4	4	3	4	3,7	1
2	Mechanical repair method	1	5	3,5	3	2,5	5
3	Cathodic protection: ceramic rod anodes	4	3	1	4	3,0	4
4	Concrete spraying, wet method	4	5	3	3	3,4	2
5	Concrete spraying, dry method	4	4	3	3	3,4	2
6	Application chloride impermeable membrane-polyurethane	5	2	2	3	3,4	2
7	Application of hydrophing agent into the concretee cover - silanes or siloxanes	3	2	2,5	4	3,1	3
	Weighting factor W_i = 0…1	0,37	0,04	0,33	0,26	1	

Table 23: Ranking orders, case 4, Parliament Station, Oslo, Norway

CASE 4:Parliament Station ,Oslo, Norway	RAMS	Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N
No.	METHODS, SYSTEMS AND MATERIALS						
1	Mechanical repair method	4	4	2	3	3,1	3
2	Concrete spraying, wet method	4	4	2	3	3,1	3
3	Cement grout injection	4	4	1	4	3,0	4
4	Silicate grout injection	4	4	1	3	2,8	5
5	Sealing by application of watertightening diffusion proof polyurethane coating	5	1	2	3	3,3	2
6	Polyurethane	4	3	5	3	4,0	1
	Weighting factor W_i = 0…1	0,38	0,04	0,33	0,26	1	

6.6 Part 3: Sensitivity Analysis

6.6.1 Effect of different correlations and weights of requirements for the weighting factors of RAMS

General Guidelines

In this part, the effect of different correlations and weights of requirements for the weighting factors of RAMS has been analysed. The analysis has been done on the basis of correlations and weights of requirements estimated by a group of Lifecon project participants (Table 24).

Section A presents the lowest and Section B the highest estimated values of correlations and weights of requirements.

With maximum correlations and weights of requirements, Lifecon properties of human conditions and economy have the highest correlations with RAMS properties, and requirements of culture the lowest. Also weights of requirements of human conditions and economy are highest, and weights of requirements of culture lowest.

When using maximum values, the order of weighting factors of RAMS is, from highest to lowest, Reliability>Availability>Maintainability>Safety. Reliability, Availability and Maintainability are classified as priority class 3 (very high) and Safety as priority class 2 (high). With minimum correlations and weights of requirements, also requirements of human conditions and economy have the highest weights and strongest correlation with RAMS, and requirements of culture the lowest.

When using minimum values the order of weighting factors of RAMS is, from highest to lowest Reliability>Maintainability>Availability>Safety. Reliability and Maintainability are classified as priority class 3 (very high), Availability as class 1 (important) and Safety as class 0 (not important). Difference between the weights of properties is remarkably higher than with maximum values so that Reliability and Maintainability have clearly higher weight than Availability and Safety.

In the Table 25, standard deviations of correlations, weight of requirements, weighting factors of RAMS and priority classes are presented.

Correlation between health/reliability has the highest standard deviation and correlation between building traditions/safety the lowest.

With weights of requirements, Lifecon requirements of health and safety have the lowest standard deviation and properties of building traditions and loss of biodiversity the highest.

Generally, RAMS properties of Reliability have the highest st.dev and properties of Availability the lowest.

Weighting factors of Reliability and Availability have the lowest st.dev and Safety the highest.
Correspondingly priority class of Reliability has the lowest st.dev. and Safety the highest.

Table 24: Sensitivity analysis, the combination of QFD and RAMS

Combination of QFD and RAMS

Sensitivity Analysis

Part 1

Effect of different correlations and weights of requirements for the weighting factors of RAMS

RAMS	Generic LIFECON Requirements	A Reliability	A Availability	A Maintainability	A Safety	A Weights of Requirements	B Reliability	B Availability	B Maintainability	B Safety	B Weights of Requirements
		Correlation Ci: Min VALUES					Correlation Ci: Max VALUES				
HUMAN CONDITIONS	Functionality and usability	1	0	3	0	2	9	3	9	9	5
	Health	0	0	0	0	4	9	9	9	9	5
	Safety	0	0	0	0	4	9	9	9	9	5
	Comfort	0	0	1	0	1	9	3	9	9	4
ECONOMY	Investment economy	0	0	1	0	2	9	9	9	3	5
	Building costs	0	0	0	0	2	9	9	3	3	5
	Life cycle costs	3	1	3	1	3	9	9	9	9	5
CULTURE	Building traditions	0	0	0	0	1	9	9	3	1	5
	Life style	0	0	0	0	1	1	1	3	9	2
	Business culture	0	0	0	0	1	3	3	3	3	4
	Aesthetics	0	0	0	0	1	9	9	3	1	5
	Architectural styles and trends	0	0	0	0	1	9	9	9	1	4
	Image	0	0	0	0	1	3	1	3	3	2
ECOLOGY	Raw materials resources economy	2	1	0	0	1	9	9	9	3	4
	Energy resources economy	1	1	0	0	2	9	9	9	3	4
	Environmental burdens economy	1	0	1	0	2	9	9	9	3	4
	Loss of biodiversity	1	0	0	0	1	9	3	3	3	5
	Waste economy	2	0	0	0	2	6	6	3	3	4
		22,0	*6,0*	*20,0*	*3,0*	*51,0*	*629,0*	*541,0*	*501,0*	*359,0*	*2030,0*
	Weight Wi	**0,43**	**0,12**	**0,39**	**0,06**	*1,00*	**0,31**	**0,27**	**0,25**	**0,18**	*1,00*
	Priority class Npi (1)	**3**	**1**	**3**	**0**		**3**	**3**	**3**	**2**	

Table 25: The effect on RAMS by using different correlations and weighting factors

Combination of QFD and RAMS
Sensitivity Analysis
Part 1
Effect of different correlations and weights of requirements for the weighting factors of RAMS

No.		RAMS / Generic LIFECON Requirements	Reliability	Availability	Maintainability	Safety	Weights of Requirements
			Correlation Ci: ST. DEV.				
1	HUMAN CONDITIONS	Functionality and usability	3,5	1,2	3,2	3,2	1,1
2		Health	4,2	4,0	3,6	3,3	0,4
3		Safety	3,6	3,9	3,4	3,2	0,4
4		Comfort	2,7	1,5	2,6	2,8	0,9
5	ECONOMY	Investment economy	3,2	3,4	3,0	1,4	1,2
6		Building costs	3,7	3,6	1,3	1,2	1,1
7		Life cycle costs	3,1	2,7	3,1	2,3	0,6
8	CULTURE	Building traditions	3,9	3,9	1,2	0,4	1,6
9		Life style	0,5	0,5	1,0	3,7	0,5
10		Business culture	0,9	1,2	1,2	1,2	1,1
11		Aesthetics	3,8	3,0	1,2	0,5	1,5
12		Architectural styles and trends	3,9	2,8	3,8	0,5	1,2
13		Image	1,2	0,5	1,4	1,2	0,5
14	ECOLOGY	Raw materials resources economy	3,2	3,8	3,0	1,1	1,0
15		Energy resources economy	3,3	2,4	3,4	1,3	0,7
16		Environmental burdens economy	2,5	3,1	2,5	1,4	0,9
17		Loss of biodiversity	3,4	1,2	0,9	1,0	1,6
18		Waste economy	1,2	2,0	1,2	1,2	0,6
			74,1	53,1	70,9	71,4	196,6
		Weight Wi	0,05	0,05	0,08	0,09	71,4
		Priority class Npi (1)	0,00	0,74	0,83	1,13	

(1)
0= Not important
1= Important
2= High
3= Very high

6.6.2 Sensitivity Analysis - Effect of different weighting factors of RAMS and RAMS classifications on ranking numbers of different methods, systems and materials

In case 1, Folkets Hus (Table 26): Since there was no variation between estimated RAMS classification values, only the effect of 2 different weighting factors of RAMS has been analysed.

Section 1 presents the ranking order with general guiding weighting factors and Section 2 with individual weighting factors. Section 3 presents standard deviations of ranking numbers N.

In the case 1, it can be seen that both variations give for the methods 1,10 and 9 ranking numbers 1,2 and 3 in same order and for the methods 4 and 5 last ranking. Also, the standard deviation of methods 1,9 and 10 is 0.

In the cases 2-4 (Tables 27 to 29) RAMS classification had been done using a range of values for some methods. In these cases analysis have been done using limit values of the classifications taking into account different weighting factors and calculating standard deviations for them. Four first tables present Priority numbers P and Ranking numbers N with estimated min and max RAMS classification values and general and individual weighting factors of RAMS. The end column in tables 27 to 29 present standard deviations of Ranking Numbers N calculated from the first four tables.

Comparing results of sections A-B to results of sections C-D (Table 27), it can be seen that the effect of variety of RAMS classification values is higher than the effect of changes in weighting factors. Ranking orders for the highest ranked methods are mainly the same in each case, except for the method no. 8, where the large range of RAMS classification values causes a remarkable change of ranking orders in part tables 15 and 16 comparing to ranking orders in part tables 13 and 14. This also results in a relatively high standard deviation for the method no.8. Methods 1 and 2 are ranked either first or second in every part table, as in the part table where ranking had been done by using mean values of classifications and individual weighting factors. Also, the relatively low standard deviation in the ranking order of these 2 methods supports their choice.

In the case 3 (Table 28), the highest ranked method is same in every table and method no 1 was also ranked highest when using mean values of classifications and individual weighting factors. Method no4 is ranked second highest in the first 3 tables, and also in the referring table. Method no 2 is ranked among the 2 lowest in all 4 tables. The standard deviation of method no. 1 is 0, while method no. 7 has relatively high standard deviation.

In case 4 (Table 29), Parliament Station, method 6 has the highest ranked in all tables, also when using mean values of classifications and individual weighting factors. Also st.dev of method 6 supports the choice. Method 4, which was ranked lowest in referring table, has been ranked lowest also in the three other tables.

Table 26: The effect of changing ranking numbers

Sensitivity Analysis

Part 3: Effect of different weighting factors of RAMS to ranking numbers of different methods, systems and materials

CASE1: Folkets Hus, Oslo, Norway

No.	METHODS, SYSTEMS AND MATERIALS (RAMS)	Section 1: Reliability	Section 1: Avaiability	Section 1: Maintainability	Section 1: Safety	Section 1: Priority number P	Section 1: Ranking Number N	Section 2: Reliability	Section 2: Avaiability	Section 2: Maintainability	Section 2: Safety	Section 2: Priority number P	Section 2: Ranking Number N	Section 3: STANDARD DEVIA
		General weighting factors						Individual weighting factors						
1	Norcure realkalisation	5	5	4	4	4,5	**1**	5	5	4	4	4,5	**1**	**0,0**
2	Mechanical repair	1	5	4	3	3,0	**6**	1	5	4	3	2,7	**5**	**0,7**
3	Cathodic protection, category 1:embedded ceramic rod anodes	4	3	2	4	3,3	**4**	4	3	2	4	3,3	**3**	**0,7**
4	Cathodic protection, category 2: embedded mesh	2	4	2	4	2,8	**7**	2	4	2	4	2,6	**6**	**0,7**
5	Cathodic protection, category 3: embedded ribbon	2	4	2	4	2,8	**7**	2	4	2	4	2,6	**6**	**0,7**
6	Cathodic protection, category 4: conductive coating	2	5	2	4	3,0	**6**	2	5	2	4	2,7	**5**	**0,7**
7	Paints and coatings, category 1: organic paints and coatings, CO_2 barriers	1	5	4	4	3,2	**5**	1	5	4	4	2,9	**4**	**0,7**
8	Protective paints and coatings, category 1: organic paints and coatings	1	5	4	4	3,2	**5**	1	5	4	4	2,9	**4**	**0,7**
9	Protective paints and coatings, cat. 2: cementitious paints and coatings excl. polymer admixtures and enhancers	2	5	4	4	3,5	**3**	2	5	4	4	3,3	**3**	**0,0**
10	Aesthetic coatings: cementitious paints and coatings	4	5	4	4	4,2	**2**	4	5	4	4	4,1	**2**	**0,0**
	Weighting factor W_i = 0…1	0,34	0,20	0,24	0,22	1		0,38	0,04	0,33	0,26	1		

Table 27: Affecting ranking numbers by changing the RAMS classification values and the weighting factors

Sensitivity Analysis

Part 2

Effect of different RAMS classification values and weighting factors of RAMS to ranking numbers of different methods, systems and materials

CASE 2: Baeckbron Gaevle, Sweden

	RAMS	A						B						C						D						
		Reliability	**Avaiability**	**Maintainability**	**Safety**	Priority number P	Ranking Number N	**Reliability**	**Avaiability**	**Maintainability**	**Safety**	Priority number P	Ranking Number N	**Reliability**	**Avaiability**	**Maintainability**	**Safety**	Priority number P	Ranking Number N	**Reliability**	**Avaiability**	**Maintainability**	**Safety**	Priority number P	Ranking Number N	**STANDARD DEVIATION**
No.	**METHODS, SYSTEMS AND MATERIALS**	1						2						3						4						
1	Electrochemical desalination	5	3	1	4	3,4	**1**	5	3	1	4	3,4	**1**	5	3	3	4	3,8	**2**	5	3	3	4	4,1	**1**	**0,5**
2	Elecktrochemical realkalisation	5	3	1	4	3,4	**1**	5	3	1	4	3,4	**1**	5	3	3	4	3,8	**2**	5	3	3	4	4,1	**1**	**0,5**
3	Mechanical repair method	3	5	1	3	2,9	**3**	3	5	1	3	2,5	**3**	3	5	3	3	3,3	**4**	3	5	3	3	3,1	**7**	**1,9**
4	Cathodic protection	1	1	1	1	1,0	**5**	1	1	1	1	1,0	**5**	4	4	4	3	3,7	**3**	4	4	4	3	3,8	**3**	**1,2**
5	Concrete spraying, wet method	4	5	1	3	3,3	**2**	4	5	1	3	2,8	**2**	4	5	3	3	3,7	**3**	4	5	3	3	3,5	**4**	**1,0**
6	Concrete spraying, dry method	4	3	3	3	3,3	**2**	4	3	3	3	3,4	**1**	4	3	3	3	3,3	**4**	4	3	3	3	3,4	**5**	**1,8**
7	Application of bridge membrane	3	4	1	3	2,7	**4**	3	4	1	3	2,4	**4**	5	4	1	3	3,3	**4**	5	4	1	3	3,2	**6**	**1,0**
8	External reinforcement	1	1	1	1	1,0	**5**	1	1	1	1	1,0	**5**	4	4	4	4	3,9	**1**	4	4	4	4	4,0	**2**	**2,1**
	Weighting factor W_i = 0…1	0,34	0,20	0,24	0,22	1		0,38	0,04	0,33	0,26	1		0,34	0,20	0,24	0,20	1		0,38	0,04	0,33	0,26	1		

1	MIN CLASSIFICATION VALUES + GENERAL WEIGHTING FACTORS
2	MIN CLASSIFICATION VALUES + INDIVIDUAL WEIGHTING FACTORS
3	MAX CLASSIFICATION VALUES + GENERAL WEIGHTING FACTORS
4	MAX CLASSIFICATION VALUES + INDIVIDUAL WEIGHTING FACTORS

Table 28: Affecting ranking numbers by changing the RAMS classification values and the weighting factors

Sensitivity Analysis

Part 2

Effect of different RAMS classification values and weighting factors of RAMS to ranking numbers of different methods, systems and materials

CASE 3: The wharf of Ormsund, Norway

A

No.	METHODS, SYSTEMS AND MATERIALS (RAMS)	Reliability (1)	Avaiability (1)	Maintainability (1)	Safety (1)	Priority number P	Ranking Number N
1	Electrochemical desalination	4	4	3	4	3,8	**1**
2	Mechanical repair method	1	5	3	3	2,7	**6**
3	Cathodic protection: ceramic rod anodes	4	3	1	4	3,1	**4**
4	Concrete spraying, wet method	4	5	3	3	3,7	**2**
5	Concrete spraying, dry method	4	4	3	3	3,5	**3**
6	Application chloride impermeable membrane-polyurethane	5	1	1	3	2,8	**5**
7	n of hydrophing agent into the concretee cover - silanes or siloxanes	3	1	1	4	2,3	**7**
	Weighting factor W_i = 0...1	0,34	0,20	0,24	0,22	1	

B

No.	RAMS	Reliability (2)	Avaiability (2)	Maintainability (2)	Safety (2)	Priority number P	Ranking Number N
1	....	4	4	3	4	3,7	**1**
2	....	1	5	3	3	2,3	**6**
3	....	4	3	1	4	3,0	**4**
4	....	4	5	3	3	3,5	**2**
5	....	4	4	3	3	3,4	**3**
6	....	5	1	1	3	3,0	**4**
7	hes	3	1	1	4	2,5	**5**
	....	0,37	0,04	0,33	0,26	1	

C

No.	Reliability (3)	Avaiability (3)	Maintainability (3)	Safety (3)	Priority number P	Ranking Number N
1	4	4	3	4	3,8	**1**
2	1	5	4	3	3,0	**5**
3	4	3	1	4	3,1	**4**
4	4	5	3	3	3,7	**2**
5	4	4	3	3	3,5	**3**
6	5	3	3	3	3,7	**2**
7	3	3	4	4	3,5	**3**
	0,34	0,20	0,24	0,22	1	

D

No.	Reliability (4)	Avaiability (4)	Maintainability (4)	Safety (4)	Priority number P	Ranking Number N	STANDARD DEVIATION
1	4	4	3	4	3,7	**1**	**0,0**
2	1	5	4	3	2,7	**6**	**0,5**
3	4	3	1	4	3,0	**5**	**0,5**
4	4	5	3	3	3,5	**3**	**0,5**
5	4	4	3	3	3,4	**4**	**0,5**
6	5	3	3	3	3,7	**1**	**1,8**
7	3	3	4	4	3,6	**2**	**2,2**
	0,37	0,04	0,33	0,26	1		

1	MIN CLASSIFICATION VALUES + GENERAL WEIGHTING FACTORS
2	MIN CLASSIFICATION VALUES + INDIVIDUAL WEIGHTING FACTORS
3	MAX CLASSIFICATION VALUES + GENERAL WEIGHTING FACTORS
4	MAX CLASSIFICATION VALUES + INDIVIDUAL WEIGHTING FACTORS

Table 29: Affecting ranking numbers by changing the RAMS classification values and the weighting factors

Sensitivity Analysis

Part 2

Effect of different RAMS classification values and weighting factors of RAMS to ranking numbers of different methods, systems and materials

CASE 4:Parliament Station ,Oslo, Norway

A

No.	METHODS, SYSTEMS AND MATERIALS (RAMS)	Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N
		1					
1	Mechanical repair method	4	4	1	3	3,1	3
2	Concrete spraying, wet method	4	4	1	3	3,1	3
3	Cement grout injection	4	4	1	4	3,3	2
4	Silicate grout injection	4	4	1	3	3,1	3
5	Sealing by application of watertightening diffusion proof polyurethane coating	5	1	1	3	2,8	4
6	Polyurethane	4	3	5	3	3,8	1
	Weighting factor W_i = 0...1	0,34	0,20	0,24	0,22	1	

B

No.	RAMS	Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N
	......	2					
1	......	4	4	1	3	2,8	3
2	hod	4	4	1	3	2,8	3
3	......	4	4	1	4	3,1	2
4	......	4	4	1	3	2,8	3
5	......	5	1	1	3	3,1	2
6	......	4	3	5	3	4,1	1
	......	0,38	0,04	0,33	0,26	1	

C

No.	RAMS	Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N
	......	3					
1	......	4	4	3	3	3,5	2
2	thod	4	4	3	3	3,5	2
3	......	4	4	1	4	3,3	3
4	......	4	4	1	3	3,1	4
5	......	5	1	3	3	3,3	3
6	......	4	3	5	3	3,8	1
	......	0,34	0,20	0,24	0,22	1	

D

No.	RAMS	Reliability	Avaiability	Maintainability	Safety	Priority number P	Ranking Number N	STANDARD DEVIATION
	......	4						
1	......	4	4	3	3	3,5	3	0,5
2	ethod	4	4	3	3	3,5	3	0,5
3	......	4	4	1	4	3,1	4	1,0
4	......	4	4	1	3	2,8	5	1,0
5	......	5	1	3	3	3,7	2	1,0
6	......	4	3	5	3	4,1	1	0,0
	......	0,38	0,04	0,33	0,26	1		

1	MIN CLASSIFICATION VALUES + GENERAL WEIGHTING FACTORS
2	MIN CLASSIFICATION VALUES + INDIVIDUAL WEIGHTING FACTORS
3	MAX CLASSIFICATION VALUES + GENERAL WEIGHTING FACTORS
4	MAX CLASSIFICATION VALUES + INDIVIDUAL WEIGHTING FACTORS

7 Conclusions

A conclusion can be made, that RAMS classification has the determining effect on priorities and rankings compared to the effect of weighting factors. This can be seen by sensitivity analysis of all 4 cases. Thus it is important to pay proper attention to correct RAMS classification, and also to take into account the uncertainty (standard deviation) of different methods, systems and materials, as well as the level of differences between priority numbers when making final decisions.

On the other hand, examples show that QFD method can be applied to maintenance and repair planning, and that the combination method of QFD and RAMS can be used as an adjutant decision making tool, which takes into account basic Lifecon requirements when considering best alternatives between different repair methods and systems.

8 References

[1] D2.3 Methods for optimisation and decision making in lifetime management of structures. Part II: Quality function deployment (QFD)

[2] D2.1 Reliability based methodology for lifetime management of structures