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Environmental life cycle assessment of railway bridge materials using UHPFRC

Okoljska analiza in sanacija železniškega mostu z UHPFRC

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Abstract

The railway infrastructure is a very important component of the world's total transportation network. Investment in its construction and maintenance is significant on a global scale. Previously published life cycle assessment (LCA) studies performed on road and rail systems very seldom included infrastructures in detail, mainly choosing to focus on vehicle manufacturing and fuel consumption. This article presents results from an environmental study for railway steel bridge materials for the demonstration case of the Buna Bridge in Croatia. The goal of these analyses was to compare two different types of remediation works for railway bridges with different materials and construction types. In the first part, the environmental impact of the classical concrete bridge construction was calculated, whereas in the second one, an alternative new solution, namely, the strengthening of the old steel bridge with ultra-high-performance fibre-reinforced concrete (UHPFRC) deck, was studied. The results of the LCA show that the new solution with UHPFRC deck gives much better environmental performance. Up to now, results of LCA of railway open lines, railway bridges and tunnels have been published, but detailed analyses of the new solution with UHPFRC deck above the old bridge have not previously been performed.

Key words: railway, materials, life cycle assessment, bridge, environmental

Izvleček

Železniška infrastruktura je zelo pomemben del celotnega transportnega omrežja. Gradnja in vzdrževanje prog tudi v svetovnem merilu predstavlja velik strošek. Dosedanje LCA študije (analiza življenjskega cikla), izvedene na cestnih in železniških omrežjih zelo redko vključujejo podrobno analizo infrastrukture, večinoma se osredotočijo na porabo goriva za proizvodnjo in pogon vozil. V prispevku so predstavljeni rezultati iz okoljske študije za uporabljene materiale železniškega mostu »Buna most« na Hrvaškem. Cilj te analize je bil primerjati dve različni metodi sanacije starega mostu s poudarkom na uporabi različnega materiala in za različne tipe konstrukcij. V prvem delu je bil izračunan vpliv na okolje za klasično betonsko konstrukcijo mostu, medtem ko je v drugem prikazan izračun za novo alternativno rešitve sanacije mostu; ojačanje starega jeklenega mostu s UHPFRC (mikroarmiran beton zelo visokih zmogljivosti) ploščo. Rezultati LCA kažejo, da ima nova rešitev z UHPFRC ploščo veliko manjši vpliv na okolje kot klasična betonska konstrukcija. Do sedaj objavljene LCA študije so se večinoma osredotočale na analize gradnje in sanacije odprtih železniških prog, železniških mostov in predorov. Za novo alternativno metoda, sanacije železniškega mostu z UHPFRC ploščo, okoljska LCA analiza do sedaj še ni bila objavljena.

Ključne besede: železnica, materiali, LCA, most, okolje

Introduction

Railway infrastructure is significant all over the world and is a key component of world transport as a whole, moving both people and freight. Investment for construction and maintenance of railways is large, and the system needs to be built to withstand a long service life. Railway infrastructure is a complex system and therefore, it is difficult to analyse. Environmental impacts of transport are widely recognised by society, but most of the research is focussed on the operation of vehicles (direct energy use). However, it seems that a significant part of energy consumption is derived from the construction, maintenance and operation of infrastructure; manufacture and maintenance of vehicles; as well as fuel production. All these activities are also called indirect energy use [1]. Federici [2] noted that LCA studies published on road and rail systems very seldom include infrastructures in detail, mainly focussing on the construction of vehicles and their fuel use. Thus, we may assume that if vehicles become more energy efficient, then energy use and greenhouse gas emissions during the indirect phases of transport infrastructure might increase their shares in the environmental impact of transport throughout its life cycle.

In this study, research on environmental LCA analysis of innovative rehabilitation methods for existing steel bridges is presented. The research is based on the case study of a rehabilitation project of a non-ballasted steel bridge – Buna Bridge – in Croatia. The innovation of this research lies in the use of ultra-high-performance fibre-reinforced concrete (UHPFRC) for the construction of the composite deck. The reason for using this material is, apart from its demonstrated mechanical properties and extraordinary durability, smaller deck thickness is required than with normal concrete. This means less added dead load for the existing structure (girders), and it minimises problems related to adjustment of the substructure (track) geometry on both sides of the bridge to the new height of the bridge. In addition, as no traditional reinforcement is needed, the construction of a UHPFRC deck is thinner in relation to the standard reinforced concrete deck. In this way, the railway line will be closed to traffic for a shorter period of time. The described strengthening concept has been evaluated for a 60-year-old bridge superstructure, which has been removed from its original location on a mainline railway route in Croatia and then tested in the laboratory.

The existing European Union (EU) railway network has many bridges, built more than 50 years ago, which were not designed for current loads and high-speed trains. These bridges were largely made from hot rolled steel or cast iron with riveted connections. For economic and environmental reasons, it would be a great benefit to extend the service life of these bridges, instead of demolition or reconstruction. The main idea behind strengthening existing steel bridges is consideration of the possibility of adding a load-bearing deck above the main girders without replacing them [3–5]. Conversion of the metal section to a composite cross-section raises the centre of gravity so that the new cross-section can carry additional loads. In addition, the concrete deck stiffens the upper steel flange and thus eliminates the problem of stability of the compressed part of the cross-section.

The LCA methodology proposed by Lounis [6] for the sustainable design of highway bridges was used to compare two bridge deck designs: a high-performance concrete (HPC) bridge deck and a conventional concrete bridge deck. It was found that the CO_2 emissions due to cement production were almost three times less important for HPC than for conventional concrete. The conclusions from the literature review were very different according to the goals and scopes of the studies. Concrete and timber bridges appear to provide better environmental performance than steel or composite concrete–steel bridges. The material production stage usually has the greatest impact on the environment, followed by the maintenance and repair stages. Improvements in material design and the use of recycled materials are important if overall emissions are to be reduced.

LCAs have been already applied for the Sherbrooke Footbridge in Canada, the Kassel Gärtnerplatz [7] Footbridge in Germany and the Wapello road bridge in the USA. The LCA was performed using the Swiss process–and-material database Ecoinvent. The ecological effects of global warming (total 100-year global warming potentials: GWP100), depletion of the stratospheric ozone (ozone depletion potential: ODP), photo-oxidant formation (photochemical oxidants creation potential: POCP), acidification (acidification potential: AP) and eutrophication (nutrification potential: NP) were adopted as impact category indicators according to the Dutch Institute of Environmental Sciences (CML) method. The results show that UHPC used in the Sherbrooke Footbridge and the Gärtnerplatz Footbridge causes approximately 60–85% of the environmental impact in comparison with normal concrete. In addition, appreciable contributions are made by the steel truss and the prestressing of the UHPC. In case of the Wapello road bridge, the contribution of UHPC to environmental impact was from 44 to 74%.

The concept of application of UHPFRC for the rehabilitation of structural members was proposed by Brühwiler [8]. UHPFRC, characterised by a very low water/binder ratio, high binder content and an optimised fibrous reinforcement, provides the structural engineer with a unique combination of extremely low permeability, high strength and tensile strain-hardening material. UHPFRC is perfectly suited to the rehabilitation of reinforced concrete structures in critical zones subjected to an aggressive environment and significant mechanical stresses, to provide long-term durability and thus avoid multiple interventions on structures during their service life. An extensive research-and-development activity during the European Commission's Fifth Framework Programme for Research and Technological Development (FP5) project SAMARIS and various full-scale applications on bridges in Switzerland [8–11] have demonstrated that UHPFRC technology is mature for cast in situ applications of rehabilitation using standard equipments. Since the first full-scale application of UHPFRC for the rehabilitation of a bridge took place within the SAMARIS project [10], numerous applications have followed [12]. Considerable efforts have been invested during the FP6 project ARCHES [13] to demonstrate the applicability of this innovative rehabilitation technique. Special emphasis was placed on the use of locally available components, improved rheological properties (tolerance to slope of the substrate at fresh state), processing techniques and reducing the GWP of the UHPFRC.

In this report, the LCA for a demonstration project in Croatia has been made for the FP7 project SmartRail, which – besides the renovation methods of railway bridges – includes also renovation methods for transition zones and open lines [14]. The goal of this analysis is to compare the classical concrete bridge construction with an alternative new solution, the strengthening of an old steel bridge with UHPFRC deck. In the future, the application of environmental LCA analyses for railway infrastructure can give an opportunity for green technology to support sustainable development. For example, the Swedish Railways Company has set the target of cutting the emissions of CO_2 to zero [15].

General methodology

LCA is a technique used to assess the environmental impacts associated with all the stages of a product's life from cradle to grave (i.e. from raw material extraction through materials processing, manufacture, distribution, use, repair, maintenance and disposal/recycling). LCA can help to avoid a narrow outlook on environmental concerns by the following actions:

- Compiling an inventory of relevant energy and material inputs, as well as environmental releases;
- Evaluating the potential impacts associated with identified inputs and releases; and
- Interpreting the results to help make a more informed decision.

LCA can assist in identifying opportunities and encouraging improvement in the environmental performance of products at various points in their life cycle and informing decision-makers in industry, government or non-government organisations.

The International Organization for Standardization (ISO) standard 14040:2006 [16, 17] and the Product Category Rules (PCRs) for railways [18] have been used in the LCA.The European Standard (EN) equivalent of ISO14040:2006 standard (Environmental management – Life cycle assessment – Principles and framework) on LCA gives the principles of the analyses and details on the techniques. LCA consists of four steps:

1. Definition of goal, scope and functional unit

The goal and scope of an LCA shall be clearly defined and shall be consistent with the intended application. Due to the iterative nature of LCA, the scope may have to be refined during the study. The functional unit is the quantified performance of a product system for use as a reference unit.

2. Life cycle inventory (LCI)

LCI involves creating an inventory of flows from and to nature for a product system. Inventory flows include inputs of water, energy and raw materials, as well as releases to air, land and water.

3. Life cycle impact assessment (LCIA)

This phase of LCA is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the produce and evaluating the significance of the potential environmental impacts based on the LCI flow results.

4. Interpretation of the study

This phase of LCA involves evaluation of the findings of either the inventory analysis or the impact assessment, or both, in relation to the defined goal and scope in order to reach conclusions and recommendations. Various techniques are used to identify, quantify, check and evaluate information from the results of the LCI and/or the LCIA. The results from the inventory analysis and impact assessment are summarised during the interpretation phase.

LCI is the most important step in performing LCAs. Data is collected for the background and foreground systems. Background data includes data on generic materials, energy, materials and waste management system. Usually, 80% of data is readily available in databases. Foreground data refers to specific data such as a particular product system or a particular specialised production system. In many cases, it has to be collected from companies.

The PCRs describe the rules for the assessment of environmental performance of Rail Transport and Railway Infrastructure within the Environmental Product Declaration (EPD) framework. The PCR describes how to perform the underlying LCA and other environmental assessments for the development of an EPD according to ISO 14025 and ISO 14040.

The PCR specifies rules separately for Rail Transport and Railway Infrastructure. The rules that are specified for Railway Infrastructure also make it possible to develop EPDs for the following:

— Specific railway infrastructure systems
— Parts of a railway infrastructure system, e.g. a railway tunnel or a bridge

The PCR document may also be used to develop data for comparison of different system solutions for railway infrastructure or transports. It may also be used to develop data for a specific system in order to assess and optimise the environmental performance of, for instance, different materials used in the infrastructure.

For the LCA calculation, it is necessary to define the following:

1. Functional unit

The declared unit for railway infrastructure is defined as 1 km of main line.

2. Boundaries for railway infrastructure:

For railway infrastructure, all processes that are needed to construct, operate and maintain the railway shall be included.

3. Boundaries in time

As per PCR, 60 years were used as the calculation period for the environmental impact from railway infrastructure. That is the same period of time that is used in socioeconomic calculations for infrastructure projects. The time period should be regarded as depreciation time for the environmental impact from new infrastructure. This gives that the annual environmental load from parts of the infrastructure that is assumed to have longer physical lifetime than 60 years (for example tunnels and bridges) will be overestimated.

According to PCR, processes connected to the building of the infrastructure, e.g. extraction of raw materials and construction work, shall be omitted for infrastructure older than 60 years.

4. Cutoff rules

According to PCR, processes/activities that altogether do not contribute to more than 1% of the total environmental impact for any impact category are allowed to be omitted from the inventory analysis. The “1% rule” should be based on the inflow of materials to the system,

provided no exceptional environmental concerns exist.
5. Recycling
For both resource inputs that come from recycling processes and waste outputs that go to recycling processes, no allocation should be made. This means that inputs of recycled materials or energy to a product system shall be included in the dataset without adding their environmental impact caused in "earlier" life cycles. However, potential environmental impact from recycling processes (e.g. collection, treatment etc.) shall be included in the system under study.

Impact categories

Pollutant emissions and resources of use were taken into consideration. Pollutant emissions are analysed as follows:

Global warming (GWP 100 years)
[kg CO_2 equivalents],
Climate change is caused by the greenhouse effect, which is induced by emission of greenhouse gases into the air. The GWP is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide. GWP is calculated over a specific time interval, commonly 20, 100 or 500 years. GWP is expressed as a factor of carbon dioxide (whose GWP is standardised to 1).

Acidification [kg SO_2 equiv.]
Acidification is caused by direct outlets of acids or by outlets of gases that form acid on contact with air humidity and are deposited to soil and water. Examples are sulphur dioxide (SO_2), nitrogen oxides (NO_x) and ammonia (NH_3). Acid depositions have negative impacts on natural ecosystems and the man-made environment including buildings. The main sources for emissions of acidifying substances are agriculture and combustion of fossil fuel for electricity production, heating and transport.

Ozone depletion [kg chlorofluorocarbon 11 equiv.]
This parameter represents the integrated change in total stratospheric ozone per unit mass emission of a specific compound, relative to the integrated change in the total ozone per unit mass of a reference emission (e.g. chlorofluorocarbon [CFC]-11)

Photochemical oxidant formation
[kg ethene equiv.]
This includes chemical reactions brought about by the light energy of the sun. The reaction of NO_x with hydrocarbons in the presence of sunlight to form ozone is an example of a photochemical reaction.

Eutrophication [kg $(PO_4)^{3-}$ equiv.]
The NP is set at one for phosphate (PO_4). Other emissions also influence eutrophication, notably NO_x and ammonium.

Photochemical ozone creation potential
[kg ethene equiv.]
The photochemical oxidation, very often defined as summer smog, is the result of reactions that take place between NOx and volatile organic compounds (VOCs) exposed to UV radiation. The POCP is described by reference to C_2H_4.

Case study of LCA analysis for the Buna Bridge in Croatia

The LCA analysis was performed for the demonstration site in Croatia, namely, the Buna bridge, which is situated on the railway track M104 Novska–Sisak–Zagreb at km 398+422. For the project SmartRail [19], the bridge has been replaced by new concrete bridge instead of the old steel one (Figure 1).
For the alternative method, in the IGH and ZAG laboratories, the old steel bridge was tested and numerically analysed with a UHPFRC plate. With the developed LCA tool, calculations for the new concrete bridge as well as the old steel bridge reinforced with the UHPFRC deck were performed (Figure 2).
The procedure used for the LCA of the two different bridges in this study is shown in Figure 3. In the first stage of the procedure, the boundary conditions are defined, and then the LCI is formulated for a new concrete railway bridge and a new solution for the renovation of steel bridge with the UHPFRC plate. Based

Figure 1: *Old steel bridge.*

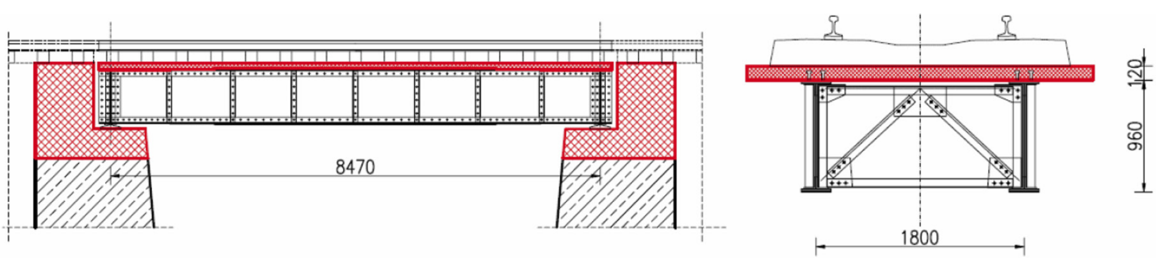

Figure 2: *Concept of strengthening of the old steel bridge with the UHPFRC deck.*

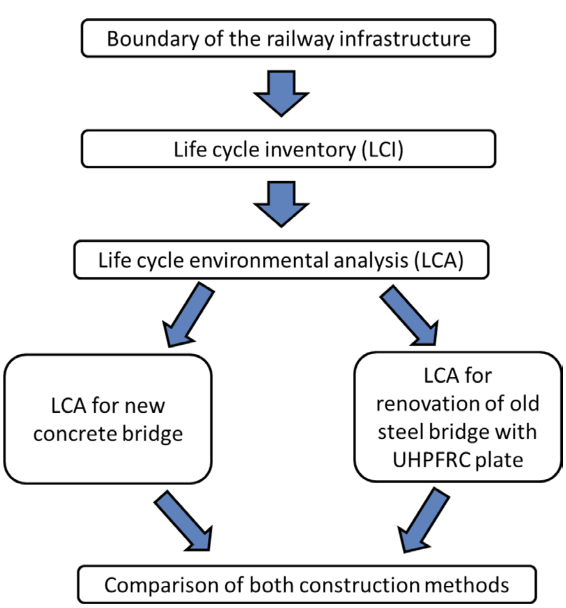

Figure 3: *Stages of the analyses for the railway bridges.*

on the LCI, calculations are performed for both types of railway bridges, and at the end, these are compared with regard to the emissions that are prescribed in the PCR document. The model, which takes into account material production, renewal work, maintenance and end of life (EOL), is presented in Figure 4. For each of these stages, the specifics of the used materials and machines are defined. For the LCA calculation, the CML 2001 – ver. Nov. 2010 midpoint methodology was used. This methodology, which was developed at the Institute of Environmental Sciences at the University of Leiden in the Netherlands, is the most widely used and frequently considered to be the most complete methodology. It uses primarily European data to derive its impact factors. Almost all the inventory data are from the GABi 4.4 [20] database – Ecoinvent ver. 2.2, except for data on machinery gas emissions, which was obtained from the operators of the Slovenian and Croatian Railways.

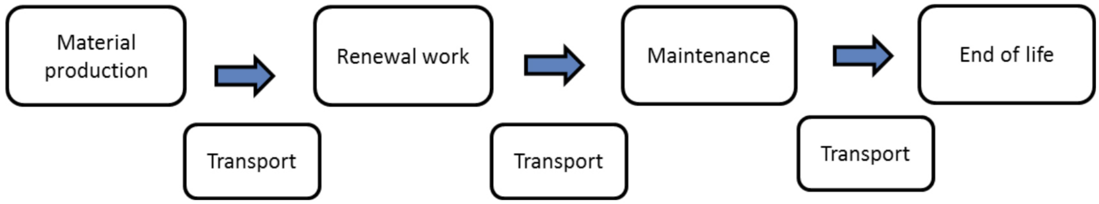

Figure 4: *LCA model for railway bridges.*

Assumptions and limitations

The functional unit for open track construction is the length of the railway bridge, which is in our case 11.8 m. In our study case, we have taken the prescribed 60-year period from the PCR for rail. For recently built infrastructure that is less than 60 years old, the environmental load from materials and building processes shall be included in the proportion $x/60$, where x is the age of the infrastructure.

According to PCR, for the LCA analysis of open track construction, all of the system boundaries during the 60-year period are not included. The reason is because the main purpose of our study is to find the difference in renovation works of railway steel bridge between two scenarios:

- Demolition of the old steel bridge and construction of the new concrete bridge
- Strengthening of the old steel bridge with the UHPFRC plate

For the test field in Croatia, the boundary conditions are defined in such a way as to find the difference between the construction of the new concrete bridge and strengthening of the old bridge with the UHPFRC plate. In both cases, the abutments are not changed. Boundaries had to be defined for the upper track part of the railway and included renovation of the bridge and its maintenance.

Maintenance of the bridge includes all the functions needed for operating the infrastructure needed during the lifetime prescribed for the analysis. Operation process is not included in the presented calculation.

Data not included in the calculation in accordance with the 1% threshold rule are as follows:

- Nylon pads (represents negligible contribution to overall mass input)
- Rail welding process (represents negligible contribution to overall energy and mass input)

Technical description and input data for the analysis

The technical description of the material and production, which are used for the LCA, is presented for railway track in Table 1, for concrete bridge in Table 2 and for the UHPFRC plate in Table 3. The related environmental gas emissions and use of energy were obtained from the Ecoinvent ver. 2.2 database.

For the ballast, the limestone material is used as it is a usual material in Croatia. The material is transported from the nearest quarry with truck trailer. On the ballast, there are prestressed reinforced concrete sleepers. The types of steel rails used are UIC 60 with the fastening system Skl12 for system 49E1 with elastomeric pads. Data about the used materials was obtained from the Ecoinvent ver. 2.2 database.

For the renewal works, machines for digging, compacting, tamping, profiling, milling and

Table 1: *Material characteristics for the railway track system*

	Description	Material	Dimensions
Ballast	Unbound material under the sleepers	Unbound material, 0/32 mm gravel, density 2000 kg/m^3	Thickness of layer 0.3 m, average width 3.95 m
Sleepers	Prestressed reinforced concrete sleepers	Concrete C 30/37 Steel rebars	280 kg per sleeper: concrete 274 kg, steel 6 kg
Rails	UIC 60	Steel	60.4 kg/m
Fastening system	SKL-14 for system 49E1	Steel	2.4 kg per sleeper
Elastomeric pads	SKL-14 for system 49E1	Ethylene–vinyl acetate	1 kg per sleeper

Table 2: *Material characteristics for concrete bridge*

	Description	Material	Dimensions
Concrete	C 30/37	Concrete	73500 kg
Panelling oil		Oil	1 kg per construction
Waterproof insulation	Waterproof insulation	Bitumen	65.2 kg
Profiles and reinforcement	Profiles and reinforcement	Steel	Steel profiles 14541 kg Reinforcement 2090.1 kg

Table 3: *Material characteristics for bridge with the UHPFRC deck*

	Description	Material	Dimensions
UHPFRC deck	UHPFRC	Concrete	8000 per bridge construction
Panelling oil		Oil	1 kg per construction

Table 4: *Renovation work and maintenance work*

Machine	Activity	Database/ data	Fuel consumption
Excavator 100 kW	Extraction of unbound material from the quarry	Ecoinvent	4 L/h
Tamping rammer	Compaction of embankment and embankment cement stabilisation-roller	Railway operator	1 L/h
Ballast tamper	Ballast stabilisation	Railway operator	60 L/layer
Railway profiling machine	Rail profiling	Railway operator	40 L/km
Railway stabilisation machine	Track stabilisation	Railway operator	1 L/km
Railway milling machine	Rail milling	Railway operator	100 L/km
Auto crane	Lifting of old bridge, construction of new bridge	Ecoinvent	8.3 kg/h

stabilisation are needed. The renewal phase takes into account the diesel fuel burned in this construction machinery. A description of the machines used, together with data about their individual fuel consumption, is presented in Table 4. The data about fuel consumption was supplied, in nearly all cases, by the Slovenian and Croatia railway operators.

The same machines are used for maintenance works. The period of maintenance is determined by the railway operator and also depends on the lifetime of the individual materials (Table 5). The regular maintenance by Croatian Railways includes ballast tamping, rail profiling, stabilisation and milling. These works are performed every 2 years, except for rail milling, which is performed every 4 years. Construction with the UHPFRC plate does not have the ballast layer, just sleepers on the plate, and accordingly, the maintenance work is much lower.

At the EOL stage, the gravel and steel material are extracted and sorted for different waste treatment methods. The unbound material that is primarily used for ballast, as well as the unbound material for the embankment and sub-ballast layer, will, at the end of their lives, be mostly used to construct service roads. For this reason, the recycling rate will be quite high, approximately 90%. The remainder of the material will be transported to a landfill site for inert material. Data about gas emissions for landfill was obtained from the Ecoinvent ver. 2.2 database.

In the case of the rails and the fastening system, an 80% recycling rate was assumed (according to data provided by the railway operator). It is assumed that the remaining material will be transported to a landfill site for steel inert material. Data about gas emissions for the landfill was again taken from the Ecoinvent ver. 2.2 database.

Table 5: *Maintenance of the bridges*

	Lifetime (in years)				Maintenance interval (in years)				
	Ballast	Sleepers	Rails and fastening system	Elastomeric pads	Ballast tamping	Ballast profiling	Ballast stabilisation	Rail milling	Painting, sandblasting
New concrete bridge	25	20	40	40	2	2	2	4	0
Renovation with UHPFRC deck	25	20	40	40	0	0	0	0	10

Table 6: *Characteristics of transport, maintenance and end of life*

	Construction	Type of transport	Transport distance	Maintenance	End of life
Ballast	The maximum thickness of each compacted layer is 30 cm	Railway	The nearest quarry is located at a distance of 50 km	Tamping machine Stabilising machine	Transport: Train 20 km Recycling: 90%
Sleepers	Manual installation	Railway	50 km	None (replacement after reference service lifetime)	Transport: Train 20 km Recycling: 80%
Rails	Manual installation	Railway	400 km	Rail milling machine	Transport: Train 20 km Recycling: 80%
Fastening system	Manual installation	Railway	400 km	Replacement after reference service lifetime	Transport: Train 20 km Recycling: 80%
Elastomeric pads	Manual installation	Truck	200 km	Replacement after reference service lifetime	Transport: Train 20 km Recycling: 80%
Concrete bridge					
Concrete	Auto crane Crane	Truck	50 km	Replacement after reference service lifetime	Transport: Train 20 km Recycling: 80%
Waterproof insulation	Waterproof insulation	Bitumen	100 km	Replacement after reference service lifetime	Transport: Train 20 km Recycling: 80%
Profiles and reinforcement	Profiles and reinforcement	Steel	400 km	Replacement after reference service lifetime	Transport: Train 20 km Recycling: 80%
Steel bridge with HUPFRC deck					
UHPFRC	Crane	Truck	100 km	Replacement after reference service lifetime	Transport: Train 20 km Recycling: 80%

Table 7: *Normalisation factors [21]*

Impact category	Unit (equivalents/year)	Normalisation factor (equivalents/year)
Acidification	kg $SO_{2\ eq}$	2.81E+10
Eutrophication	kg $(PO)_4^{3-}{}_{eq}$	1.32E+10
Global warming	kg $CO_{2\ eq}$	5.02E+12
Ozone depletion	kg CFC-11 $_{eq}$	6.79E+6
Photochemical oxidation	kg Ethene $_{eq}$	8.48E+9

In the case of the other materials (i.e. sleepers, elastomeric pads), an 80% recycling rate was assumed in the calculations.

The characteristics involving transport, maintenance and EOL are presented in Table 6 for both methods of construction.

Results and discussion

Taking into account all the presented input data and the calculation methods according to the described procedures, the environmental impact related to the production of material, the renewal works and maintenance, as well as EOL was calculated. According to the PCR, five impact categories oriented at the midpoint of human health and the ecosystem need to be investigated: global warming (GWP), acidification (AP), ozone depletion (ODP), photochemical oxidant formation (POCP) and eutrophication (EP). The CML 2001 assessment method was applied, and the results were normalised using the normalisation factor proposed in CML 2001. In Table 7, the normalisation factors are presented for all of the impact categories. According to the PCR, ozone depletion should be calculated for CFC-11equiv., which is not supported by CML 2001. For this reason, this parameter was assumed based on the recommendations made by Sleeswijk et al. [21].

The calculation was performed for the following two different scenarios:

— Old steel bridge is removed and new concrete bridge is constructed
— Old steel bridge is strengthened with a thin UHPFRC deck above it

The calculated environmental impact for the new concrete bridge is presented in Table 8 and for the old bridge with UHPFRC plate in Table 9. Figure 5 shows the normalised results of the environmental impact for both types of constructions for railway bridges. The results for material production, renewal works, maintenance and EOL also take into account transport at every stage. The results of the LCA show that the new solution with UHPFRC deck above the old steel bridge gives better environmental performance in the impact categories: AP, EP, GWP and POCP. All five impact categories have higher values in the case of construction of concrete bridge. Especially in the case of GWP, the differences are quite clear. The GWP resulting from the strengthening renewal works using UHPFRC deck is lower by 76% relative to that for the concrete bridge construction. The result is in correlation with the LCA analysis for the Sherbrooke Footbridge and the Gärtnerplatz Footbridge [7], wherein the calculated reduction was approximately 60–85% in comparison with normal concrete.

A comparison between the material production, renewal works, maintenance and EOL shows that material production has the highest impact in the case of both types of bridges. The environmental impact for the railway concrete bridge is presented in Figure 6 and for the bridge with UHPFRC plate in Figure 7.

If we look closer at the material production for the concrete bridge, it can be seen that the GWP emissions produce the higher environmental impact. The highest value of GWP emission is for steel girder and concrete, which represent 85% of the total gas emission during material production (Figure 8). In comparison with the solution with UHPFRC, additional steel girders are not needed.

Table 8: *Pollutant emissions during construction of new concrete bridge*

	AP	EP	GWP	ODP	POCP
	[kg SO2 equiv]	[kg (PO4)3- equiv]	[kg CO2 equiv]	[kg CFC 11 equiv]	[kg Ethene equiv]
Total	**8,21866E-09**	**3,2137E-09**	**1,21131E-08**	**1,41467E-09**	**3,45214E-09**
Material production	5,27355E-09	1,09774E-09	1,00422E-08	3,81039E-12	2,32118E-09
Production of concrete UHPFRC plate	0	0	0	0	0
Production of concrete plate	4,24284E-10	1,55985E-10	1,69804E-09	8,54496E-14	1,6378E-10
Production of steel profiles	4,23269E-09	7,94278E-10	6,68608E-09	8,64599E-14	1,89387E-09
Production of steel reinforcement for concrete plate	2,6279E-10	4,43601E-11	5,27825E-10	3,41554E-12	1,34642E-10
Production of hydroisolation above concrete slab	4,97457E-12	8,32639E-13	9,66995E-12	3,47036E-16	2,94715E-12
Production of ballast	6,33846E-11	1,8917E-11	2,04609E-10	6,2229E-14	1,82421E-11
Production of rails	2,61129E-10	4,66901E-11	5,16188E-10	1,33095E-13	6,79324E-11
Production of fastening system	1,74377E-11	3,11787E-12	3,447E-11	8,8878E-15	4,53639E-12
Production of sleepers	3,42606E-12	1,67784E-11	1,82649E-10	9,19135E-15	1,7617E-11
Production of elastomeric pads	3,42606E-12	1,67784E-11	1,82649E-10	9,19135E-15	1,7617E-11
Renewal work	4,6514E-10	8,52785E-10	1,27856E-12	1,41076E-09	7,68051E-13
Transport of materials and machines	6,33064E-13	8,51896E-10	1,35179E-21	1,41076E-09	3,46832E-17
Operating of machines during build-in process	4,64507E-10	8,89323E-13	1,27856E-12	1,58053E-17	7,68017E-13
Maintenance	2,38057E-09	1,2269E-09	1,76389E-09	2,18048E-14	1,05955E-09
Transport of ballast and machines	2,27712E-09	1,17358E-09	1,68724E-09	2,08572E-14	1,0135E-09
Renewal of steel sections	0	0	0	0	0
Operating of machines during maintenance	1,0345E-10	5,33158E-11	7,66512E-11	9,47544E-16	4,60434E-11
End of life	9,94051E-11	3,62822E-11	3,05784E-10	8,31212E-14	7,06425E-11

Table 9: *Pollutant emissions from strengthening of the old bridge with UHPFRC deck*

	AP	EP	GWP	ODP	POCP
	[kg SO2 equiv]	[kg (PO4)3- equiv]	[kg CO2 equiv]	[kg CFC 11 equiv]	[kg Ethene equiv]
Total	**2,63E-09**	**1,04E-09**	**2,94E-09**	**1,13E-10**	**9,22E-10**
Material production	6,78E-10	1,74E-10	1,78E-09	1,75E-11	2,50E-10
Production of concrete UHPFRC plate	3,93E-10	9,09E-11	8,64E-10	1,74E-11	1,42E-10
Production of concrete plate	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Production of steel profiles	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Production of steel reinforcement for concrete plate	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Production of hydroisolation above concrete slab	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Production of ballast	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Production of rails	2,61E-10	4,67E-11	5,16E-10	1,33E-13	6,79E-11
Production of fastening system	1,74E-11	3,12E-12	3,45E-11	8,89E-15	4,54E-12
Production of sleepers	3,43E-12	1,68E-11	1,83E-10	9,19E-15	1,76E-11
Production of elastomeric pads	3,43E-12	1,68E-11	1,83E-10	9,19E-15	1,76E-11
Renewal work	4,44E-10	9,41E-11	4,43E-22	9,56E-11	1,01E-18
Transport of materials and machines	4,78E-14	9,41E-11	4,43E-22	9,56E-11	1,01E-18
Operating of machines during build-in process	4,44E-10	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Maintenance	1,50E-09	7,65E-10	1,12E-09	2,40E-14	6,62E-10
Transport of ballast and machines	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Renewal of steel sections	1,74E-11	2,09E-12	2,07E-11	1,05E-14	3,43E-12
Operating of machines during maintenance	1,48E-09	7,63E-10	1,10E-09	1,36E-14	6,59E-10
End of life	1,37E-11	4,83E-12	4,21E-11	9,89E-15	9,75E-12

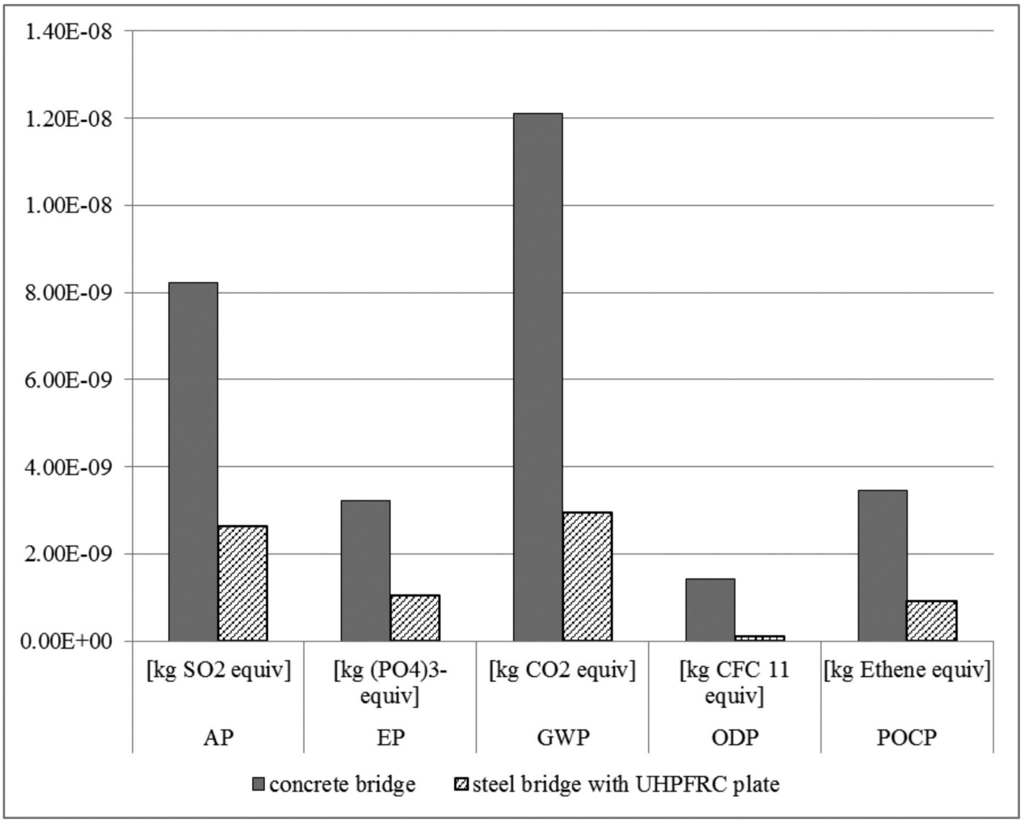

Figure 5: *The environmental impact (normalised) of the concrete bridge and steel bridge strengthened with UHPFRC deck.*

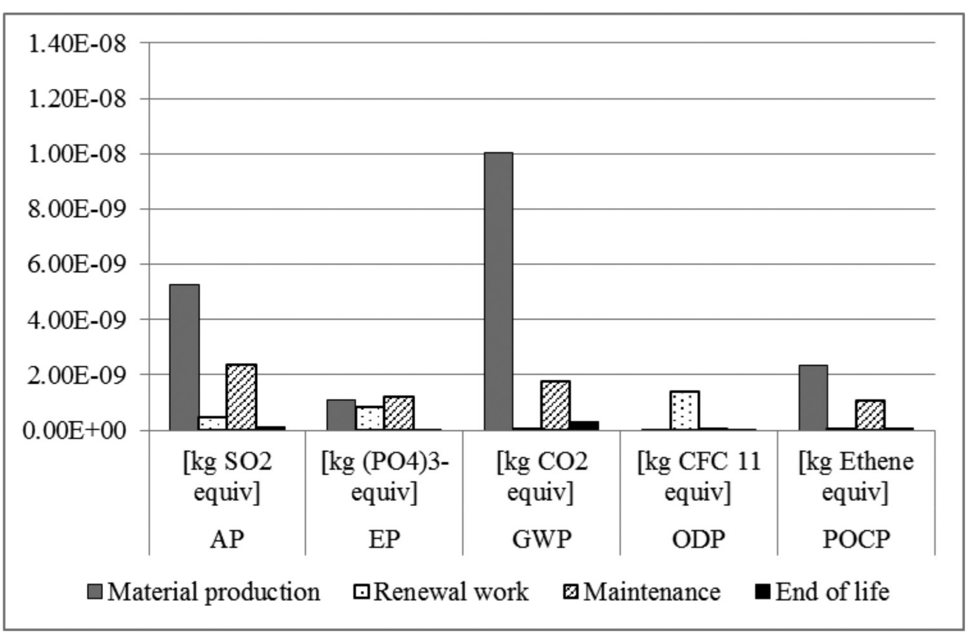

Figure 6: *The normalised environmental impact for the concrete bridge.*

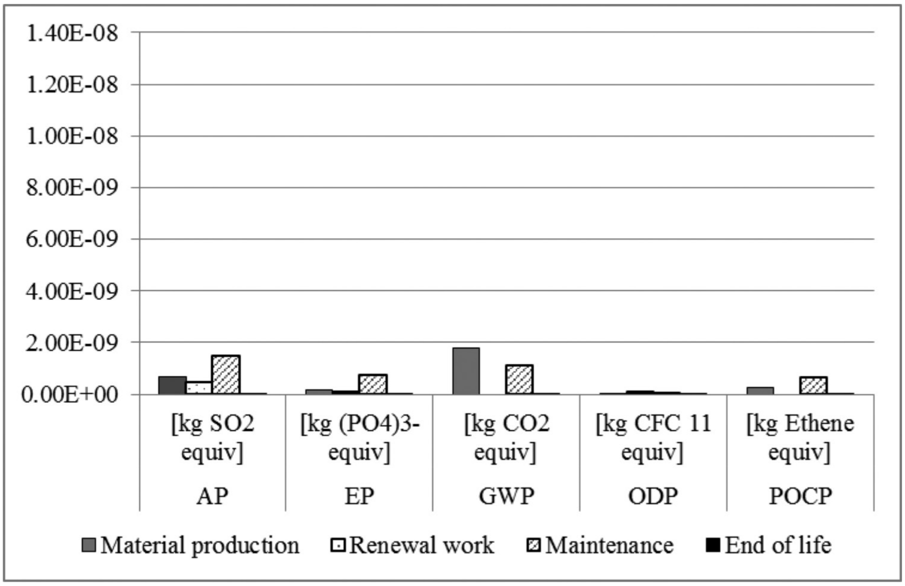

Figure 7: *The normalised environmental impact for the strengthened bridge with UHPFC deck.*

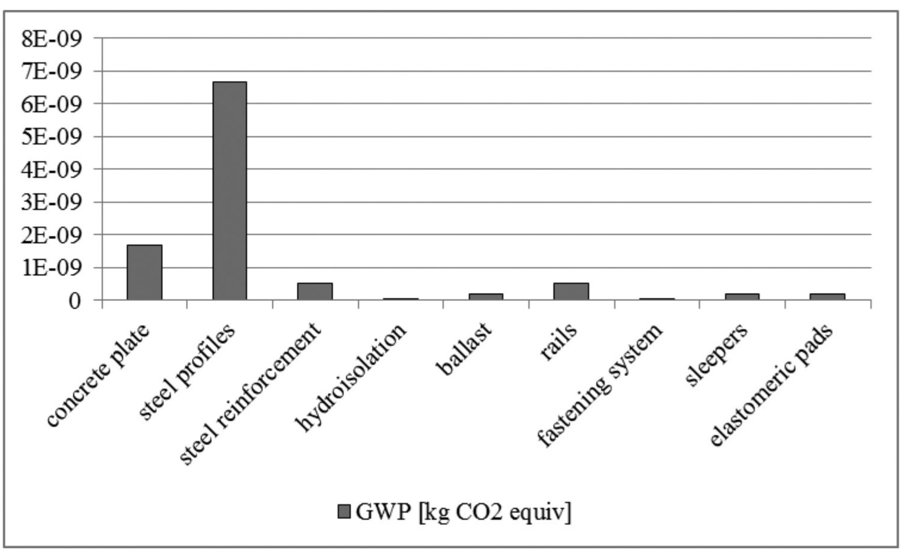

Figure 8: *The normalised environmental impact of material production on the transition zone with cement stabilisation.*

Conclusions

UHPC is an innovative upcoming cementitious material for the building industry. Typically, compressive strengths close to 200 MPa and tensile strengths around 15 MPa are achieved by the use of a high cement content, a low water-to-cement ratio, a low maximum aggregate size and the addition of fine reactive components such as silica fume. Due to the high load-bearing capacity of structures made of UHPC, it is possible to reduce the cross-sections of construction elements and thus the weight of the construction as a whole. Hence, on the one hand, a smaller amount of raw materials is needed to build durable structures. On the other hand, the portion of energy-intensive constituents must be increased to guarantee the aforementioned properties.

As a conclusion, the LCIA method allows the comparison of different solutions of bridge rehabilitation from an environmental point of view. It shows that the impact due to the production of materials is the major contribution to the environmental impact regardless of the rehabilitation systems used. The results of the analysis show that the newly proposed method of construction or reconstruction of the steel railway bridge is much more acceptable to the environment and can thus contribute to sustainable development of the railway infrastructure.

The final results could vary due to the use of different LCA methods, because there are no authoritative guidelines that define the criteria for method selection. This in turn puts significant emphasis on the importance of minimising emissions from the performance of rail infrastructure renovation, focussing on the use of lower-carbon materials.

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