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D7.5 Report on environmental and economic viability of the novel products based on the findings of the LCA and LCCA

WP 7, T 7.1

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Executive Summary

This document is the final outcome of EnDurCrete project WP7 (Life cycle assessment and economic evaluation, standardization and health and safety aspects), Task 7.1 (Environmental and economic viability of the novel products based on LCA and LCCA).

It follows the preceding D7.2 (Life Cycle at Material Level) and D7.3 (Recyclability Analysis). It is also based on the outcomes of the other work packages, mainly D3.9 (Optimized mix designs using novel binders and additives) and D4.4 (Report on modelling of service life).

Four different applications of the new EnDurCrete products were analysed in this study: tunnel, bridge, offshore and marine constructions. For each of these case studies the functional unit was defined based on the design of the real-life construction. The concrete mixes as defined in D3.9 were used for comparison.

A detailed inventory of all the inputs and outputs of the production processes of the EnDurCrete and reference products was done in close collaboration with the responsible project partners (HeidelbergCement, Acciona, Aker Solutions, Nuova Tesi, and ZAG).

The inventory was followed by Life Cycle Impact Assessment Analysis using SimaPro 9. The outcomes of Concrete EPD tool as presented in D7.2 were used as inputs for concrete mixes. The results of the analysis of EnDurCrete products and the reference ones were compared. The analysis was always divided into two parts – the first one covering the production phase (cradle-to-gate) and the second one including the use phase (based on the expected service life for the particular application as reported in D4.4).

The LCA at product level **confirmed the expected environmental advantages of the EnDurCrete products in comparison to the reference ones** based on standard commercially available products. The key parameter analysed in EnDurCrete project is Global Warming Potential (GWP) expressed as equivalent of CO_2 emissions.

The EnDurCrete products show significant reduction of Global Warming Potential in all the use cases; the best result (18 % reduction during the production phase and 56 % reduction during the complete life cycle) was achieved for tunnel application.

The only exception is the production phase of the marine precast concrete elements – in this case the values of GWP of EnDurCrete products are slightly higher than reference but it should be emphasized that CEM III/A (cement with very high content of secondary materials leading to relatively small environmental impacts of cement production) was used in the reference marine mix. However, use of EnDurCrete cement, corrosion inhibiting nanoclays and protective acrylic paint leads to extension of the service life and potential GWP reduction of 32 % during the whole life cycle also for marine application.

The Life Cycle Cost Analysis (LCCA) was carried out in parallel with LCA. The inventory of the production inputs/outputs/processes was complemented by the inputs on prices of the particular components. Additional inputs on the expected market prices of the novel materials were provided by IBOX and AM Solutions.

Similarly to the LCA results, the use of the EnDurCrete concrete mix achieved the best performance in the tunnel use case (potential 22% savings during the whole life cycle at product level). In some cases the production costs of the EnDurCrete products are slightly higher than reference but this is always compensated by the extended service life and consequentially by the reduced complete life cycle costs.

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Abbreviations and Acronyms

ADPE – Abiotic depletion potential for non-fossil resources

ADPF - Abiotic depletion potential for fossil resources

AP – Acidification potential

AWARE – Available Water REmaining

CSI – Cement Sustainability Initiative

EPD – Environmental product declaration

EP – Eutrophication potential

GWP – Global warming potential

LCA – Life cycle assessment

LCCA – Life cycle cost analysis

LCI – Life cycle inventory

LCIA – Life cycle impact assessment

LCM – Life Cycle Management

ODP – Ozone depletion potential

OPC – Ordinary Portland cement

PCC – Portland composite cement

PCR – Product category rules

OPCP – formation potential of tropospheric ozone photochemical oxidants

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1 Methodology

1.1 Context

The Deliverable 7.5 “Report on environmental and economic viability of the novel products based on the findings of the LCA and LCCA” has been created in frame of the Project “New Environmental friendly and Durable conCrete, integrating industrial by-products and hybrid systems, for civil, industrial and offshore applications” (Project Acronym: EnDurCrete; Grant Agreement No.: 760639).

This deliverable represents the final output pf WP7 “Life cycle assessment and economic evaluation, standardization and health and safety aspects”, Task 7.1 “Environmental and economic viability of the novel products based on LCA and LCCA”.

EnDurCrete project has been implemented as “Research *Innovation Action*” funded under call H2020-NMBP-2016-2017/H2020-NMBP-2017-two-stage and addressing the topic “Improved material durability in buildings and infrastructures, including offshore “.

EnDurCrete has been carried out by the consortium of 15 partners including research organizations and leading European cement producers.

1.2 Methodology

This report represents the final outcome of the environmental and economic performance assessment of the novel products (precast concrete elements for various applications) developed and demonstrated in frame of EnDurCrete project. New materials (cements, corrosion inhibitors and protective paints) developed in the initial phase of the project were separately analyzed and compared to traditional alternatives in the previous step (cradle-to-gate analysis). The results that were reported in D7.2 (Life Cycle Analysis at Material Level) represent the baseline for the analyses performed in this second step, Life Cycle Analysis at product level.

Life Cycle Assessment (LCA) was chosen to perform this study. LCA has been used in many industries since the early 1990’s to gage the environmental impact of the entire life cycle of a product including manufacture, use, and disposal. LCA is based on an inventory of the inputs of the raw materials, capital goods, factories, transportation, energy and fuels needed to create a product. The input, modification, and emissions of energy and materials are known as process flows.

Inputs can be materials or energy and the infrastructure required to create them. The outputs of each process are assessed for impacts in specific categories. The sum of emissions in each category is used to judge the overall impact of the product. A product or life cycle phase may be modelled using the process or input-output (I/O) method. These methods are approximations of the use of a material or energy source based on large amounts of data collected by a third party from many sources.

This life cycle assessment is performed in accordance with ISO 14044. Life Cycle Assessment allows the evaluation of potential environmental impacts of a product or an activity on its entire life cycle. It is therefore a holistic approach that takes into account the extraction and processing of raw materials, the manufacturing processes, transport and distribution, use, reuse and, finally, recycling and disposal at the end of life. However, the process boundaries can be amended according to actual needs defined in the initial phase (goal and scope definition).

Figure 1 illustrates the major steps of the life cycle assessment of a product as usually described in the literature.

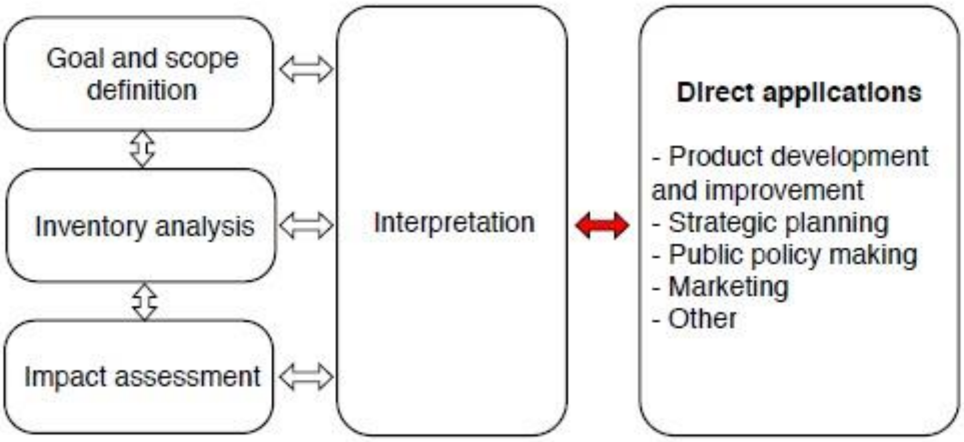

Figure 1: Overview of LCA phases

Traditional LCA consists of four major phases:

Goal and scope definition

Goal and scope definition is the first stage of an LCA, where the purpose of the study is described. Also the boundaries of the product system are defined according to factors such as time constraints, data available and depth of study required. At this point a ''functional unit'' is defined, which provides a reference to which the inputs and outputs of the analysis are related.

Inventory analysis

Inventory analysis involves data collection related to the inputs and outputs of the system described in the ''goal scope and definition''. It inventories quantities of raw materials, waste flows and emissions attributed to the product life cycle.

Life cycle impact assessment

Life cycle impact assessment involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts.

Interpretation

Here results are interpreted, summarised and discussed, conclusions are drawn and recommendations made against the initial goals.

1.3 Tools

As mentioned above, Life Cycle Analysis is a very complex task; collection of detailed data about inputs, outputs and processes related to the considered stages of the product life cycle and detailed calculation of all emissions and other environmental impacts would be extremely complicated. Large teams of experts have been collecting these data and performing detailed measurements and calculations in order to simplify the elaboration of LCAs. Several software tools allowing semi-automated impacts assessment are now available; there are also several databases describing the inputs, outputs, processes and emissions related to the most common materials and products. These datasets can be used directly for calculations or in combination with the dedicated software; their use allows certain "standardization" of the achieved results, as well as it simplifies the whole process.

SimaPro 9.2.0.2

LCA of the remaining new materials (multifunctional coatings, modified nano-clays used as corrosion inhibitors and carbon-based materials used for mechanical and self-sensing properties) has been carried out with SimaPro version 9.2.02, one of the two most commonly used tools worldwide. Ecoinvent database values as created by the Swiss Centre for Life Cycle Inventories were used where possible. This database provides scientifically sound and transparent international life cycle assessment and life cycle management (LCM) data. The database also provides the LCI data of the materials and processes used in the background system.

Concrete EPD Tool

The World Business Council for Sustainable Development's Cement Sustainability Initiative (CSI - https://www.wbcsdcement.org/), which transferred to the Global Cement & Concrete Association (GCCA) as of 1 January 2019, developed Product Category Rules (PCR) for unreinforced concrete. Based on that the CSI commissioned company Quantis to develop a **web-based Concrete EPD Tool** (https://concrete-epd-tool.org/).

The online tool produces two major outputs:

- A self-declaration in CSI format that can be used for communication and/or sales purposes. The self- declaration is not a "validated" official EPD, but can serve as a user-friendly document that contains the main general/background information as well as the environmental performance (LCA results) of the specific product for all indicators.

- **A detailed background report with the complete set of input data and results of the specific product.** This document is in the form of an Excel file that contains all the information required to produce an EPD and also for a verifier to validate it.

The Concrete EPD Tool allows calculating and reporting the environmental impacts **of clinker, cement and concrete systems** according to and in agreement with the PCR. Therefore it was selected as the most suitable tool for the first phase of the LCA for novel EnDurCrete cements.

1.4 Life Cycle Impact Assessment Methodology

EPD (2018) method as included in the SimaPro SW was used for all the analyses carried out in this SW because it is commonly used in the construction sector, it includes the most important impact categories and it is based on CML method which makes it compatible to the results coming from the Concrete EPD Tool. In the standard EPDs the following impact categories are reported:

- Acidification potential
- Eutrophication potential
- Global warming potential
- Photochemical oxidant creation potential
- Abiotic resource depletion, elements
- Abiotic resource depletion, fossil fuels
- Water Scarcity Footprint
- Ozone depletion potential

Most impact categories are taken directly from the CML-IA baseline method (eutrophication, global warming, ozone depletion and abiotic resource depletion) and CML-IA non baseline method (acidification). Water scarcity category is based on AWARE method and Photochemical oxidation is based on ReCiPe 2008. All those individual methods can be found in SimaPro.

However, it has to be clearly stated that **the aim of this study was not to create final and validated EPD of any of the products developed and assessed in frame of the EnDurCrete project.** This will only be possible when the products are produced at industrial scale.

1.5 Electricity

The energy mix of the country where the particular material/product is supposed to be produced was used for calculations when possible. In other cases the average value for Europe was used.

1.6 Life Cycle Cost Assessment (LCCA)

Life Cycle Costs have also been analyzed in frame of the study. The data were collected together with the inputs to LCA, covering the whole production chain. Later on, the costs of the operation phase have been calculated. Details are provided in chapter 5 of this report.

2 Goal and Scope Definition

2.1 Goal

The main goal of this study is *"to verify the environmental and economic viability of EnDurCrete sustainable concrete products, with a view to assessing its positive impact in comparison to other concrete materials and products in the market".*

It has been decided already in the preparation stage of the project proposal that the LCA would have been split in two phases. Indeed, the first phase considered only the production phase of the new materials without taking into account the assembly of complete products (precast elements) as well as operational and end-of-life phase. Its main focus was the comparison of the novel materials with the reference (commercially available) materials.

The results of the analysis carried out during the first phase were later used as inputs to the second phase performed at product level and considering the real products (pre-cast concrete elements for various applications) based on the new materials. This LCA therefore compares the environmental impacts and economic viability of precast concrete elements based on the standardized commercially available materials (reference) and the products based on the new materials (EnDurCrete cements, nanoclay corrosion inhibitors and protective paints) developed and demonstrated in frame of the EnDurCrete project**.**

This study and its results is **not intended to be directly used for the marketing purposes** of the new products because some inputs are based on theoretical assumptions and do not represent the real production data in the specific location.

2.2 Scope

2.2.1 Products and functional units

The study involves the following new products:

Functional unit	Reference product description	New EnDurCrete product(s) description
1 **tunnel** ring precast element (continental environment)	Element made of reference concrete mix based on CEM II/A-S 42.5 R	Element made of concrete mix based on EDC CEM VI (S-V)
1 **bridge** precast element (continental environment)	Element made of reference concrete mix based on CEM II/A-S 42.5 R	Element made of concrete mix based on EDC CEM VI (S-V)
1 precast element of slab for wharves (**marine** environment)	Element made of reference concrete mix based on CEM III/A 42.5 N	Element made of concrete mix based on EDC CEM II/C-M (S-LL)
		Element made of concrete mix based on EDC CEM II/C-M (S-LL) with addition of nanoclay corrosion inhibitor
		Element made of concrete mix based on EDC CEM II/C-M (S-LL) painted with EnDurCrete acrylic paint
		Element made of concrete mix based on EDC CEM II/C-M (S-LL) with addition of nanoclay corrosion inhibitor and painted with EnDurCrete acrylic paint
1 precast element of riegel foundation (**offshore** application in marine environment)	Element made of reference concrete mix based on CEM I 52.5 R	Element made of concrete mix based on EDC CEM II/C-M (S-LL)
		Element made of concrete mix based on EDC CEM II/C-M (S-LL) with addition of nanoclay corrosion inhibitor
		Element made of concrete mix based on EDC CEM II/C-M (S-LL) painted with EnDurCrete acrylic paint
		Element made of concrete mix based on EDC CEM II/C-M (S-LL) with addition of nanoclay corrosion inhibitor and painted with EnDurCrete acrylic paint

Table 1: Overview of analysed products

More details about all products are provided in chapter 3 of this report (Inventory analysis). Although the study is based on the design of real precast concrete elements it has to be emphasized that we have not modelled any specific real life construction and therefore all the functional units have to be considered as “theoretical” in terms of exact location and external conditions such as topography or geology of the construction site, transport distances from/to the casting/construction site, availability of types of transport and energy sources, positioning of the element in the whole construction, necessary preparatory works (engineering geology, foundation works, drilling works), supportive infrastructure etc.

This approach allows focusing on differences between the EnDurCrete and reference product at the defined functional unit level (1 precast concrete element for selected application).

2.2.2 System boundaries

The detailed analysis includes all the life cycle stages, from cradle to grave, along with transportation between each stage. Summary is given in the table below.

Included	Excluded
• Raw materials extraction • Energy and fuel inputs • Operation of the equipment • Further processing materials (e.g. chemicals, solvents, etc.) • Processing of raw materials and semi-finished products • Transportation of raw and processed materials • Internal transportation of materials • Use phase (maintenance)	• Purchase and maintenance of capital equipment* • Overhead of manufacturing facilities* • Human labour* • End-of-life**

Table 2: Summary of system boundaries

* The marked items are excluded from the LCA due to high complexity of related processes and difficult data inventory. However, these items are included in the LCCA when possible.

** The end-of-life scenarios are not included in the LCA and LCCA because it was verified and reported in D7.3 (Recyclability analysis) that the new materials and products made thereof are 100% recyclable and it is expected that it will be obligatory to fully recycle these constructions at the end of their service life and therefore there is only one realistic end-of-life scenario (recycling). The expected service life is very long (> 100 years for most use cases) and it is almost impossible to anticipate what technologies will be used for this recycling and what will be the related costs. In addition, the EnDurCrete products are expected to be recycled in exactly the same way as the reference products and therefore there would be no difference.

3 Inventory analysis

3.1 Concretes

EnDurCrete concretes represent the main constituent of all the assessed precast elements. The composition of the concrete mixes used in this analysis is presented below (taken from D3.9 Optimized mix designs using novel binders and additives ready for upscaling in WP).

Material	Unit	EDC Marine C35/45	EDC Marine C35/45 with nanoclays	EDC Tunnel C40/50	EDC Offshore
EDC CEM II/C-M (S-LL)	kg/m^3	360	375	-	440
EDC CEM VI (S-V)	kg/m^3	-	-	480	
Total aggregate	kg/m^3	1933	1941	1764	1816
Sika VisoCrete-2014 (superplasticizer)	kg/m^3	1,0	0,6	0,9	1
Sika ViscoFlow-10150666 (superplasticizer)	kg/m^3	1,5	2,3	1,4	1,5
SikaAer Solid (air entrainer)	kg/m^3	-	-	-	3,5
Nanoclay	kg/m^3	-	3,8	-	-
Water	kg/m^3	162	162	187	159

Table 3: Inventory of EnDurCrete concretes

Inventory of reference concretes				
Material	**Unit**	**Marine C35/45 REF**	**Tunnel C40/50 REF**	**Offshore REF**
CEM III/A 42.5N	kg/m^3	375	-	-
CEM II/A-S 42.5R	kg/m^3	-	430	-
CEM I 52.5 R	kg/m^3	-	-	447,5
Silica fume	kg/m^3	-	-	23,5
Total aggregate	kg/m^3	1871	1759	1751
PC2 (SIKA superplasticizer)	kg/m^3	0,8	1,07	2,40
PC3 (SIKA superplasticizer)	kg/m^3	1,2	1,6	3,60
Sika stabilizer 4R (viscosity modifying)	kg/m^3	-	1,3	-
SIKA LPS A-94 (air entrainer)	kg/m^3	-	-	0,36
Water	kg/m^3	162	198	170

Table 4: Inventory of reference concretes

3.2 Tunnel precast element

3.2.1. Functional unit characterization

Tunnel precast element use case scenario is based on the description of the functional unit and inventory inputs provided by ACCIONA. The functional unit model was created according to the specification of the **precast tunnel element (segment)** which is a part of the Segmental Tunnelling System. Each tunnel ring is completed by joining together a number of the precast segments and locking the arrangement in position using a trapezoidal key segment. The pictures below depict the plan of a precast ring with 6+1 configuration, with a detailed design of the trapezoidal key precast segment that was produced for the construction of Bolaños Tunnel in Spain.

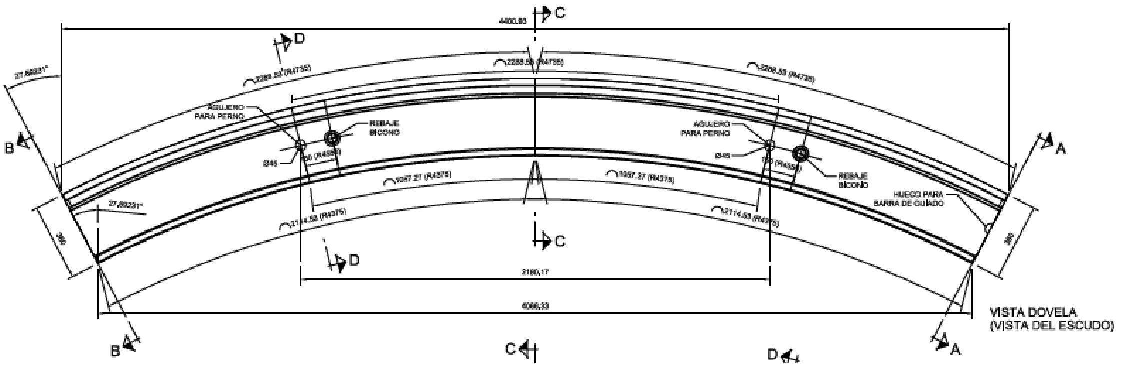

Figure 2: Cross section of the tunnel ring segment

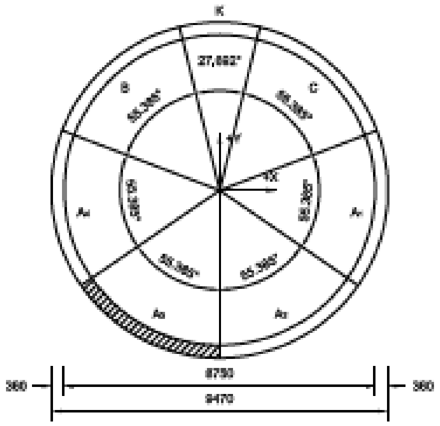

Figure 3: Cross section of the tunnel ring, analyzed segment highlighted

When installed in the tunnel, the segments fit together naturally due to their shape and moulding pattern and are joined together using specialized connecting devices at the circumferential and radial joints, as per the design provided.

Segment casting includes the following operations: mould preparation, concrete batching, finishing, steam curing, demoulding, micro finish / inspection and segment marking. In case of the Bolaños Tunnel, the Automated Carousal system, where the moulds are moving and the people and machinery remain stationary in fixed workstations where all the production activities are carried out simultaneously, was used.

3.2.2. Consumption of inputs (inventory)

Tunnel precast segment input inventory		
Input name	**Unit**	**Consumption per 1 piece of the precast element**
Concrete	m^3	18,82
Steel (rebar)	kg	1880
Diesel (fuel for on-site electricity generator)	l	83

Table 5: Inventory of tunnel precast element

3.3 Bridge precast element

3.3.1. Functional unit characterization

Tunnel precast element use case scenario is based on the description of the functional unit and inventory inputs provided by ACCIONA. The functional unit model was created according to the specification of **precast bridge element**: 36-meter bridge span, the most repeated length in the construction of DUBAI metro route.

Segment casting includes the following operations: mould preparation, concrete batching, finishing, steam curing, demoulding, micro finish / inspection and segment marking. The segments are cast directly on the construction site or very close to it due to their enormous size and weight. Therefore the transport distance of the complete element is very small and is usually performed by a set of special trucks and/or cranes.

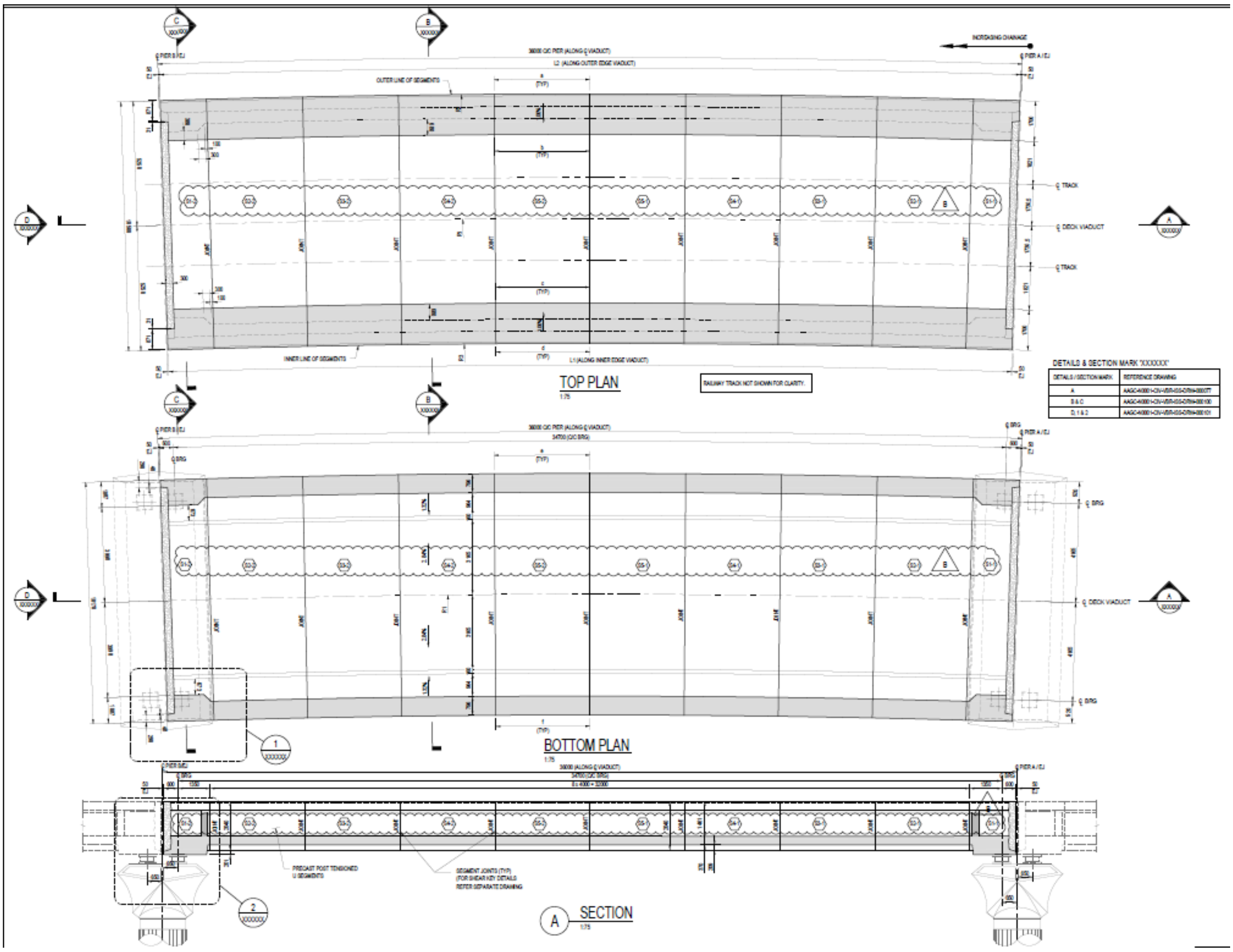

Figure 4: Plan and elevation of the bridge span

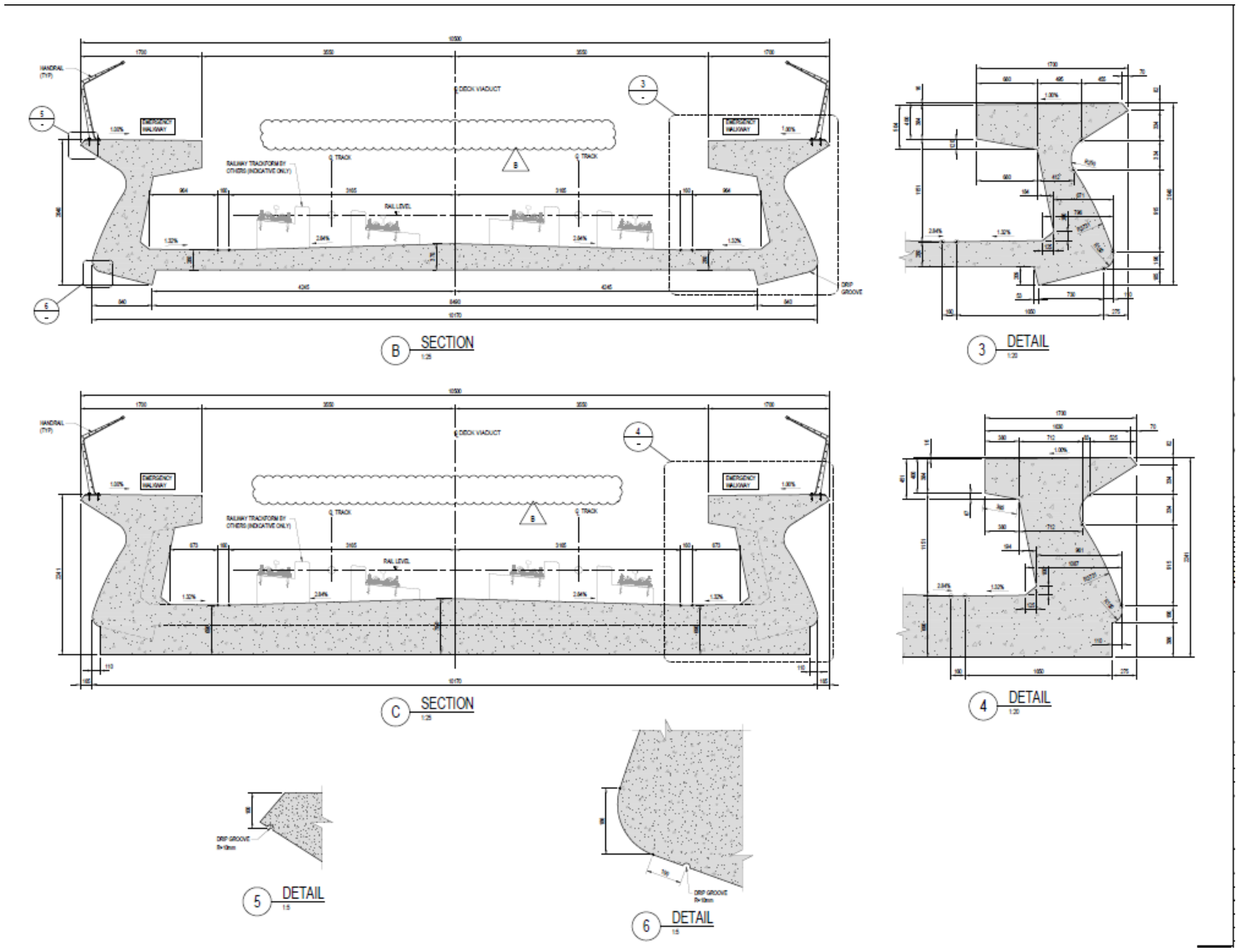

Figure 5: Cross section of the bridge span

3.3.2. Consumption of inputs (inventory)

Bridge precast segment input inventory		
Input name	**Unit**	**Consumption per 1 piece of the precast element**
Concrete	m^3	220
Steel (rebar)	kg	58 000
Diesel (fuel for on-site electricity generator)	l	1 000

Table 6: Inventory of bridge precast element

3.4 Marine construction precast element

3.4.1. Functional unit characterization

Marine precast element use case scenario is based on the description of the functional unit and inventory inputs provided by ZAG and Nuova Tesi (ZAG provided the description of the element; since it is not a precast element production company, the inputs related to the production process, such as needed equipment, energy and fuel consumption, labor costs and indirect costs, were provided by Nuova Tesi).

The functional unit in this case is **precast deck slab for wharves**. Wharves are marine structures which serve for mooring ships while loading and unloading cargo or passengers. They are either fixed structures with a substructure transferring the load of the deck to the sea bottom, or floating structures where the deck is anchored in place but allowed to move vertically and maintain a fixed alignment with the vessel regardless of the sea level. Concrete must fulfil the requirements for the exposure class XS3 "Risk of corrosion induced by chlorides from water – Tidal, splash and spray zone" (*EN 206*, 2016). For this exposure class, the minimum recommended strength class is C35/45 and maximum recommended water-cement (wc) ratio is 0.45 (*EN 206*, 2016).

For the purpose of this LCA study, precast reinforced solid slabs for a fixed wharf are considered. In this case slabs are 5.2 m long, 2.4 m wide and 250 mm thick. An example is shown in Fig. 5.

In this use case scenario the precast elements are produced (typically in series) in the dedicated facility and transported to the construction site by truck (or train if possible but truck was considered in this LCA).

Figure 6: Precast reinforced solid slabs for wharf construction.

3.4.2. Consumption of inputs (inventory)

Marine precast segment input inventory		
Input name	**Unit**	**Consumption per 1 piece of the precast element**
Concrete	m^3	3,11
Steel (rebar)	kg	80
Diesel (fuel for concrete mixer)	l	2
Electric energy from the grid	kWh	20
EnDurCrete acrylic coating (for selected scenarios)	kg	2,59

Table 7: Inventory of marine precast element

3.5 Offshore construction precast element

3.5.1. Functional unit characterization

Offshore precast element use case scenario is based on the description of the functional unit and inventory inputs provided by AKER SOLUTIONS.

The functional unit is **slab in a riegel on offshore structure**. Its purpose is to connect the concrete shaft together. The precast element was 7.5 x 12.5 m and with a thickness of 0.5 m. This element was 1 of several precast elements installed on the top of 4 concrete legs coming together as a part of a riegel foundation. Several horizontal almost similar pre-cast elements are installed as part of a riegel slab and concrete is placed in all joints to make the riegel slab as one element. After the installation, the whole riegel is submerged in sea water at 80 m water depth. The element is pre-cast onshore. The production sequence was first installation of rebar (about 250 kg/m^3 concrete) and then formwork before casting the concrete. At the end, each element was lifted by a rigid crane boat and installed at the top of the 4 legs offshore structure.

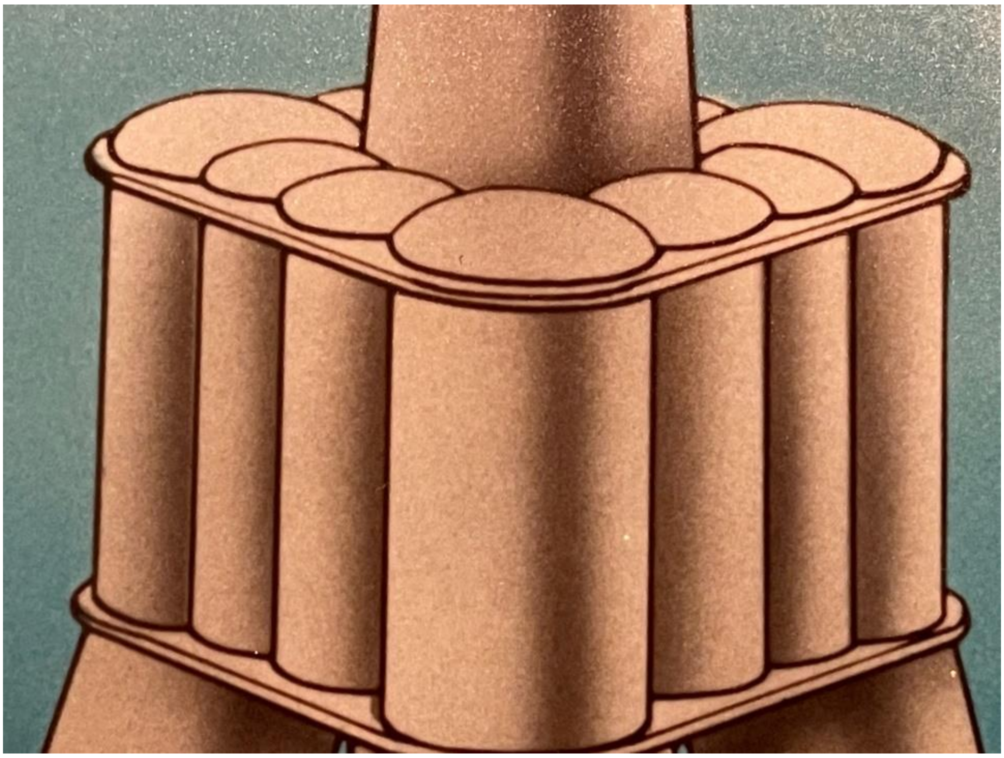

Figure 7: Riegel foundation on the bottom

3.5.2. Consumption of inputs (inventory)

Bridge precast segment input inventory		
Input name	**Unit**	**Consumption per 1 piece of the precast element**
Concrete	m^3	45,6
Steel (rebar)	kg	11 725
Diesel	l	20
Electric energy from the grid	kWh	170
EnDurCrete acrylic coating (for selected scenarios)	kg	18,68

Table 8: Inventory of offshore precast element

3.6 Transport of materials and products

In this study we do not assess the products to be constructed in the specific location. Therefore the transport distances of materials and products are not based on any particular production or construction site. Therefore the transport distances were only estimated, taking into account that the assessment of environmental and economic impacts of transportation is not part of this study and therefore the transport distances were set to rather conservative values as follows. Of course in real life the transport distances can vary significantly due to local conditions, distribution channels etc.

The concrete is supposed to be mixed on-site, therefore the transport distances of concrete constituents are included in the calculation of the concrete mix reported in D7.2 (Life cycle analysis at material level)

Materials and means of transport	**Distance (km)**
Transport of all other materials to the casting production site by truck	100
Transport of marine slab for wharves (truck)	100
Transport of tunnel elements (crane, special trucks)	5
Transport of offshore riegel foundation elements (crane, bulk carrier boat)	5
Transport of bridge element (crane, special trucks)	1

Table 9: Means of transport distances and estimated average transport distances

3.7 Service life

The estimation of service life was carried out in frame of EnDurCrete project WP4 and reported in D4.4 (Report on computational analyses for macrostructures for service life estimation, including corrosion phenomena and critical environments).

The calculation of exact values for offshore concrete structure service life was not carried out in frame of WP4, but the conclusion of the authors of D4.4 is that the increase in service life shown by Marine structure is similar to the increase of the service life of the Offshore structure (detailed explanations are provided in the part of D4.4 dealing with parametric analysis). The baseline service life of the reference structure was therefore set to 100 years and the expected increase was calculated using the service life multiplication factor of the Marine structures.

It should be emphasized that the modelling of service life carried out in WP4 is based on theoretical assumptions and that mainly the impact of corrosion inhibiting nanoclays on durability/service life is still under investigation, since the results of the analyses performed in other WPs have shown some contradictory results.

The longest service life (for the specific use case scenario) was always taken as a baseline for the comparison of the use case scenarios and the impacts of the other scenarios were calculated according to the ratio of the corresponding scenario to the baseline (i.e. if the baseline is 169 years and the service life of the other scenario is 91 years, the impact of the later is multiplied by 169/91).

Type of application (functional unit)	Materials used	Service life (years)	Service life multiplication factor
Tunnel element (continental environment)	EDC Tunnel C40/50	169	1
	Tunnel C40/50 REF	91	1,86
Bridge element (continental environment)	EDC Tunnel C40/50	133	1
	Tunnel C40/50 REF	97	1,37
Slab for wharves element (marine environment)	EDC Marine C35/45 + nanoclay + acrylic paint	146	1
	EDC Marine C35/45 + nanoclay	139	1,05
	EDC Marine C35/45 + acrylic paint	104	1,40
	EDC Marine C35/45	98	1,48
	Marine C35/45 REF	84	1,74
Riegel foundation element (marine environment)	EDC Offshore + EDC acrylic paint	124	1
	EDC Offshore	106	1,17
	Offshore REF	100	1,24

Table 10: Service life estimations and multiplication factors

4 Life cycle impact assessment and interpretation

4.1 Life cycle impact assessment methodology

The environmental impacts associated with a life cycle inventory can be calculated using a life cycle impact assessment (LCIA) methodology. SimaPro 9 software package offers several methods of life cycle assessment. EPD (2018) was selected to be used in this assessment because it is commonly used in the construction sector. The following impact categories are defined in EPD (2018) method:

Acidification potential (AP)

Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). Acidification Potential (AP) for emissions to air is calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances. AP is expressed as kg SO_2 equivalents/ kg emission. The time span is eternity and the geographical scale varies between local scale and continental scale. Characterization factors including fate were used when available. When not available, the factors excluding fate were used (in the CML baseline version only factors including fate were used). The method was extended for Nitric Acid, soil, water and air; Sulphuric acid, water; Sulphur trioxide, air; Hydrogen chloride, water, soil; Hydrogen fluoride, water, soil; Phosphoric acid, water, soil; Hydrogen sulphide, soil, all not including fate. Nitric oxide, air (is nitrogen monoxide) was added including fate. Unit is kg of SO_2 eq.

Eutrophication potential (EP)

Eutrophication (also known as nutrification) includes all impacts due to the excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil. Nutrification potential is based on the stoichiometric procedure of Heijungs (1992), and expressed as kg PO_4 equivalents per kg emission. Fate and exposure is not included, time span is eternity, and the geographical scale varies between local and continental scale. Unit is kg of PO_4^{3-} eq.

Global warming potential (GWP)

Climate change can result in adverse effects upon ecosystem health, human health and material welfare. Climate change is related to emissions of greenhouse gases to air. The characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterization factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in kg carbon dioxide/kg emission. The geographic scope of this indicator is global scale. Unit is kg of CO_2 eq.

Formation potential of tropospheric ozone photochemical oxidants (POCP)

Photo-oxidant formation is the formation of reactive substances (mainly ozone) which are injurious to human health and ecosystems and which also may damage crops. This problem is also indicated with “summer smog”. Winter smog is outside the scope of this category. Photochemical Ozone Creation Potential (POCP) for emission of substances to air is calculated with the UNECE Trajectory model (including fate), and expressed in kg ethylene equivalents/kg emission. The time span is 5 days and the geographical scale varies between local and continental scale. Unit is kg of kg NMVOC eq.

Additional (optional) indicators are:

Ozone depletion potential (ODP)

Because of stratospheric ozone depletion, a larger fraction of UV-B radiation reaches the earth surface. This can have harmful effects upon human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and on materials. This category is output-related and at global scale. The characterization model is developed by the World 5 Meteorological Organization (WMO) and defines the ozone depletion potential of different gasses (kg CFC-11 equivalent/kg emission). The geographic scope of this indicator is global scale. The time span is infinity. Unit is kg of CFC-11 eq.

Depletion of abiotic resources

This impact category is concerned with protection of human welfare, human health and ecosystem health. This impact category indicator is related to extraction of minerals and fossil fuels due to inputs in the system. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration reserves and rate of de-accumulation. The geographic scope of this indicator is global scale. The depletion of abiotic resources is covered by two indicators:

- **Abiotic depletion potential for non-fossil resources (ADPE, unit kg of Sb eq.)**
- **Abiotic depletion potential for fossil resources (ADPF, unit MJ)**

In this chapter the results of life cycle impact assessment of each of the precast concrete products defined in chapter 3 are presented in two steps:

1) **Cradle-to-gate.** The calculation includes only the production process.
2) **Cradle-to-grave.** The calculation includes production, use phase and potential reproduction according to the estimated service life (see chapter 3.7). The end-of-life is excluded because all constructions are supposed to be treated in the same way once their service life ends (100% recycled).

4.2 Tunnel precast element – LCIA results and interpretation

The environmental impacts of the precast tunnel element based on EDC Tunnel concrete (using EDC CEM VI (S-V)) was calculated and compared to the environmental impacts of the same precast tunnel element based on the reference concrete mix (using CEM II/A-S 42.5R).

The results of LCIA per impact categories are summarized in Figure 8 and Figure 9. Detailed results are provided in Annex 1 to this summary report.

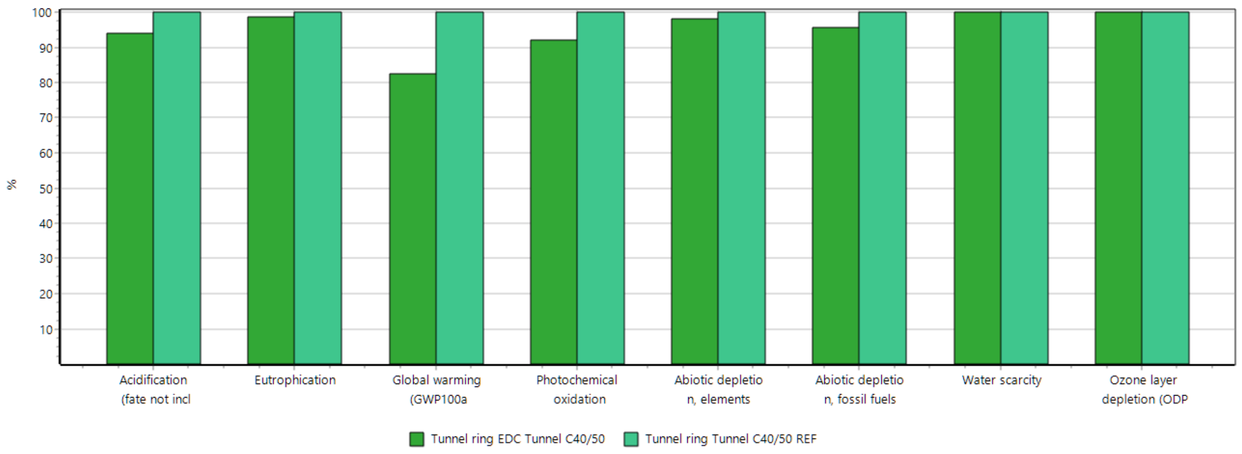

Figure 8: Comparison of environmental impacts of production of EDC Tunnel ring element and reference tunnel ring element (cradle-to-gate)

The key parameter analysed in EnDurCrete project is Global Warming Potential expressed as equivalent of CO_2 emissions. In this parameter the use of EnDurCrete concrete leads to reduction of GWP by 18 % during the production phase. The reduction of the remaining parameters is below 10 %.

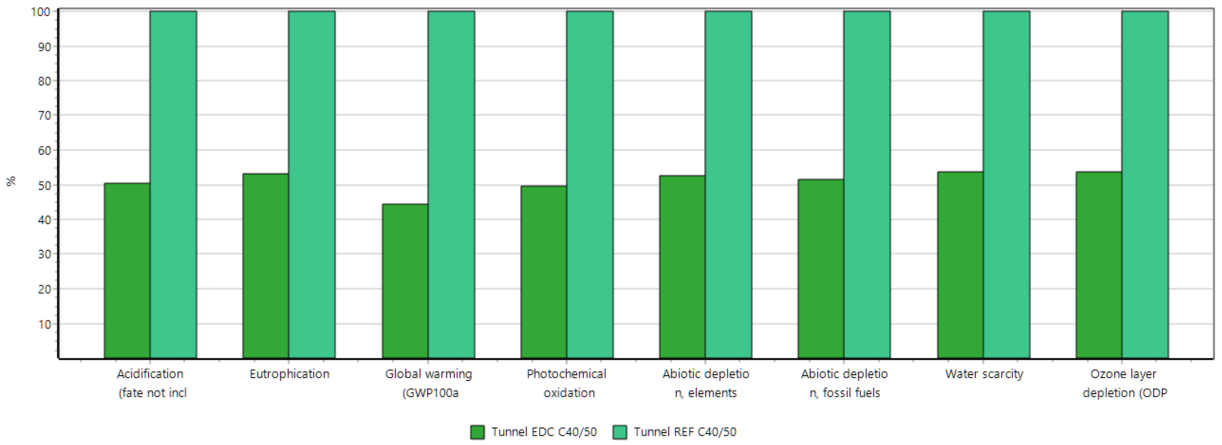

Figure 9: Comparison of environmental impacts of complete service life of EDC Tunnel ring element and reference tunnel ring element (cradle-to-grave)

When we look at the complete service life (169 years for EnDurCrete element and 91 years for the reference product as modelled in D4.4) the reduction of the environmental impact in all categories is much more significant and reaches 56 % of saved CO_2 in the Global Warming Potential parameter. The reduction in other parameters is between 46 % and 51 %.

4.3 Bridge precast element – LCIA results and interpretation

The environmental impacts of the precast bridge element based on EDC Tunnel concrete mix (using EDC CEM VI (S-V)) was calculated and compared to the environmental impacts of the same precast bridge element based on the reference concrete mix (using CEM II/A-S 42.5R).

The results of LCIA per impact categories are summarized in Figure 10 and Figure 11. Detailed results are provided in Annex 1 to this summary report.

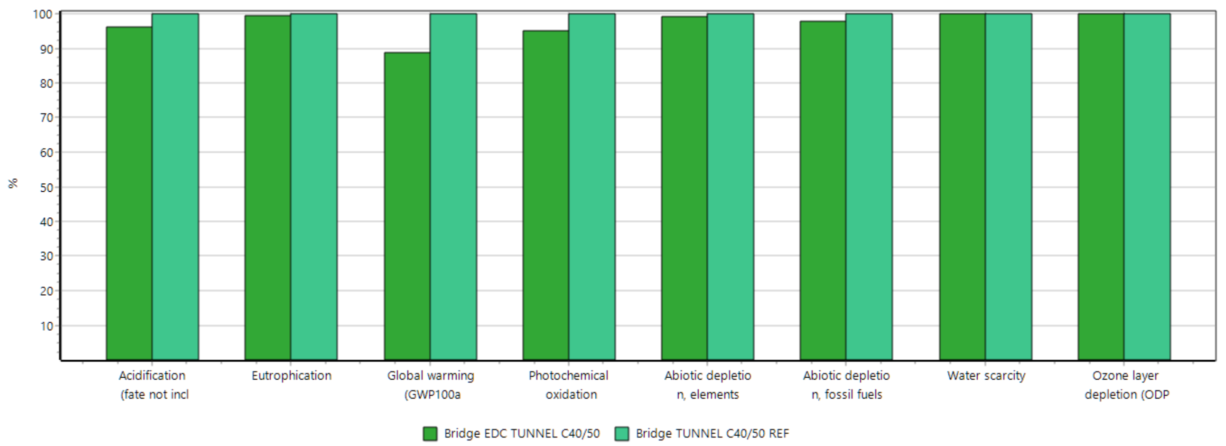

Figure 10: Comparison of environmental impacts of production of EDC bridge element and reference bridge element (cradle-to-gate)

In this case the use of EnDurCrete concrete leads to reduction of GWP by 11 % during the production phase, although the concrete mixes considered are the same as in the tunnel use case scenario. The difference is caused mainly by the fact that the bridge element contains much more steel reinforcement and therefore the impact of steel on the overall result is more significant while the impact of more environmentally friendly EnDurCrete cement/concrete is smaller. The reduction of the remaining parameters is below 10 %.

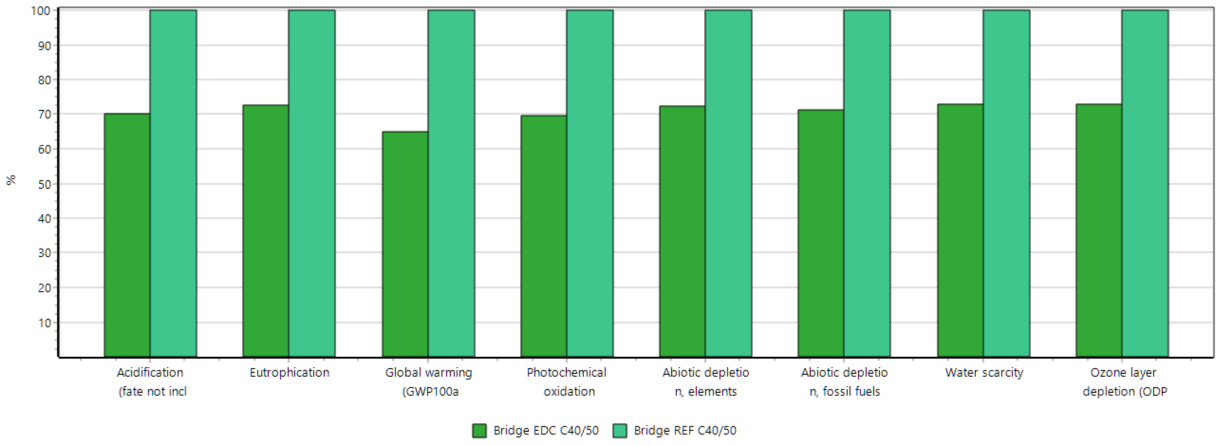

Figure 11: Comparison of environmental impacts of complete service life of EDC bridge element and reference bridge element (cradle-to-grave)

The service life calculated in D4.4 for the bridge application was 133 years for EnDurCrete element and 97 years for the reference product. **The difference in Global Warming Potential (CO_{2eq}) calculated for the whole service life is 35 %.** The reduction in other parameters is between 27 % and 31 %. The main reasons why the achieved reduction is smaller than in the tunnel use case scenario are 1) difference in service life is smaller and the design of the element is different with bigger amount and 2) bigger content of steel reinforcement.

4.4 Offshore precast element – LCIA results and interpretation

The environmental impacts of the precast bridge element based on EDC Offshore concrete mix (using EDC CEM II/C-M (S-LL)) was calculated and compared to the environmental impacts of the same precast offshore element painted with EnDurCrete acrylic paint. Finally it was also compared to the same element based on the reference concrete mix (using CEM I 52.5R).

The results of LCIA per impact category are summarized in Figure 12 and Figure 13. Detailed results are provided in Annex 1 to this summary report.

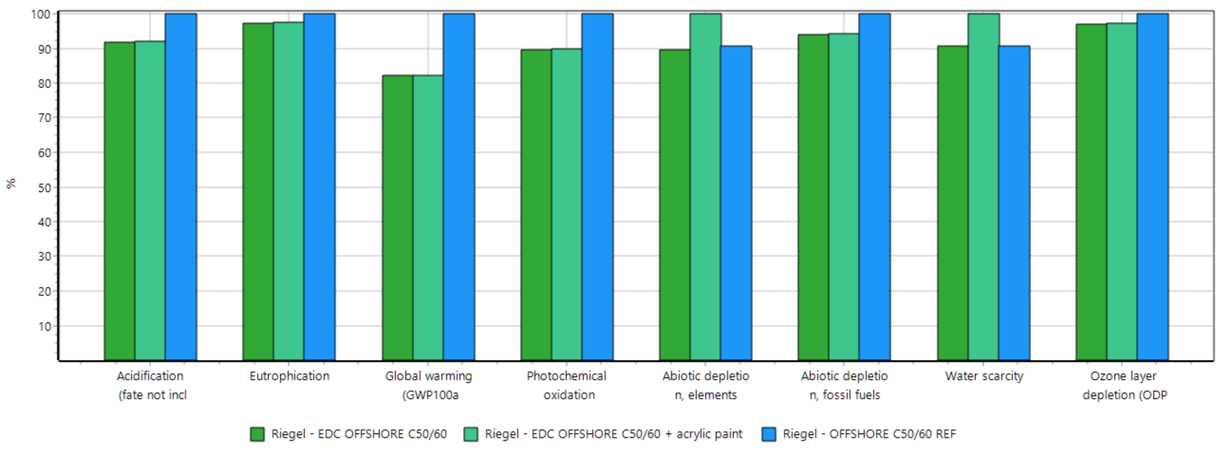

Figure 12: Comparison of environmental impacts of production of EDC offshore element and reference offshore element (cradle-to-gate)

The environmental impacts of EDC Offshore and EDC Offshore with EDC acrylic paint are smaller in comparison to the reference mix in all parameters except abiotic depletion (elements) and water scarcity (increase caused by the acrylic paint).

In the key parameter, global warming potential, the EnDurCrete precast elements achieve **18% reduction of CO_{2eq} in comparison to the element made of reference concrete during the production phase.**

The service life estimation was again based on D4.4 and set to 100 years for the reference offshore element, 106 years for EnDurCrete Offshore and 124 years for EnDurCrete Offshore with acrylic paint.

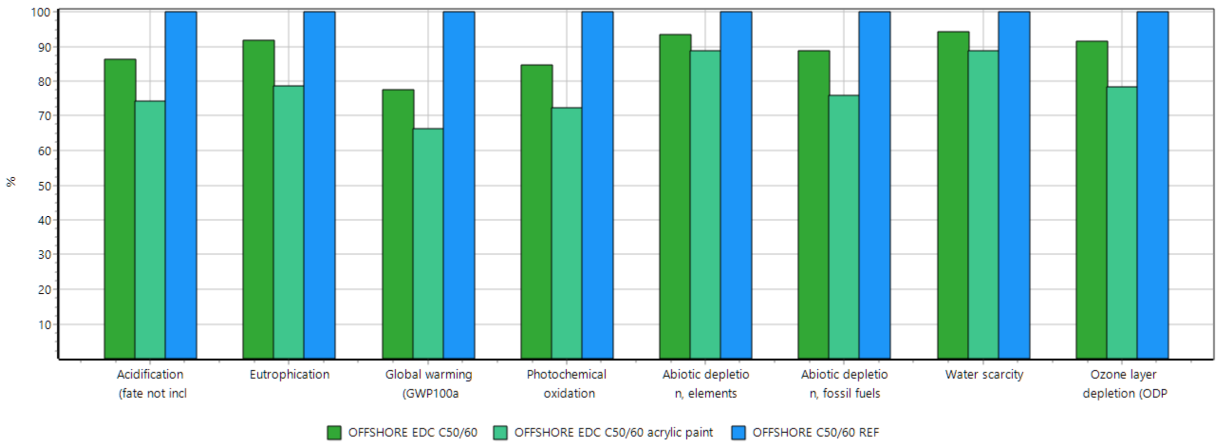

Figure 13: Comparison of environmental impacts of complete service life of EDC offshore element and reference offshore element (cradle-to-grave)

The reduction of Global Warming Potential (CO_{2eq}) calculated for the whole service life is 23 % for EDC Offshore and 34 % for EDC Offshore with acrylic paint. These values clearly demonstrate that using the EnDurCrete cement with the new protective paint is environmentally positive when we consider the complete life cycle, despite the increased impacts during the production phase.

4.5 Marine precast element – LCIA results and interpretation

The environmental impacts of the precast marine element based on EDC Marine concrete mix (using EDC CEM II/C-M (S-LL)) was calculated and compared to the environmental impacts of the same precast marine element produced of the concrete mix with corrosion protective novel admixture (nanoclays) and/or painted with EnDurCrete acrylic paint. Finally it was also compared with the same element based on the reference concrete mix (using CEM III/A 42.5N). It should be noted that the cement used in this reference mix has extremely small environmental impacts because it contains even higher dosage of secondary materials than EnDurCrete CEM II/C-M (S-LL) – the reference CEM III contains 53% of slag whereas EnDurCrete CEM II contains only 38 % of this secondary material.

The results of LCIA per impact category are summarized in Figure 14 and Figure 15. Detailed results are provided in Annex 1 to this summary report.

The use of CEM III/A 42.5N in the reference mix leads to the fact that the environmental impacts during the production phase of all the elements based on EnDurCrete Marine concrete mixes are slightly higher than reference (in case of GWP the increase is 7% for EDC Marine C35/45, 8 % for EDC Marine C35/45 with acrylic paint, 19 % for EDC Marine C35/45 with nanoclay and 20 % for EDC Marine C35/45 with nanoclay and acrylic paint).

As already reported in D7.2 (Life Cycle Analysis at Material Level), the environmental impacts of production of innovative corrosion inhibiting nanoclays are relatively big mainly due to high energy demand and also due to consumption of several chemicals with significant carbon footprint (mainly the 11-aminoundecanoic acid). It is also worth mentioning that the addition of nanoclays causes an enormous increase in the impact category “ozone layer depletion”. This is caused by the use of 3-(chloropropyl)-trimethoxysilane. Production of this chemical is reported to cause significant emissions of CFC-11 (trichlorofluormethane or freon-11) or its equivalent. It should be noted that the parameter “ozone layer depletion” is considered optional in EPD 2018 method and that the difference is relative to the reference values of the concrete without additives whose production causes only limited emissions of CFC-11 equivalent.

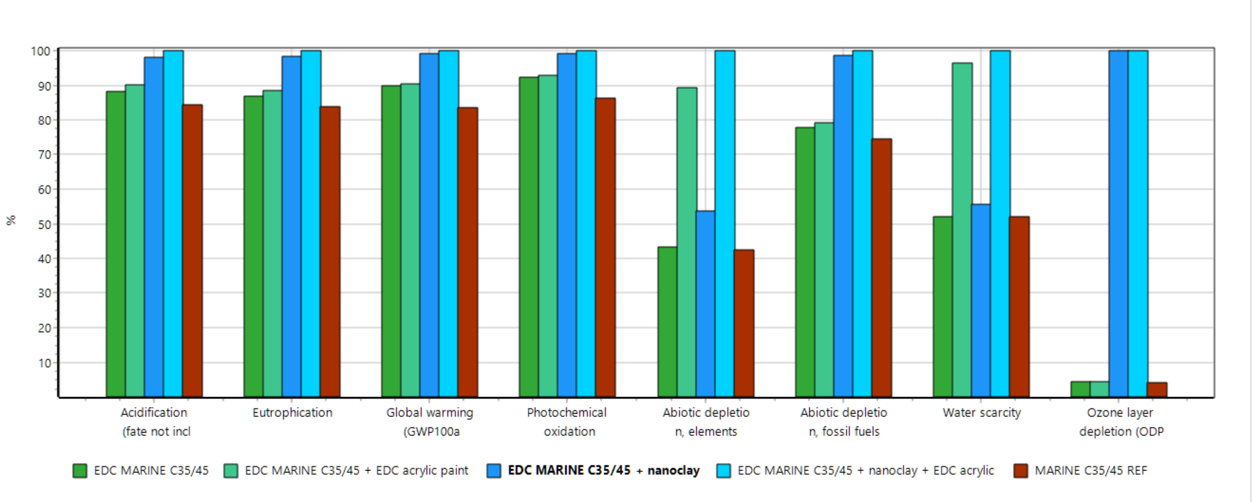

Figure 14: Comparison of environmental impacts of production of EDC marine element (with additives and paints) and reference offshore element (cradle-to-grave)

The service life for marine application was calculated in D4.4 as follows: 84 years for the reference Marine C35/45 element, 98 years for EnDurCrete Marine C35/45, 104 years for EnDurCrete Marine C35/45 with acrylic paint, 139 years for EnDurCrete Marine C35/45 with nanoclays and 145 years for EnDurCrete Marine C35/45 with nanoclays and innovative acrylic paint.

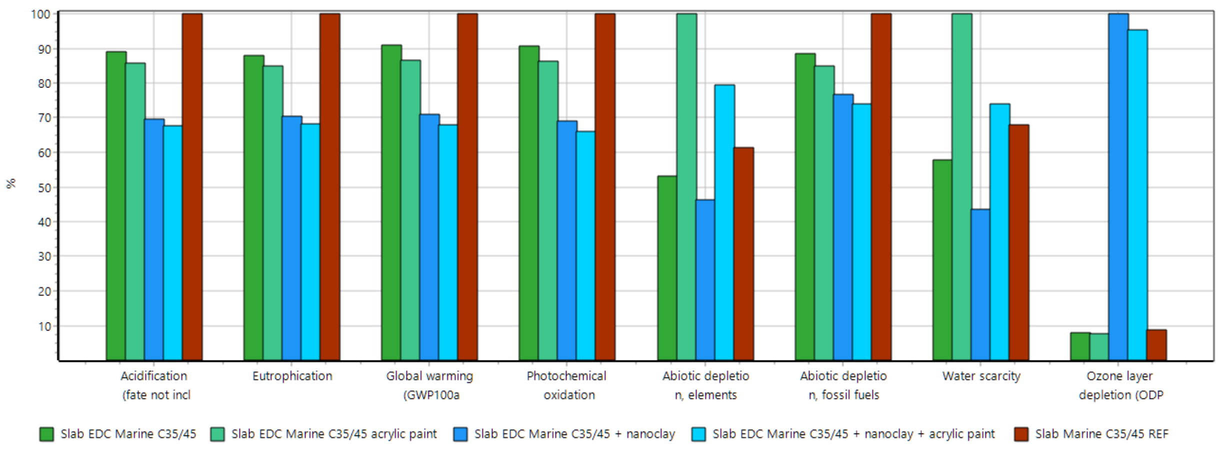

Figure 15: Comparison of environmental impacts of complete service life of EDC marine element (with additives and paints) and reference bridge element (cradle-to-grave)

Although the environmental impacts during the production phase are slightly higher compared to reference, the results for the complete life cycle are better for all the EnDurCrete use case scenarios due to extended service life. **The reduction of Global Warming Potential (CO_{2eq}) calculated for the whole service life is 9 % for EDC Marine C35/45, 13 % for EDC Marine C35/45, 29 % for EDC Marine C35/45 with nanoclays and 32 % for EDC Marine C35/45 with nanoclays and acrylic paint.**

The only exception is the “ozone layer depletion” where the difference of the impacts during the production of nanoclays is so big that the complete life cycle balance remains negative even considering the prolonged service life. It should therefore be mentioned that the production of nanoclays is still environmentally questionable and alternative production routes using chemicals with smaller impacts should be investigated.

5 Life cycle cost assessment

Life cycle cost assessment has been carried out based on the inputs from all the partners responsible for the various parts of the whole production chain of the theoretical functional units – precast concrete elements presented in the four use cases (Heidelberg Cement, Acciona, ZAG, Kvaerner, Nuova Tesi, AM Solutions, IBOX).

The data were collected together with the inventory for the LCA and also the methodology (life cycle model) was similar. This means that service life estimation was again based on the outcomes of D4.4 as presented in the chapter 3.7 of this report.

It is also important to remind that according to the definition of the functional unit and scope of the study (see chapter 2.2) this study does not have the intention to model the complex large scale construction (such as the whole tunnel or bridge) but that its scope covers only the selected types of precast elements for various applications.

This approach leads to certain generalization and simplification in the parameters that are constant for both EnDurCrete and reference products (precast element production and installation processes, transport, labor, maintenance) in order to demonstrate the difference between EnDurCrete and reference products.

Because we do not model any specific constructions with clearly defined local conditions it is impossible to exactly anticipate the necessary maintenance works and costs since these depend strongly on many external factors such as specific design of the whole construction, ways of use of the structure (including traffic load etc.), local conditions, availability of resources and many others. In addition, the specific use cases could include the additional costs arising from traffic delay and vehicle operations during the maintenance periods (the so called user costs). Therefore the maintenance/repair costs were estimated as average values for generic concrete structures. The repair and maintenance costs can be expected to be between 1 – 2 % of the structure construction costs per year[1,2]. In this study we consider the maintenance/repair costs to be constant 1 % for all types of constructions.

5.1 Material costs of 1 m^3 of concrete

The costs of concrete are in principle the only difference between the EnDurCrete and reference products during the production phase (cradle-to-gate) while all other costs remain constant. The costs of cements were provided by HeidelbergCement and represent the final price for the customer including all direct and indirect costs related to the production, administrative costs (such as emission allowances) and profit margin according to company strategy. **The prices were estimated for the production of the HeidelbergCement plant located in Germany; in other locations the prices can differ according to local conditions.**

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[1] Frangopol and Liu, 2007. Collection of monitored data will reduce asset integrity uncertainty.

[2] Yang, Lim, Kwon, Kim, 2020, Repair cost estimation techniques for reinforced concrete structures located at the seashore: Considering various probabilistic service life functions and actual mix proportions

Input	Unit	Unit price (EUR)	PRICE OF MATERIALS PER 1 m^3 OF CONCRETE – TUNNEL MIXES				
			EDC Tunnel C40/50		Tunnel C40/50 REF		Source of information
			Amount	Price	Amount	Price	
EDC CEM VI (S-V)	kg	0,1525	480,00	73,20			HeidelbergCement
CEM II/A-S 42.5R	kg	0,1505			430,00	64,72	HeidelbergCement
Sand 0/4 mm	kg	0,012	908,00	10,90	873,00	10,48	Nuova Tesi
Gravel 5/15 mm	Kg	0,011	980,00	10,78	886,00	9,75	Nuova Tesi
Superplasticizers	lt	2,25	2,30	5,18	2,70	6,08	Sika
Stabilizer (Sika 4R)	lt	3,7			1,30	4,81	Sika
Water	Kg	0,004	187,00	0,75	198,00	0,79	Nuova Tesi
Total (EUR)				**100,80**		**96,61**	

Table 11: Cost of materials needed for production of 1m^3 of tunnel concrete mixes

The price of 1 m^3 of EnDurCrete tunnel concrete mix with EDC CEM VI is slightly higher than reference concrete mix based on CEM II/A 42.5R mainly because of the higher cement content in the mix; the price of the compared cements is almost identical.

Input	Unit	Unit price (EUR)	PRICE OF MATERIALS PER 1 m^3 OF CONCRETE – OFFSHORE MIXES				
			EDC Offshore		Offshore REF		Source of information
			Amount	Price	Amount	Price	
EDC CEM II/C-M (S-LL)	kg	0,1485	440,00	65,34			HeidelbergCement
CEM I 52.5 R	kg	0,167			447,50	74,73	HeidelbergCement
Silica fume	kg	0,7			24,50	17,15	HeidelbergCement
Sand 0/4 mm	kg	0,012	831,00	9,97	744,00	8,93	Nuova Tesi
Gravel 5/15 mm	kg	0,011	985,00	10,84	1007,00	11,08	Nuova Tesi
Superplasticizers	l	2,25	2,50	5,63	6,00	13,50	Sika
Sika Aer Solid (air entrainer)	l	5	3,50	17,50			Sika
Sika LPC A-94 (air entrainer)	l	1,7			0,70	1,19	Sika
Water	kg	0,004	159,00	0,64	170,00	0,68	Nuova Tesi
Total (EUR)				**109,91**		**127,26**	

Table 12: Cost of materials needed for production of 1m^3 of offshore concrete mixes

One cubic meter of EnDurCrete mix is almost 18 EUR cheaper in offshore use case because the EDC-CEM II/C-M (S-LL) cement is cheaper than CEM I and the reference mix contains quite significant amount of silica fume affecting the final mix price. On the other hand the EnDurCrete offshore mix contains a very expensive Sika Aer Solid air entrainer whose content should probably be reconsidered in potential commercial applications.

Input	Unit	Unit price (EUR)	PRICE OF MATERIALS PER 1 m^3 OF CONCRETE – MARINE MIXES						
			EDC Marine C35/45		EDC Marine C35/45 + nanoclay		Marine C35/45 REF		Source of information
			Amount	Price	Amount	Price	Amount	Price	
EDC CEM II/C-M (S-LL)	kg	0,1485	360,00	53,46	375,00	55,69			HeidelbergCement
CEM III/A 42.5N	kg	0,1525					375,00	57,19	HeidelbergCement
Sand 0/4 mm	kg	0,012	968,00	11,62	908,00	10,90	962,00	11,54	Nuova Tesi
Gravel 5/15 mm	kg	0,011	965,00	10,62	1033,00	11,36	909,00	10,00	Nuova Tesi
Superplasticizers	l	2,25	2,50	5,63	2,90	6,53	2,00	4,50	Sika
Nanoclay	kg	4,26			3,80	16,19			IBOX
Water	kg	0,004	162,00	0,65	162,00	0,65	162,00	0,65	Nuova Tesi
Total (EUR)				**81,96**		**101,31**	**2410**	**83,88**	

Table 13: Cost of materials needed for production of 1m^3 of marine concrete mixes

Also in the case of the marine mixes the prices of EnDurCrete cement EDC CEM II/C-M (S-LL) and reference CEM III/A 42.5 are very similar. Therefore also the price of 1m^3 of EDC marine mix and EDC marine reference mix is very similar. The price of the cement mix with nanoclays is almost 20 % higher because of the relatively big amount of the admixture with not negligible unit price.

5.2 Equipment and labor costs

The costs of equipment needed for production and installation of the precast concrete elements were estimated by the partners providing inventories of the four use cases. It should again be emphasized that these costs refer to "theoretical" or "average" precast element of the given parameters and that the real life costs can vary significantly depending on many factors including exact location and external conditions, local prices of all inputs etc. The estimated prices are summarized in the tables below.

Equipment name	**Investment cost (EUR)**	**Expected lifetime (years)**	**Annual Production Time (minutes)**	**TUNNEL ELEMENT**		**BRIDGE ELEMENT**	
				Time used (minutes)	**Costs**	**Time used (minutes)**	**Costs**
Concrete mixing plant	170 000	20	120 000				
Concrete mixing plant	156 000	8	120 000	40	6,5	150	24,4
Precast Concrete Carousel Plant	1 100 000	8	120 000	40	45,8		
On-site casting infrastructure	1 000 000	8	120 000			600	625,0
Total equipment costs (EUR)				**52,3**		**649,4**	
Labor costs (EUR)				**446,5**		**5 926**	
Equipment name	**Investment cost (EUR)**	**Expected lifetime (years)**	**Annual Production Time (minutes)**	**MARINE ELEMENT**		**OFFSHORE ELEMENT**	
				Time used (minutes)	**Costs**	**Time used (minutes)**	**Costs**
Concrete mixing plant	170 000	20	120 000	40	2,8	180	12,8
Production site equipment (storage, pump, conveyor, crane...)	350 000	15	120 000	60	11,7	300	58,3
Total equipment costs (EUR)				**14,5**		**71,1**	
Labor costs (EUR)				**175**		**3 300**	

Table 14: Capital costs of equipment and labor costs

5.3 Life cycle costs - results

The life cycle costs include the costs of materials, the capital costs of equipment needed for casting and installation of the precast concrete elements, costs of labor, fuel, energy and transport of all inputs during the production phase. The above listed costs are considered to be "direct costs" of the precast concrete element production. The indirect costs include all the other costs of the concrete casting and construction companies that cannot be directly allocated to the product. Based on the experience of the partners providing inputs to this LCA, the average share of indirect costs was set to 35% of direct costs (this figure can also vary a lot according to local conditions, complexity of the constructed structure etc). The service life estimations are summarized in chapter 3.7 of this report. The results for all theoretical use cases analyzed in this study are summarized below.

5.3.1. Life cycle costs of precast concrete tunnel elements

Input	**Unit**	**Unit price (EUR)**	**TUNNEL ELEMENT LIFE CYCLE COSTS**			
			EDC TUNNEL C40/50		**TUNNEL C40/50 REF**	
Service life (years)			169		91	
Durability multiplication factor			1		1,86	
Total weight of element (kg)			47 669		46878	
			Amount	**Price (EUR)**	**Amount**	**Price (EUR)**
Factory and equipment			1	52,33	1	52,33
EDC Tunnel C40/50	m^3	100,80	18,82	1 897,04		0,00
Tunnel C40/50 REF	m^3	96,61		0,00	18,82	1818,28
Steel (rebar)	kg	0,013	1880,00	24,44	1 880,00	24,44
Diesel (power generator)	lt	1,5	70,10	105,15	70,10	105,15
Transport of materials (50 km average)	tkm	0,1	2383,45	238,35	2343,90	234,39
Labor costs				446,50		446,50
Direct costs				2 763,81		2 681,09
Indirect costs - 35% of direct costs				967,33		938,38
Total production costs				3731,14		3619,47
Reduction of costs during production phase				**-3%**		
Annual maintenance/repair costs (1%)				37,31		36,19
Production + reproduction + maintenance costs in 169 years				**10 036,76**		**12 849,12**
Potential life cycle cost savings				**22%**		

Table 15: Life cycle costs of tunnel precast concrete elements

The results of the life cycle cost analysis of the precast tunnel element demonstrate that potential savings during the whole life cycle of the element achieve 22 % despite the fact that the production costs of the EnDurCrete element are slightly higher (due to higher cement content – see table 11). This is caused by the significant increase in service life of EnDurCrete precast tunnel elements.

5.3.2. Life cycle costs of precast concrete bridge elements

Input	**Unit**	**Unit price (EUR)**	**BRIDGE ELEMENT LIFE CYCLE COSTS**			
			EDC TUNNEL C40/50		**TUNNEL C40/50 REF**	
Service life (years)			133		97	
Durability multiplication factor			1		1,37	
Total weight of element (kg)			593 260		584 020	
			Amount	**Price (EUR)**	**Amount**	**Price (EUR)**
Factory and equipment			1	649,38	1	649,38
EDC Tunnel C40/50	m^3	100,80	220	22 175,78		0,00
Tunnel C40/50 REF	m^3	96,61		0,00	220	21 255,08
Steel (rebar)	kg	0,013	58 000	754,00	58 000	754,00
Diesel (power generator)	lt	1,5	1 000	1 500,00	1 000	1 500,00
Transport of materials (50 km average)	tkm	0,1	29 663	2 966,30	29 201	2 920,10
Labor costs				5 926,00		5 926,00
Direct costs				33 971,46		33 004,56
Indirect costs - 35% of direct costs				11 890,01		115 51,59
Total production costs				45 861,46		44 556,15
Reduction of costs during production phase				**-3%**		
Annual maintenance/repair costs (1%)				458,61		445,56
Production + reproduction + maintenance costs in 133 years				**106 857,21**		**120 301,60**
Potential life cycle cost savings				**11%**		

Table 16: Life cycle costs of bridge precast concrete elements

The production costs of the EnDurCrete precast bridge element are also 3% higher in comparison to the reference because the tunnel concrete mix was also used in bridge use case scenario. In this case the potential savings during the whole life cycle achieve only 11 %, because the expected increase of service life of the EnDurCrete bridge element is smaller than in the tunnel use case scenario.

5.3.3. Life cycle costs of precast concrete offshore construction elements

Input	Unit	Unit price (EUR)	OFFSHORE ELEMENT LIFE CYCLE COSTS					
			EDC OFFSHORE		EDC OFFSHORE + acrylic paint		OFFSHORE REF	
Service life (years)			106		124		100	
Durability multiplication factor			1,17		1,00		1,24	
Total weight of element (kg)			122 122		122 141		121 151	
			Amount	**Price (EUR)**	**Amount**	**Price (EUR)**	**Amount**	**Price (EUR)**
Factory and equipment			1	71,08	1	71,08	1	71,08
EDC OFFSHORE	m^3	109,91	45,60	5 011,80	45,60	5 011,80		0,00
OFFSHORE REF	m^3	127,26					45,60	5 802,94
Steel (rebar)	kg	0,013	11 725	152,43	11 725	152,43	11 725	152,43
Electric energy	kWh	0,2	170	34,00	170	34,00	170	34,00
Diesel	lt	1,5	20	30,00	20	30,00	20	30,00
Transport of materials (50 km average)	tkm	0,1	6106,10	610,61	6107,05	610,71	6057,55	605,76
EDC acrylic paint	lt	9,7			18,70	181,39		
Labor costs				3 300,00		3 300,00		3 300,00
Direct costs				**9 209,92**		**9 391,41**		**9 996,21**
Indirect costs - 35% of direct costs				3 223,47		3 286,99		3 498,67
Total production costs				**12 433,40**		**12 678,40**		**13 494,88**
Reduction of costs during production phase				**8%**		**6%**		
Annual maintenance/repair costs (1%)				124,33		126,78		134,95
Production + reproduction + maintenance costs in 124 years				**29 964,48**		**28 399,62**		**33 467,30**
Potential life cycle cost savings				**10%**		**15%**		

Table 17: Life cycle costs of offshore precast concrete elements

The production costs of EnDurCrete precast element for offshore application were calculated to be 8 % lower in comparison to the reference product based on CEM I. The potential savings of 10 % can be achieved during the whole life cycle (the difference between potential savings during production phase and the whole life cycle is relatively small because of the relatively small difference in the expected service life).

The price of concrete with acrylic paint is slightly higher and therefore the potential savings during the production phase achieve only 6 %. However, the extended service life could lead to potential savings of 15 % during the whole life cycle.

5.3.3. Life cycle costs of precast concrete marine construction elements

Input	Unit	Unit price (EUR)	MARINE ELEMENT LIFE CYCLE COSTS									
			EDC MARINE C35/45		EDC MARINE C35/45 + nanoclay		EDC MARINE C35/45 + acrylic paint		EDC MARINE C35/45 + nanoclay + acrylic paint		MARINE C35/45 REF	
Service life (years)			98		139		104		146		84	
Durability multiplication factor			1,48		1,05		1,40		1,00		1,74	
Total weight of element (kg)			7 721		7 733		7 724		7 736		7 575	
			Amount	**Price**	**Amount**	**Price**	**Amount**	**Price**	**Amount**	**Price**	**Amount**	**Price**
Factory and equipment			1	14,50	1	14,50	1	14,50	1	14,50	1	14,50
EDC MARINE C35/45	m^3	81,96	3,11	254,91		0,00	3,11	254,91		0,00		0,00
EDC MARINE C35/45 + nanoclay	m^3	101,31		0,00	3,11	315,07		0,00	3,11	315,07		0,00
MARINE C35/45 REF	m3	69,07		0,00		0,00		0,00		0,00	3,11	260,86
Steel (rebar)	kg	0,013	80,00	1,04	80,00	1,04	80,00	1,04	80,00	1,04	80,00	1,04
Electric energy	kWh	0,2	20,00	4,00	20,00	4,00	20,00	4,00	20,00	4,00	20,00	4,00
Diesel	lt	1,5	2,00	3,00	2,00	3,00	2,00	3,00	2,00	3,00	2,00	3,00
Transport of materials (50 km average)	tkm	0,1	386,05	38,61	386,65	38,67	386,20	38,62	386,80	38,68	378,75	37,88
EDC acrylic paint	lt	9,7					2,59	25,12	2,59	25,12		
Labor costs				150,00		150,00		150,00		150,00		150,00
Direct costs				466,05		526,27		491,19		551,41		471,28
Indirect costs - 35% of direct costs				163,12		184,19		171,92		192,99		164,95
Total production costs				**629,17**		**710,47**		**663,11**		**744,40**		**636,22**
Difference of costs during production phase				**1%**		**-12%**		**-4%**		**-17%**		**0%**
Annual maintenance/repair costs (1%)				6,29		7,10		6,63		7,44		6,36
Production + reproduction + maintenance costs in 146 years				**1 849,76**		**1 783,27**		**1 896,49**		**1 831,23**		**2 035,92**
Life cycle cost savings compared to reference				**9%**		**12%**		**7%**		**10%**		

Table 18: Life cycle costs of marine precast concrete elements

The production costs of EnDurCrete precast element are almost identical to the costs of the reference product because the price of 1 m^3 of the EnDurCrete marine and reference mix is also almost identical. The price of the element with acrylic paint is slightly higher (4 % increase) whereas the price of the product including nanoclay corrosion inhibitors is supposed to be 12 % higher; increase of price of the production of marine precast element with nanoclays and acrylic protective paint is 17 %.

The potential savings during the whole life cycle achieve 9 % for pure EnDurCrete mix, 12 % for the mix with nanoclays, 7 % for the mix with protective acrylic paint and 10 % for the marine element with nanoclay corrosion inhibitors and protective acrylic paint.

6 Conclusions and recommendations

The most important results and conclusions of the first step of task 7.1, life cycle analysis at material level, are included once more in this report because it is supposed to be the final report of the whole WP7 of EnDurCrete project. The life cycle analysis of EnDurCrete cements at material level (cradle-to-gate) confirmed the correctness of the initial assumption that these materials cause **significantly lower environmental impacts in comparison to traditional materials.** The reduction in GWP is substantial as summarized in the following table (values per ton of material produced):

Global Warming Potential				
	CEM I 52.5R (REF)	**CEM II/C-M (S-LL) (EDC-D)**	**CEM II/C-M (S-V) (EDC-PL)**	**CEM VI (S-V) (EDC-PL)**
kg CO_2 eq.	825,8	469,1	471,6	425,5
% of CEM I	**100%**	**57%**	**57%**	**52%**

Table 19: GWP – EnDurCrete cements compared to CEM I

The **environmental performance of EnDurCrete concretes is significantly better than the reference concretes for the mixes for tunnel and offshore applications in all impact categories** (73% of reference for tunnel and 61% of reference offshore application in Global Warming Potential impact category). The performance of the marine concrete mix is slightly worse (109 % of CO_2 eq in Global Warming Potential impact category). This is caused mainly by the fact that the reference concrete has been produced with CEM III/A 42.5N, a cement containing even higher dosage of secondary materials than EnDurCrete CEM II/C (S-LL) – the reference CEM III contains 53% of slag while EnDurCrete CEM II contains only 38 % of this secondary material. However, EnDurCrete concretes should achieve significantly longer service life as reported in D4.4.

The results of the Life Cycle Analysis at material level reported in D7.2 were used as the main inputs to the Life Cycle Analysis at product level. The impacts during the production phase of the defined precast concrete element and the impacts during the whole life cycle were calculated for all use case scenarios and compared to the reference products based on standard commercially available materials.

The results confirm that the **EnDurCrete products achieve significant reduction in the most important impact category, Global Warming Potential**, when compared to products based on ordinary Portland cement (CEM I – offshore use case) and to products based on CEM II (tunnel and bridge use cases) already during the production phase; this reduction becomes even more significant when prolonged service life is considered. **The biggest potential improvement in GWP in comparison to the reference product can be achieved in tunnel use case – 18 % during the production phase and 56 % during the whole life cycle.**

If we compare the EnDurCrete products to the reference products based on CEM III (marine use case), the Global Warming Impacts during the production phase is slightly higher due to the reasons explained above but this is compensated by the increase in service life. The results of LCA covering the whole life cycle demonstrate the environmental viability of EnDurCrete products also in this use case scenario. **The marine use case also demonstrates positive impact of innovative acrylic paint and nanoclay corrosion inhibitors on the environmental impacts calculated for the whole life cycle.** The Global Warming Potential results for all scenarios during the production phase and complete life cycle are summarized in the tables 20 and 21.

<table>
<tr><th colspan="9">Global Warming Potential (in kg CO_{2eq}) comparison – production phase</th></tr>
<tr><th colspan="9">Tunnel precast element</th></tr>
<tr><th colspan="3">Tunnel C40/50 REF</th><th colspan="3">EDC Tunnel C40/50</th><th colspan="3">Reduction</th></tr>
<tr><td colspan="3">10 440</td><td colspan="3">8 595</td><td colspan="3">18%</td></tr>
<tr><th colspan="9">Bridge precast element</th></tr>
<tr><th colspan="3">Bridge C40/50 REF</th><th colspan="3">EDC Bridge C40/50</th><th colspan="3">Reduction</th></tr>
<tr><td colspan="3">193 323</td><td colspan="3">171 763</td><td colspan="3">11%</td></tr>
<tr><th colspan="9">Offshore precast element</th></tr>
<tr><th colspan="2" rowspan="2">OFFSHORE C50/60 REF</th><th colspan="4">EDC OFFSHORE</th><th colspan="3">EDC OFFSHORE + acrylic paint</th></tr>
<tr><th colspan="2">GWP</th><th colspan="2">Reduction</th><th colspan="2">GWP</th><th>Reduction</th></tr>
<tr><td colspan="2">42 835</td><td colspan="2">35 174</td><td colspan="2">18%</td><td colspan="2">35 227</td><td>18%</td></tr>
<tr><th colspan="9">Marine precast element</th></tr>
<tr><th rowspan="2">MARINE C35/45 REF</th><th colspan="2">EDC MARINE C35/45</th><th colspan="2">EDC MARINE + acrylic paint</th><th colspan="2">EDC MARINE C35/45 + nanoclay</th><th colspan="2">EDC MARINE + nanoclay + acrylic paint</th></tr>
<tr><th>GWP</th><th>Reduction</th><th>GWP</th><th>Reduction</th><th>GWP</th><th>Reduction</th><th>GWP</th><th>Reduction</th></tr>
<tr><td>806</td><td>865</td><td>-7%</td><td>873</td><td>-8%</td><td>957</td><td>-19%</td><td>964</td><td>-20%</td></tr>
</table>

Table 20: GWP – EnDurCrete products compared to reference, production phase

<table>
<tr><th colspan="9">Global Warming Potential (in kg CO_{2eq}) comparison – complete life cycle</th></tr>
<tr><th colspan="9">Tunnel precast element</th></tr>
<tr><th colspan="3">Tunnel C40/50 REF</th><th colspan="3">EDC Tunnel C40/50</th><th colspan="3">Reduction</th></tr>
<tr><td colspan="3">19 456</td><td colspan="3">8 615</td><td colspan="3">56%</td></tr>
<tr><th colspan="9">Bridge precast element</th></tr>
<tr><th colspan="3">Bridge C40/50 REF</th><th colspan="3">EDC Bridge C40/50</th><th colspan="3">Reduction</th></tr>
<tr><td colspan="3">264 921</td><td colspan="3">171 816</td><td colspan="3">35%</td></tr>
<tr><th colspan="9">Offshore precast element</th></tr>
<tr><th colspan="2" rowspan="2">OFFSHORE REF</th><th colspan="4">EDC OFFSHORE</th><th colspan="3">EDC OFFSHORE + acrylic paint</th></tr>
<tr><th colspan="2">GWP</th><th colspan="2">Reduction</th><th colspan="2">GWP</th><th>Reduction</th></tr>
<tr><td colspan="2">74 539</td><td colspan="2">57 692</td><td colspan="2">23%</td><td colspan="2">49 323</td><td>34%</td></tr>
<tr><th colspan="9">Marine precast element</th></tr>
<tr><th rowspan="2">MARINE C35/45 REF</th><th colspan="2">EDC MARINE C35/45</th><th colspan="2">EDC MARINE + acrylic paint</th><th colspan="2">EDC MARINE C35/45 + nanoclay</th><th colspan="2">EDC MARINE + nanoclay + acrylic paint</th></tr>
<tr><th>GWP</th><th>Reduction</th><th>GWP</th><th>Reduction</th><th>GWP</th><th>Reduction</th><th>GWP</th><th>Reduction</th></tr>
<tr><td>1 521</td><td>1 383</td><td>9%</td><td>1 318</td><td>13%</td><td>1 077</td><td>29%</td><td>1 033</td><td>32%</td></tr>
</table>

Table 21: GWP – EnDurCrete products compared to reference, complete life cycle

The most important factor affecting not only GWP but also other impact categories is the content of clinker. **It is therefore recommended to use the cements with the lowest possible clinker content (as soon as they fulfil the requirements on strength, workability, durability etc.) whenever possible.**

Both EnDurCrete cements used in the analyzed concrete mixes are approximately 10 % cheaper than reference CEM I (used in reference offshore concrete mix) and their price is very similar to the price of reference CEM II and CEM III used in tunnel and marine reference concrete mixes. Therefore only the production costs of EnDurCrete offshore precast elements are significantly lower than the production costs of reference (8 % savings for pure EnDurCrete and 6 % for EnDurCrete with protective acrylic paint). The production costs of EnDurCrete precast elements for tunnel, bridge and marine application are very similar to the reference ones; when corrosion inhibiting nanoclays and protective paints are applied, the production costs are even higher than reference.

The main difference in life cycle costs results from the improved durability and longer expected service life in comparison to the reference products. Total expected costs during the whole life cycle of all EnDurCrete products are lower than reference in all use case scenarios. The best result was achieved for the tunnel use case where the potential savings during the whole life cycle were calculated to be 22 %.

Finally, it should be again noted that the real life results for other products/use cases would strongly depend on the type of construction and local conditions and that the presented values can only be considered relevant for the specific constructions based on theoretical assumptions presented in the previous chapters.

7 Annex 1 - detailed results of Life Cycle Impact Assessment – all impact categories

This annex provides detailed results of LCIA presented in graphical form in chapter 4. While the graphs in chapter 4 are mainly intended to provide and display relative comparison between EnDurCrete and reference products, the detailed tables include the absolute values of all use case and material scenarios in all impact categories. The difference between EnDurCrete and reference precast concrete elements is also presented.

7.1 Production phase (cradle-to-gate)

Results of LCIA of precast tunnel elements – production phase				
Method:	**EPD (2018) V1.02**			
Impact category	**Unit**	**Tunnel C40/50 REF**	**EDC Tunnel C40/50**	**Reduction**
Acidification	kg SO_2 eq	36,5328	34,2933	6%
Eutrophication	kg PO_4--- eq	10,6810	10,5386	1%
Global warming (GWP100a)	kg CO_2 eq	10 440,0347	8 595,6747	18%
Photochemical oxidation	kg NMVOC	40,2579	37,0585	8%
Abiotic depletion, elements	kg Sb eq	0,0255	0,0250	2%
Abiotic depletion, fossil fuels	MJ	65 913,7609	63 068,1769	4%
Water scarcity	m^3 eq	1 998,0545	1 998,0545	0%
Ozone layer depletion	kg CFC-11 eq	0,000446	0,000446	0%

Results of LCIA of precast bridge elements – production phase				
Method:	**EPD (2018) V1.02**			
Impact category	**Unit**	**Bridge C40/50 REF**	**Bridge EDC C40/50**	**Reduction**
Acidification	kg SO_2 eq	683,5346	657,3546	4%
Eutrophication	kg PO_4--- eq	249,3769	247,7126	1%
Global warming (GWP100a)	kg CO_2 eq	193 323,6996	171 763,6996	11%
Photochemical oxidation	kg NMVOC	776,9539	739,5539	5%
Abiotic depletion, elements	kg Sb eq	0,6473	0,6412	1%
Abiotic depletion, fossil fuels	MJ	1 435 780,1792	1 402 516,1792	2%
Water scarcity	m^3 eq	49 392,7030	49 392,7030	0%
Ozone layer depletion	kg CFC-11 eq	0,008954	0,008954	0%

Results of LCIA of precast bridge elements – production phase						
Method:	**EPD (2018) V1.02**					
Impact category	**Unit**	**OFFSHORE REF**	**EDC OFFSHORE**	**Reduction**	**EDC OFFSHORE + acrylic paint**	**Reduction**
Acidification	kg SO_2 eq	146,1820	134,0527	8%	134,6545	8%
Eutrophication	kg PO_4--- eq	51,4844	50,1438	3%	50,2738	2%
Global warming (GWP100a)	kg CO_2 eq	42 835,0888	35 174,3425	18%	35 227,2960	18%
Photochemical oxidation	kg NMVOC	168,5037	151,1760	10%	151,3906	10%
Abiotic depletion, elements	kg Sb eq	0,1317	0,1304	1%	0,1454	-10%
Abiotic depletion, fossil fuels	MJ	298 145,4542	280 373,6252	6%	281 096,0655	6%
Water scarcity	m^3 eq	10 027,0337	10 027,0375	0%	11 069,7874	-10%
Ozone layer depletion	kg CFC-11 eq	0,001817504	0,00176	3%	0,00177	3%

Results of LCIA of precast bridge elements – production phase										
Method:	**EPD (2018) V1.02**									
Impact category	**Unit**	**MARINE C35/45 REF**	**EDC MARINE C35/45**	**Reduction**	**EDC MARINE C35/45 + EDC acrylic paint**	**Reduction**	**EDC MARINE C35/45 + nanoclay**	**Reduction**	**EDC MARINE C35/45 + nanoclay + EDC acrylic paint**	**Reduction**
Acidification	kg SO_2 eq	3,6231	3,7929	-5%	3,8764	-7%	4,2114	-16%	4,2948	-19%
Eutrophication	kg PO_4--- eq	0,8767	0,9083	-4%	0,9263	-6%	1,0272	-17%	1,0452	-19%
Global warming (GWP100a)	kg CO_2 eq	806,8411	865,9327	-7%	873,2747	-8%	957,5321	-19%	964,8741	-20%
Photochemical oxidation	kg NMVOC	3,5906	3,8332	-7%	3,8630	-8%	4,1259	-15%	4,1557	-16%
Abiotic depletion, elements	kg Sb eq	0,0019	0,0019	-2%	0,0040	-111%	0,0024	-27%	0,0045	-136%
Abiotic depletion, fossil fuels	MJ	5291,2361	5533,0697	-5%	5633,2367	-6%	7003,7924	-32%	7103,9594	-34%
Water scarcity	m^3 eq	169,8102	169,8102	0%	314,3885	-85%	181,3142	-7%	325,8925	-92%
Ozone layer depletion	kg CFC-11 eq	4,213E-05	4,511E-05	-7%	4,574E-05	-9%	0,00102	-2328%	0,00102	-2329%

7.2 Complete life cycle including service life

Results of LCIA of precast tunnel elements – complete life cycle				
Method:	**EPD (2018) V1.02**			
Impact category	**Unit**	**Tunnel REF C40/50**	**Tunnel EDC C40/50**	**Reduction**
Acidification	kg SO_2 eq	68,0527	34,3479	50%
Eutrophication	kg PO_4--- eq	19,8874	10,5498	47%
Global warming (GWP100a)	kg CO_2 eq	19 456,0824	8 615,9040	56%
Photochemical oxidation	kg NMVOC	74,9958	37,1209	51%
Abiotic depletion, elements	kg Sb eq	0,0476	0,0251	47%
Abiotic depletion, fossil fuels	MJ	123 203,9174	63 393,1556	49%
Water scarcity	m^3 eq	3 718,5413	1 999,2160	46%
Ozone layer depletion	kg CFC-11 eq	0,000837	0,000450	46%

Results of LCIA of precast tunnel elements – complete life cycle				
Method:	**EPD (2018) V1.02**			
Impact category	**Unit**	**Bridge REF C40/50**	**Bridge EDC C40/50**	**Reduction**
Acidification	kg SO_2 eq	936,6317	657,5023	30%
Eutrophication	kg PO_4--- eq	341,6859	247,7434	27%
Global warming (GWP100a)	kg CO_2 eq	264 921,0718	171 816,4480	35%
Photochemical oxidation	kg NMVOC	1064,6358	739,7170	31%
Abiotic depletion, elements	kg Sb eq	0,8869	0,6414	28%
Abiotic depletion, fossil fuels	MJ	196 8089,7303	1 403 351,7512	29%
Water scarcity	m^3 eq	67 672,1894	49 395,9694	27%
Ozone layer depletion	kg CFC-11 eq	0,012280	0,008964	27%

Results of LCIA of precast offshore elements – complete life cycle						
Method:	**EPD (2018) V1.02**					
Impact category	**Unit**	**OFFSHORE REF**	**OFFSHORE EDC**	**Reduction**	**OFFSHORE EDC + acrylic paint**	**Reduction**
Acidification	kg SO_2 eq	254,5242	220,0059	14%	188,6524	26%
Eutrophication	kg PO_4--- eq	89,5993	82,2516	8%	70,3968	21%
Global warming (GWP100a)	kg CO_2 eq	74 539,8282	57692,3728	23%	49 323,7237	34%
Photochemical oxidation	kg NMVOC	293,3278	248,0539	15%	212,0538	28%
Abiotic depletion, elements	kg Sb eq	0,2292	0,2139	7%	0,2035	11%
Abiotic depletion, fossil fuels	MJ	518859,3045	459894,8542	11%	393604,6126	24%
Water scarcity	m^3 eq	17447,2172	16444,5117	6%	15497,8477	11%
Ozone layer depletion	kg CFC-11 eq	0,00316	0,00289	9%	0,00248	22%

Results of LCIA of precast marine elements – complete life cycle

Method: **EPD (2018) V1.02**

Impact category	Unit	Marine C35/45 REF	EDC Marine C35/45	Reduction	EDC Marine C35/45 acrylic paint	Reduction	EDC Marine C35/45 + nanoclay	Reduction	EDC Marine C35/45 + nanoclay + acrylic paint	Reduction
Acidification	kg SO_2 eq	6,6325	5,8981	11%	5,6962	14%	4,6243	30%	4,4875	32%
Eutrophication	kg PO_4--- eq	1,5941	1,4037	12%	1,3531	15%	1,1208	30%	1,0854	32%
Global warming (GWP100a)	kg CO_2 eq	1 521,1421	1 383,2079	9%	1 318,7683	13%	1 077,6643	29%	1 033,6873	32%
Photochemical oxidation	kg NMVOC	6,6103	5,9874	9%	5,7056	14%	4,5557	31%	4,3685	34%
Abiotic depletion, elements	kg Sb eq	0,0036	0,0031	13%	0,0058	-63%	0,0027	24%	0,0047	-30%
Abiotic depletion, fossil fuels	MJ	11 063,8905	9798,7930	11%	9 410,1468	15%	8 498,5606	23%	8 194,0074	26%
Water scarcity	m^3 eq	302,7295	257,6122	15%	446,0999	-47%	194,8542	36%	330,1536	-9%
Ozone layer depletion	kg CFC-11 eq	9,543E-05	8,595E-05	10%	8,219E-05	14%	0,001088	-1040%	0,001036	-986%