Life Cycle Sustainability Performance Assessment Method for Comparison of Civil Engineering Works Design Concepts: Case Study of a Bridge

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Article

Life Cycle Sustainability Performance Assessment Method for Comparison of Civil Engineering Works Design Concepts: Case Study of a Bridge

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Abstract: Standardized and transparent life cycle sustainability performance assessment methods are
essential for improving the sustainability of civil engineering works. The purpose of this paper is
to demonstrate the potential of using a life cycle sustainability assessment method in a road bridge
case study. The method is in line with requirements of relevant standards, uses life cycle assessment,
life cycle costs and incomes, and environmental externalities, and applies normalization and weighting
of indicators. The case study involves a short-span bridge in a design-build infrastructure project,
which was selected for its generality. Two bridge design concepts are assessed and compared:
a concrete slab frame bridge and a soil-steel composite bridge. Data available in the contractor's
tender phase are used. The two primary aims of this study are (1) to analyse the practical application
potential of the method in carrying out transparent sustainability assessments of design concepts
in the early planning and design stages, and (2) to examine the results obtained in the case study to
identify indicators in different life cycle stages and elements of the civil engineering works project
with the largest impacts on sustainability. The results show that the method facilitates comparisons
of the life cycle sustainability performance of design concepts at the indicator and construction
element levels, enabling better-informed and more impartial design decisions to be made.

Keywords: sustainability; life cycle assessment; life cycle costing; environmental externalities;
indicator; multi-criteria decision analysis; civil engineering; bridge; design
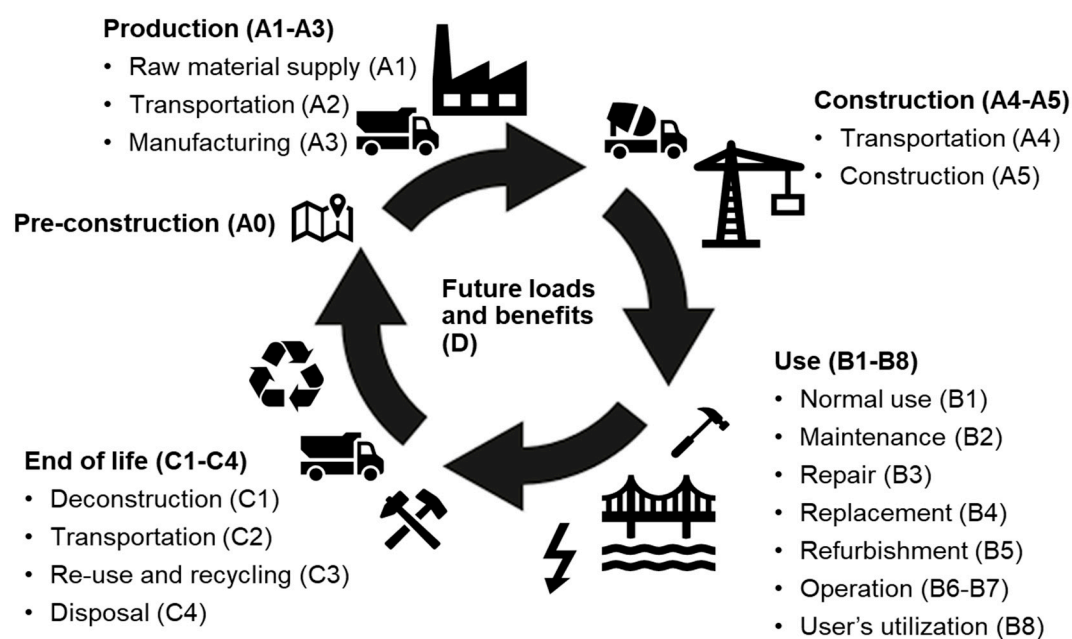
1. Introduction

In civil engineering projects, life cycle environmental, social, and economic sustainability
performance is becoming increasingly important, as reflected in the large number of standards
published on the subject in recent years [1–4]. To make better-informed decisions regarding the impact
of design choices on the sustainability of civil engineering works, sustainability performance assessment
is recommended [5,6]. It is important that assessments are performed in a harmonized way and can
be compared impartially. Current standards provide the general framework for the sustainability
assessment of civil engineering works but do not give detailed guidance on the calculation of indicators
and their aggregation [2,4]. In most studies on sustainability-based design and optimization of bridges,
simplifications are used, and the assessment is based on one or two selected indicators and only
covers certain life cycle stages [6], e.g., CO_2 emissions and the cost of construction materials [7] and
of transport and installation [8] and embodied energy of construction materials [9].

　　　The potential to influence the sustainability of a design is larger in the early stages of the design process than in later stages [10]. It is therefore important to define indicators that can support an iterative sustainability-driven design process from concept to final implementation. To enable the identification of sustainable designs, a formalized method that allows transparent, comparable, and automatable sustainability design and assessment is desired.

　　　Ek et al. presented a harmonized method for life cycle sustainability assessment and comparison of civil engineering works design concepts [11]. The proposed method includes guidance on the calculation of environmental, social and economic indicators, based on life cycle assessment (LCA), life cycle costing (LCC) and external costs, and aggregation using normalization and weighting factors, in accordance with the principles and requirements of methods for sustainability performance assessment given in the standards [2] and [4].

　　　This paper evaluates the previously proposed method by applying it in a road bridge case study. The study has two primary aims: (1) to analyse the practical application potential of the method in carrying out transparent sustainability assessments of design concepts in the early planning and design stages and (2) to examine the results obtained in the case study to identify critical indicators in different life cycle stages as well as critical elements in the civil engineering works project with the greatest impacts.

　　　Life cycle stages are classified into so-called modules by the related standards [1–4,12–15], see Figure 1.

Figure 1. Schematic illustration of the life-cycle stages of a civil engineering works project and their classification in modules.

　　　Module A0 is the pre-construction stage. Modules A1–A3 represent the production stage from raw material extraction to construction material manufacturing where A1 is material extraction, A2 is transport from extraction to manufacture, and A3 is material manufacture. A4–A5 represent the construction process stage where A4 is transport from material manufacture to the construction site and A5 is the construction site works. B1–B5 represent the use stage relating to maintenance where B1 is normal use of the bridge, B2 is maintenance, B3 is repair, B4 is replacement, and B5 is refurbishment. B6–B7 represent the use stage related to the operation where B6 is operational energy use and B7 is operational water use. B8 is the use stage related to the user's utilization of the civil engineering works. C1–C4 cover the end-of-life stage where C1 is deconstruction, C2 is transport from the deconstruction site to the waste management site, C3 is the waste processing of materials intended for reuse, recycling,

and energy recovery, and C4 is waste disposal. Module D represents the benefits and loads beyond the system boundary of the civil engineering works.

2. Materials and Methods

The new method for life cycle sustainability assessment and comparison of civil engineering works design concepts presented by Ek et al. [11] was applied to a case study. The case study involved a bridge in a design-build infrastructure project and was selected for its generality. Two alternative bridge design concepts were assessed and compared: a concrete slab frame bridge (CSF bridge) and a soil-steel composite bridge (SSC bridge). The prerequisites for the assessment are presented in Table 1.

Table 1. Case study specific prerequisites for the assessment.

Characteristic	Case Study Prerequisite
Object of assessment	Bridge 6-1282-1 on Road 26, Sweden 6 m long, 9 m wide, 3 road lanes
Intended use of the assessment	Design concept comparison
Additional functions provided	-
Functional equivalent: (a) Type/use of the civil engineering works, (b) Capacity, (c) Reference study period and pattern of use, (d) Design life (required service life, RSL)	(a) Road bridge with fauna passage (b) 7200 AADT, 100 km/h (c) 80 years, see Appendix C, Appendix D (d) 80 years
Time of assessment in the life cycle	Detailed design/tender phase
Life cycle stages assessed	A1–A5, B1–B8, C1–C4, D
Justification of the exclusion of modules	A0 was excluded because of its insignificant impact on the sustainability performance and because it does not differ between the concepts.
Area of influence	Environmental, social, and economic dimensions (environmental externalities): The surroundings and people in the direct vicinity of the bridge, receiving emissions from fuel combustion and other activities during construction, use and deconstruction from passing vehicles across the length of the bridge. Economic dimension (Life cycle costs (LCC) and incomes): The users of passing vehicles on the bridge (module B8), the client of the constructed bridge (all other modules).
Energy and mass flows considered in the assessment	See Appendix B
General assumptions and scenarios used	See Appendix B
Sources of data for the indicators	See Appendix B
Statement about whether data are specific or generic	See Appendix A
Reference year for the cost data	2019

The functional unit is 1 m of bridge length and year of required service life (RSL). The reference study period is equal to the required service life: 80 years. A functional equivalent of 1 km of bridge and year of RSL is prescribed by the product category rules (PCR) of the International EPD System [13], but it was decided to use 1 m instead, because the short length of the bridge (6 m) would yield non-representative results if scaled to 1 km.

Life cycle assessment (LCA) was performed according to the standard EN 15804 [12] using the LCA software GaBi Professional, version 9.5 (Sphera Solutions GmbH, Leinfelden-Echterdingen, Germany) [16]. The GaBi datasets used are presented in Appendix A. Normalization and weighting

factors presented in [11] (adapted from the factors used in the Product Environmental Footprint (PEF) method [17–19] were used (see Table 2). As proposed in [11], some indicators are categorized into the environmental dimension and some into the social dimension. In PEF, all indicators are in a single dimension. The PEF weighting factors of the indicators have thus been scaled to a total of 100 in the environmental and social dimension, respectively. The life cycle costing (LCC and incomes) was calculated according to the standard EN 15686-5 [14], and environmental externalities were calculated in accordance with ISO 14008 [15]. The economic indicators are presented separately in line with the standards' requirements. LCC and incomes as well as environmental externalities are presented as the net present value (NPV) using a discount rate of 3%. This discount rate was chosen as it is the rate prescribed by the currently available standard on calculation methods for economic performance (for buildings) [20]. Environmental externalities were calculated using the EPS 2015dx method [21]. Abbreviations and units of measurement used for the indicators included in the assessment are presented in Table 3.

Table 2. Normalization and weighting factors used for environmental and social indicators [11].

Dimension	Indicator	Normalization Factor (NF)	Weighting Factor (%)
Environmental	Acidification potential	55.6	8.43
	Eco-toxicity potential (freshwater)	42,683	2.61
	Potential soil quality index	819,498	10.80
	Global warming potential total (fossil + biogenic + luluc)	8096	28.63
	Abiotic depletion potential for non-fossil resources	0.0636	10.27
	Abiotic depletion potential for fossil resources	65,004	11.31
	Eutrophication potential (freshwater)	1.61	3.81
	Eutrophication potential (marine)	19.5	4.02
	Eutrophication potential (terrestrial)	177	5.04
	Ozone depletion potential	0.0536	8.58
	Photochemical ozone creation potential	40.6	6.50
Social	Potential ionizing radiation—human health	4220	18.94
	Human toxicity potential—cancer effects	0.0000169	8.05
	Human toxicity potential—non-cancer effects	0.000230	6.96
	Particulate matter emissions	0.000595	33.88
	Water user deprivation potential	11,469	32.17

The method requires the use of a life cycle inventory (LCI) to calculate the indicators. In the case study, the LCI was in the form of a bill of materials (BOM), which was calculated for each design concept for modules A1–A5 as well as for the use (B1–B8) and end-of-life (C1–C4 and D) stages. It was created based on data available in the tender phase. The BOM is presented in Appendix B. The values of modules B1–B8, C1–C4, and D were calculated based on the scenarios presented in Appendix C. Realistic and representative scenarios of the resource consumption and costs of modules B–D were developed for each design concept. Scenarios were developed based on project documentation and literature data, if available, as well as expert knowledge. Expert knowledge was based on both the project manager of the construction project used as case study, and the authors' previous experience from bridge design, construction and maintenance projects in Sweden.

For the LCC, the average market prices per unit for each of the resources included were used. Average prices were supplied by the project manager of the case study project.

Transport modes and distances are presented in Appendix D. Cut-offs were made for the transport of form oil, bitumen sheet, bitumen sealant, impregnation, geotextile, mortar, graffiti protection, polypropylene pipe, polyethylene foam, bituprimer, epoxy sealant, and plastic film.

Table 3. Sustainability dimensions, categories, indicator names, abbreviations, and units of measurement for the indicators.

Dimension	Category	Indicator Name	Abbreviation	Unit of Measurement
Environmental	Acidification	Acidification potential	AP	mol H + eq
	Biodiversity	Eco-toxicity potential (freshwater)	ETP-fw	CTUe
		Potential soil quality index	SQP	Dimensionless
	Climate change	Global warming potential total (fossil + biogenic + luluc)	GWP-total	kg CO_2 eq
	Depletion of abiotic resources—minerals and metals	Abiotic depletion potential for non-fossil resources	ADPE	kg Sb eq
	Depletion of abiotic resources—fossil fuels	Abiotic depletion potential for fossil resources	ADPF	MJ, net calorific value
	Eutrophication	Eutrophication potential (freshwater)	EP-freshwater	kg P eq
		Eutrophication potential (marine)	EP-marine	kg N eq
		Eutrophication potential (terrestrial)	EP-terrestrial	mol N eq
	Ozone depletion	Ozone depletion potential	ODP	kg CFC 11 eq
	Photochemical ozone creation	Photochemical ozone creation potential	POCP	kg NMVOC eq
Social	Health and comfort	Potential ionizing radiation—human health	PIR	kBq U235 eq
		Human toxicity potential—cancer effects	HTP c	CTUh
		Human toxicity potential—non-cancer effects	HTP nc	CTUh
		Particulate matter emissions	PM	Disease incidence
		Water user deprivation potential	WDP	m^3 world deprived eq
Economic	Life cycle economic balance	LCC and incomes	-	Euro
	External cost	Environmental externalities	-	Euro

3. Results

The results are first presented separately for the CSF bridge design concept and the SSC bridge design concept. The results for the two concepts are then compared. Positive economic indicator values indicate costs, while negative values indicate incomes. For the environmental and social indicators, positive values indicate a negative impact, and negative values indicate a positive impact.

The result for module B8 is presented in a separate figure, since it is relatively higher than that of the other modules. Furthermore, the result for module B8 was excluded from the comparison of the concepts, since it would have disguised the differences in concepts among the other modules. In addition, the result for module B8 was found to be equal for both concepts.

3.1. Concrete Slab Frame Bridge Design Concept

The results for each indicator of the sustainability assessment of the CSF bridge in units of measurement and per life cycle stage are presented in Table 4.

The results for the CSF bridge are presented per life cycle stage in Table 5. The results for the environmental and social dimensions are aggregated on the dimension level, using the normalization and weighting factors in Table 2, while the results for the economic dimension are summarized at the indicator level. The normalized and weighted results for the environmental and social dimensions are presented per life cycle stage and per indicator in Figure 2 (excluding module B8). Figure 3 shows the contribution of each resource to the total impact over the life cycle (modules A–C excluding B8) in the environmental dimension and the social dimension, respectively, for the resources with the greatest contributions. The normalized and weighted results for the environmental and social dimensions are presented for module B8 per indicator in Figure 4.

Table 4. Results for the concrete slab frame bridge (CSF) bridge design concept per indicator in units of measurement per life-cycle stage for the functional unit. Modules not assessed are abbreviated as "MNA".

Indicator	A0	A1–A3	A4–A5	B1–B5	B6–B7	B8	C1–C4	D
AP	MNA	0.78	0.57	0.049	0	4.2	0.29	−0.18
ETP-fw	MNA	1780	1642	133	0	4063	380	−333
SQP	MNA	1002	7588	22	0	22,083	167	−579
GWP-total	MNA	313	172	12	0	234	47	−70
ADPE	MNA	2.1×10^{-4}	1.6×10^{-5}	4.4×10^{-6}	0	5.4×10^{-5}	3.7×10^{-6}	-1.0×10^{-4}
ADPF	MNA	3740	2344	230	0	5229	584	−892
EP-freshwater	MNA	5.5×10^{-4}	5.6×10^{-4}	2.6×10^{-5}	0	3.110^{-2}	1.1×10^{-4}	-2.3×10^{-4}
EP-marine	MNA	0.24	0.25	0.015	0	1.68	0.10	−0.05
EP-terrestrial	MNA	2.61	2.82	0.17	0	20.4	1.1	−0.5
ODP	MNA	6.9×10^{-11}	2.6×10^{-11}	3.1×10^{-11}	0	4.9×10^{-10}	8.5×10^{-14}	-3.5×10^{-13}
POCP	MNA	0.64	0.71	0.046	0	2.7	0.28	−0.14
PIR	MNA	60	3.1	0.57	0	148.5	0.39	−13
HTP c	MNA	1.8×10^{-6}	5.6×10^{-8}	1.2×10^{-8}	0	7.1×10^{-7}	2.9×10^{-8}	-5.8×10^{-8}
HTP nc	MNA	4.8×10^{-6}	2.0×10^{-6}	4.3×10^{-7}	0	1.1×10^{-4}	2.9×10^{-6}	-6.9×10^{-7}
PM	MNA	1.5×10^{-5}	1.2×10^{-5}	5.8×10^{-7}	0	4.1×10^{-5}	2.4×10^{-6}	-3.2×10^{-6}
WDP	MNA	71	11	0.86	0	109	6.3	−16
LCC and incomes	MNA	210	287	18	0	86	12	−1.1
Environmental externalities	MNA	123	56	2.0	0	31	1.4	−7.8

Table 5. Results for the CSF bridge design concept per life cycle stage aggregated on the dimension level (and on the indicator level for the economic dimension) for the functional unit. The results for the environmental and social dimensions are normalized and weighted, and the results for the economic dimension are summarized. Modules not assessed are abbreviated as "MNA".

Dimension	Indicator *(Unit)*	A0	A1–A3	A4–A5	B1–B7	B8	C1–C4	D
Environmental	All *(dimensionless)*	MNA	2.3	1.6	0.12	4.4	0.43	−1.5
Social	All *(dimensionless)*	MNA	2.3	0.82	0.057	6.9	0.26	−1.2
Economic	LCC and incomes *(Euro)*	MNA	210	287	18	86	12	−1.1
	Environmental externalities *(Euro)*	MNA	123	56	2.0	31	1.4	−7.8
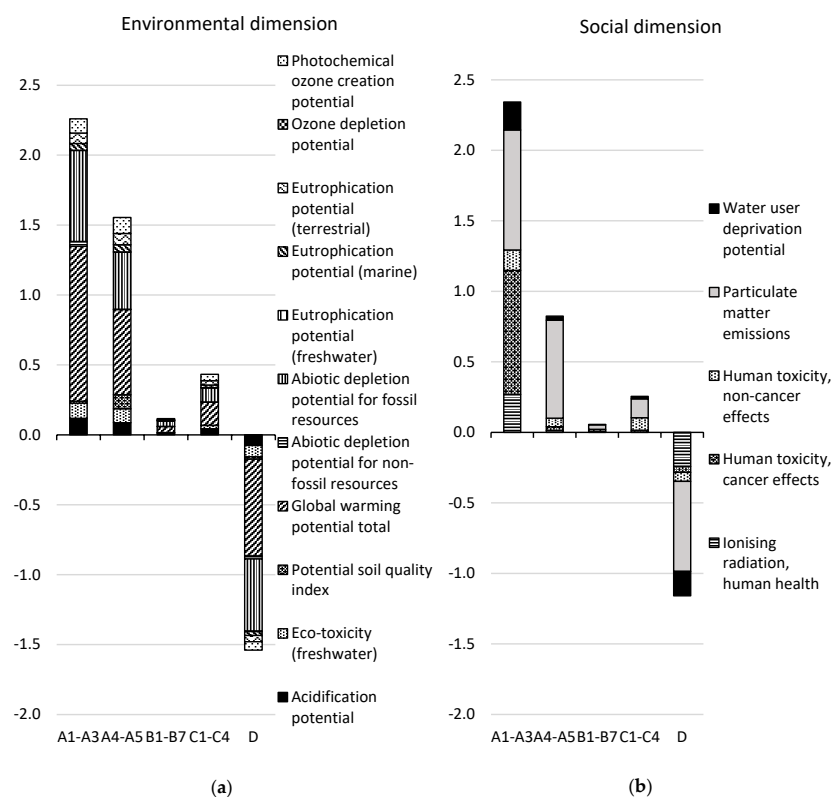
Figure 2. Normalized and weighted results for the CSF bridge design concept per life cycle stage in (**a**) the environmental dimension and (**b**) the social dimension for each indicator and for the functional unit. Module B8 is not included. See Figure 4 for module B8. Note that the ozone depletion potential indicator bar cannot be seen in the figure since it is very small.

In the environmental dimension, 52% of the total impact of life cycle stages A–C, excluding module B8, occurs in the production stage (modules A1–A3), followed by the construction stage (36%, modules A4–A5). If included, B8 would contribute to 50% of the total impact for life cycle stages A–C. Module D presents the potential to reduce the environmental impact of life cycle stages A–C (excluding module B8) by 35% through future re-use or recycling. The main contribution to the environmental impact over the life cycle (modules A–C, excluding B8) comes from the indicators "global warming potential" (44% of the total impact) and "abiotic depletion potential for fossil resources" (28% of the total impact, see Figure 2). Fifty-one percent of the global warming potential is caused by the production (29%) and transport to the construction site (22%) of 6833 tons of aggregates, while 23% is caused by the production of 472 tons of concrete, and 6% is caused by the production and combustion of diesel used on the site during construction. The production and transport of aggregates and the landfilling of aggregate waste contributes to 53% of the total environmental impact over the life cycle (see Figure 3).
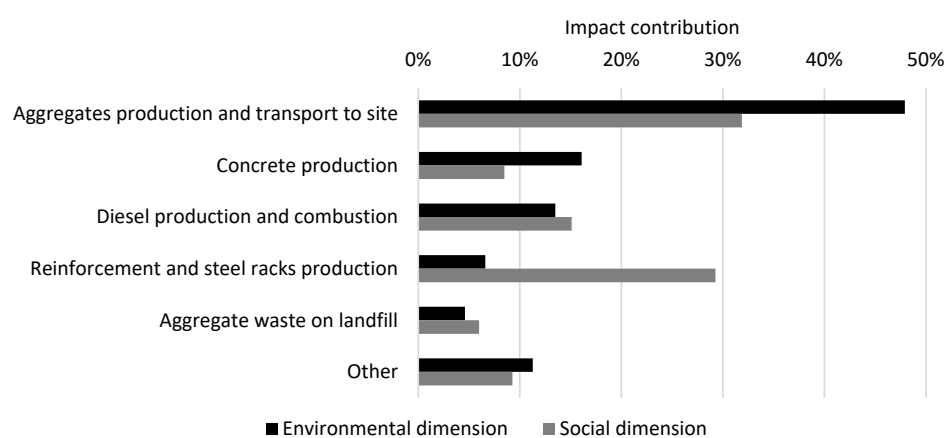

Figure 3. Contribution of resources to the total impact over the life cycle (modules A–C, excluding B8) for the CSF bridge design concept in the environmental and social dimensions.

In the social dimension, 67% of the total impact for life cycle stages A–C (excluding module B8) occurs in the production stage, followed by the construction stage (24%). If included, module B8 would contribute to 66% of the total impact for life cycle stages A–C. Module D presents the potential to reduce the social impact by 33% of the total impact for life cycle stages A–C (excluding module B8) by future re-use or recycling. The main contribution to social impact over the life cycle (modules A–C, excluding B8) comes from the indicators "particulate matter emissions" (49% of the total impact) and "human toxicity—cancer effects" (27% of the total impact). Thirty-five percent of the particulate matter emissions are caused by the production of aggregates and their transport to the construction site, and 28% is caused by the production and combustion of diesel at the construction site during construction. The production and transport of aggregates and the landfilling of aggregate waste contributes to 38% and reinforcement steel and steel rack production contributes to 29% of the total social impact over the life cycle (see Figure 3).

In the economic dimension, 54% of the total net cost for the indicator "LCC and incomes" in life cycle stages A–C (excluding module B8) occurs in the construction stage (mainly in A5), see Table 5. Forty percent occurs in the production stage. If module B8 was included, it would contribute to 14% of the total net cost for life cycle stages A–C. Module D presents the potential to reduce the future net cost (by future re-use or recycling) by 0.2% for life cycle stages A–C (excluding module B8). The main contributor (30%) to the cost of the LCC and incomes over the life cycle is the work costs during construction, followed by the costs for production and transport of aggregates (18%) and for the production and transport of concrete and reinforcement steel (17%). For the indicator "environmental externalities", 68% of the total cost in life cycle stages A–C (excluding module B8) occurs in the production stage, followed by the construction stage (31%). If module B8 was included,

it would contribute to 12% of the total cost for life cycle stages A–C. Module D presents the potential to reduce future costs of the total impact for life cycle stages A–C (excluding module B8) by 4%. The main contributors (43%) to the environmental externalities over the life cycle are the production and transport of aggregates and transport to waste disposal and the landfilling of aggregate waste.
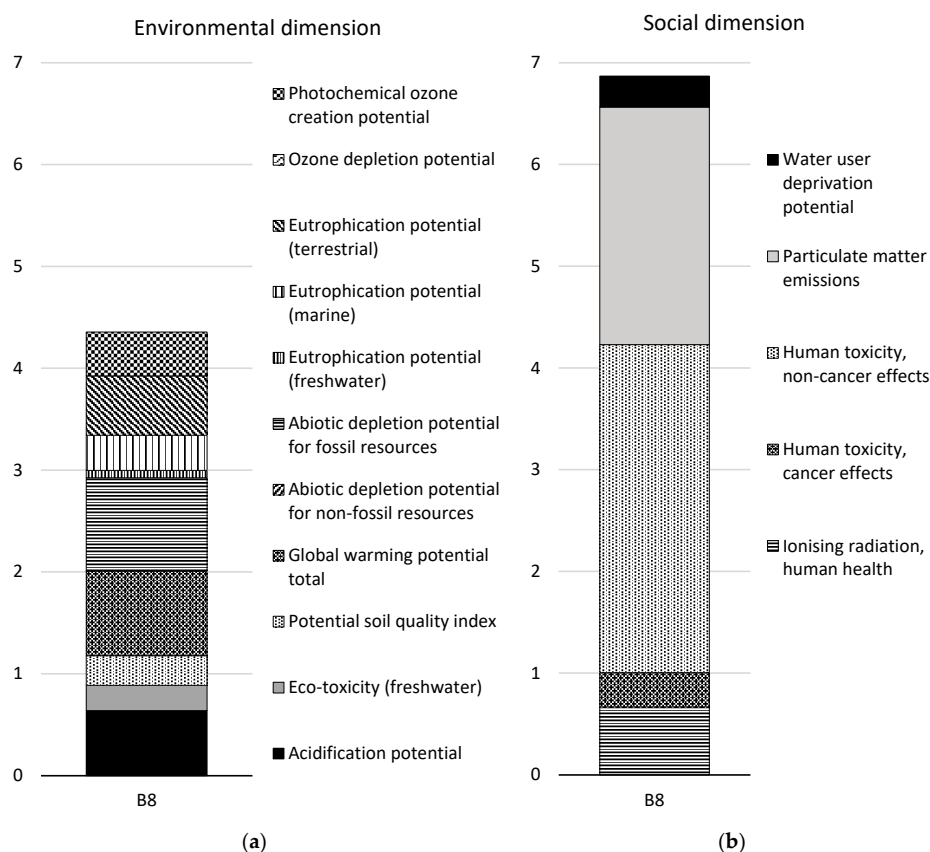
Figure 4. Normalized and weighted results for module B8 for both bridge design concepts in (**a**) the environmental dimension and (**b**) the social dimension for each indicator and for the functional unit. Note that the ozone depletion potential indicator bar cannot be seen in the figure since it is very small.

3.1.1. Modules A1–A3

In the production stage, greenhouse gas emissions have the largest impact in the environmental dimension (see Figure 2). The indicator "global warming potential" contributes to 49% of the total impact in this life cycle stage. Fifty percent of this originates from the production of 6833 tons of aggregates, 39% from the production of 472 tons of concrete, and 9% from the production of 23 tons of reinforcement steel (carbon and stainless). The production of asphalt, steel racks, and other built-in construction materials accounts for 2% of the global warming potential.

The second largest impact comes from the abiotic depletion potential for fossil resources; this constitutes 29% of the total environmental impact. Sixty-eight percent of this depletion is caused by the production of aggregates, 16% by the production of concrete, and 11% by the production of reinforcement steel.

The "acidification potential", the "eco-toxicity potential", and the "photochemical ozone creation potential" indicators also have significant impacts, each accounting for about 5% of the total environmental impact. The production of aggregates contributes to 46–69% of the total impact for each of these indicators.

The largest impact in the social dimension comes from the indicators "human toxicity—cancer effects" (38%) and "particulate matter emissions" (36%). For "human toxicity—cancer effects", 97% of the impact comes from the production of 553 kg of stainless-steel reinforcement. For "particulate matter emissions", 66% of the impact comes from the production of aggregates.

In the economic dimension, for the indicator "LCC and incomes", 39% of the total cost is for the aggregates, 23% is for the ready-mix concrete, and 19% is for carbon steel reinforcement. There is no income. For the indicator "environmental externalities", 36% of the total cost is for the production of aggregates, and 20% each is for the production of stainless-steel reinforcement and ready-mix concrete.

3.1.2. Modules A4–A5

In the construction process stage, greenhouse gas emissions have the largest impact in the environmental dimension (see Figure 2). The global warming potential accounts for 39% of the total impact in this life cycle stage. Seventy percent of this type of emission originates from the transport of aggregates from the production site to the construction site. Eighteen percent originates from the production and combustion of diesel in construction machines on the construction site.

The second largest impact comes from the abiotic depletion potential for fossil resources, having 26% of the total environmental impact. Sixty-eight percent of this is caused by the transport of aggregates to the site.

The third largest impact comes from the combination of the three indicators for eutrophication potential, together contributing to 9% of the total environmental impact. Approximately 72% of the eutrophication potential (marine) and eutrophication potential (terrestrial) comes from the production and combustion of diesel used on site, while 65% of the eutrophication potential (freshwater) comes from the transport of aggregates.

Significant impacts are also caused by the "eco-toxicity potential", the "potential soil quality index", and the "photochemical ozone creation potential" indicators, each accounting for 6–7% of the total environmental impact. The transport of aggregates contributes to 69% of the eco-toxicity potential. Ninety percent of the potential soil quality index value comes from the production of the ancillary materials wood, particleboard, and plywood for the formworks. The production and combustion of diesel used on the construction site contributes to 74% of the photochemical ozone formation potential.

The largest impact in the social dimension comes from particulate matter emissions (84%). Sixty-nine of this is caused by the production and combustion of diesel used on the construction site.

In the economic dimension, for the indicator "LCC and incomes", 65% of the total cost is for the construction workers and 11% is for the transport of aggregates. There is no income. For the indicator "environmental externalities", 62% of the total cost is for the transport of aggregates, and 25% is for the production and combustion of diesel used on the construction site.

3.1.3. Modules B1–B7

In the use stage, "global warming potential" (38%) has the largest impact in the environmental dimension, followed by "abiotic depletion for fossil resources" (35%), see Figure 2. Fifty-three percent of the global warming potential is caused by the production of 1.4 tons of steel racks, and 30% is caused by the production of 14 tons of ready-mix concrete. Thirty-two percent of the abiotic depletion potential for fossil resources is caused by the production of 10.5 tons of asphalt.

"Particulate matter emissions" (58% of the total impact) has the largest impact in the social dimension, followed the indicator "human toxicity—non-cancer effects" (23%). Thirty-nine percent of the particulate matter emissions is caused by the production of steel racks, and 21% is caused by the production of 35 kg of bituprimer. The largest contributor to "human toxicity—non-cancer effects" is the production of 77 kg of epoxy (45%).

In the economic dimension, for the indicator "LCC and incomes", 46% of the total cost is for steel racks. The cost for installation of the steel racks is 21% of the total cost. There is no income. For the indicator "environmental externalities", 61% of the total cost is for the production of steel racks, and 23% is for the production of asphalt.

3.1.4. Module B8

The impact of module B8, the stage relating to the user's utilization, is the same for both design concepts (see Figure 4, Tables 5 and 6). For the CSF bridge, the environmental impact of module B8 is equal to the environmental impact of all other modules together (excluding module D). The social impact of module B8 is 97% greater. The net cost for LCC and incomes is 84% lower for module B8 than for all other modules together (excluding module D). The "environmental externalities" indicator is 83% lower for module B8 than for all other modules together (excluding module D).

Table 6. Results for the SSC bridge design concept per life cycle stage and aggregated at the dimension level (or at the indicator level for the economic dimension) for the functional unit. The results for the environmental and social dimensions are normalized and weighted, and the results for the economic indicators are summarized. Modules not assessed are abbreviated as "MNA".

Dimension	Indicator *(Unit)*	A0	A1–A3	A4–A5	B1–B7	B8	C1–C4	D
Environmental	All *(dimensionless)*	MNA	5.0	1.4	0.078	4.4	0.44	−2.1
Social	All *(dimensionless)*	MNA	1.6	0.63	0.029	6.9	0.25	−1.4
Economic	LCC and incomes *(Euro)*	MNA	295	99	16	86	10	−0.8
	Environmental externalities *(Euro)*	MNA	1 087	52	1.5	31	1.3	−14

The indicators "abiotic depletion potential for fossil resources" and "global warming potential" account for 21% and 19% of the total impact, respectively, in the environmental dimension. Fifteen percent comes from the indicator "acidification potential", and 13% comes from the indicator "eutrophication potential" (terrestrial). However, if the results for all three eutrophication indicators are pooled, they account for 23% of the total environmental impact. Fifty-four percent of the global warming potential originates from the production and combustion of hydrogenated vegetable oil (HVO) (rapeseed methyl ester (RME) was used as a proxy for HVO). Fifty-eight percent of the abiotic depletion potential for fossil resources originates from the production of electricity. Seventy-six percent of the total eutrophication potential originates from the production and combustion of HVO.

Forty-seven percent of the total impact in the social dimension comes from the indicator "human toxicity potential—non-cancer effects", and 34% comes from "particulate matter emissions". Ninety-seven percent of the "human toxicity potential—non-cancer effects" originates from the production of HVO. For particulate matter emissions, 48% originates from the production of HVO, and 45% comes from the combustion of diesel.

In the economic dimension, for the indicator "LCC and incomes", 46% of the total cost is for steel racks. The cost for installation of the steel racks is 21% of the total cost. There is no income. For the indicator "environmental externalities", the largest contributor is the production of HVO.

3.1.5. Modules C1–C4

In the end-of-life stage, global warming potential has the largest impact in the environmental dimension (38%), followed by abiotic depletion potential for fossil resources (23%), the three eutrophication potential indicators together (12%), and photochemical ozone creation potential (11%), see Figure 2. Forty-six percent of the global warming potential and 49% of the abiotic depletion potential for fossil resources are caused by the landfilling of 683 tons of aggregate waste. Nineteen percent of the global warming potential and 21% of the abiotic depletion potential for fossil resources is caused by the production and combustion of diesel used in deconstruction.

Particulate matter emissions have the largest impact on the social dimension (56% of the total impact), followed by the indicator "human toxicity—non-cancer effects" (35%). Thirty-two percent

of the particulate matter emissions is caused by the transport of 683 tons of aggregate waste, and 23% is caused by the production and combustion of diesel used during deconstruction of the bridge. Ninety percent of the impact of "human toxicity—non-cancer effects" is caused by the landfilling of aggregate waste.

In the economic dimension, for the indicator LCC and incomes, 93% of the total cost is for deconstruction workers. There is no income. For the indicator "environmental externalities", the largest part of the cost (52%) comes from the landfilling of aggregate waste and the second largest (20%) portion comes from the production and combustion of diesel used for deconstruction.

3.1.6. Module D

Regarding benefits and loads beyond the system boundary, the largest benefit in the environmental dimension is offered by the potential avoidance of contributing to global warming potential (45% of the total benefit) and the potential avoidance of contributing to the abiotic depletion potential for fossil resources (34%), see Figure 2. The main part of this benefit is due to the potential re-use of aggregates.

The largest benefit in the social dimension is offered by the potential avoidance of particulate matter emissions (55%) and the avoidance of ionizing radiation (21%). Here, as well, the main part of this benefit is due to the potential re-use of aggregates.

In the economic dimension, for the indicator "LCC and incomes", 41% of the total income comes from the potential recycling of concrete as a filling material, and 37% comes from the potential recycling of carbon steel reinforcement. For the indicator "environmental externalities", the largest benefit comes from the potential re-use of aggregates (48%).

3.2. Soil-Steel Composite Bridge Design Concept

The results for each indicator used in the sustainability assessment of the SSC bridge per metre of bridge in units of measurement and per life cycle stage are presented in Table 7.
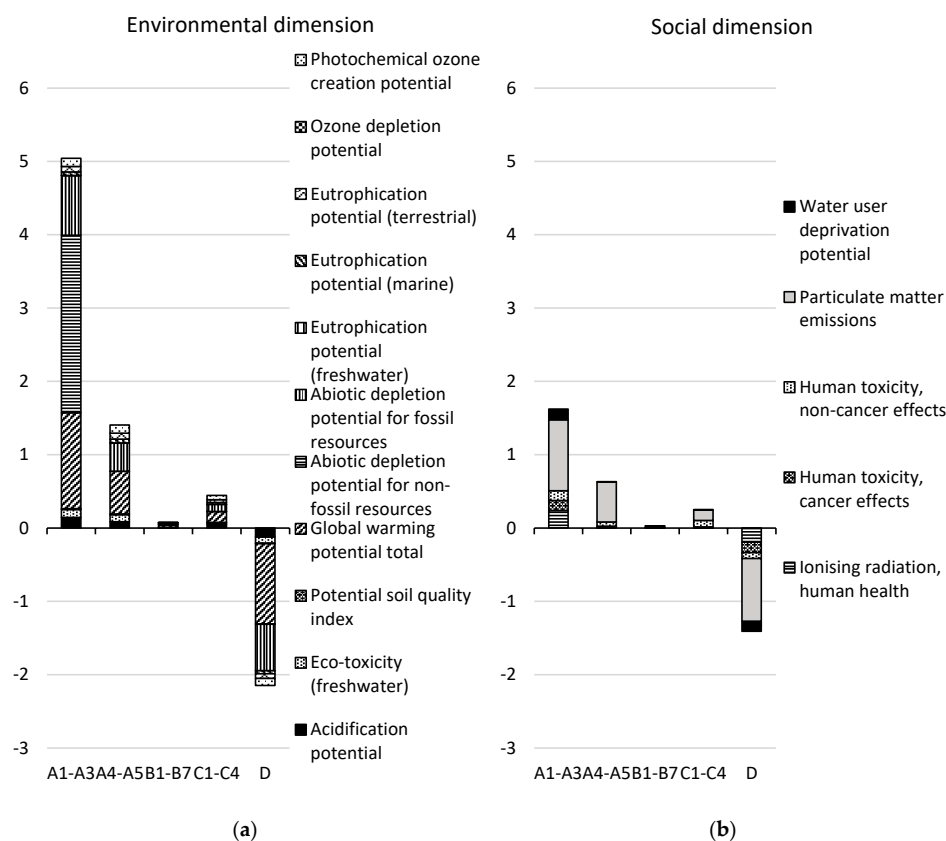
Table 7. Results for the SSC bridge design concept per indicator in units of measurement per life-cycle stage for the functional unit. Modules not assessed are abbreviated as "MNA".

Indicator	A0	A1–A3	A4–A5	B1–B5	B6–B7	B8	C1–C4	D
AP	MNA	0.95	0.56	0.031	0	4.2	0.34	−0.8
ETP-fw	MNA	1773	1571	89	0	4063	360	−1348
SQP	MNA	977	781	13	0	22,083	156	−644
GWP-total	MNA	369	164	9.1	0	233	42	−309
ADPE	MNA	1.5×10^{-2}	1.4×10^{-5}	7.5×10^{-7}	0	5.4×10^{-5}	3.5×10^{-6}	-2.9×10^{-5}
ADPF	MNA	4667	2210	149	0	5222	554	−3646
EP-freshwater	MNA	6.3×10^{-4}	5.0×10^{-4}	1.2×10^{-5}	0	3.1×10^{-2}	9.8×10^{-5}	-4.1×10^{-4}
EP-marine	MNA	0.24	0.25	0.0089	0	1.7	0.12	−0.20
EP-terrestrial	MNA	2.6	2.8	0.10	0	20	1.4	−2.2
ODP	MNA	3.8×10^{-11}	2.6×10^{-11}	2.3×10^{-14}	0	4.9×10^{-10}	8.5×10^{-14}	-1.5×10^{-12}
POCP	MNA	0.69	0.70	0.028	0	2.7	0.36	−0.59
PIR	MNA	53	2.2	0.39	0	149	0.39	−43
HTP c	MNA	2.9×10^{-7}	3.3×10^{-8}	9.4×10^{-9}	0	7.1×10^{-7}	2.8×10^{-8}	-3.0×10^{-7}
HTP nc	MNA	4.4×10^{-6}	1.9×10^{-6}	1.4×10^{-7}	0	1.1×10^{-4}	2.9×10^{-6}	-2.6×10^{-6}
PM	MNA	1.7×10^{-5}	9.6×10^{-6}	2.9×10^{-7}	0	4.1×10^{-5}	2.5×10^{-6}	-1.5×10^{-5}
WDP	MNA	53	1.9	0.47	0	109	2.5	−48
LCC and incomes	MNA	295	99	16	0	86	10	−0.8
Environmental externalities	MNA	1087	52	1.5	0	31	1.3	−14

The results for the SSC bridge are presented per life cycle stage in Table 6. The results for the environmental and social dimensions are aggregated on the dimension level, while the results for the economic dimension are aggregated on the indicator level. The results for the environmental and social dimensions are normalized and weighted using the factors in Table 2, and the results for the economic indicators are summarized. Normalized and weighted results for the environmental and social dimensions per life cycle stage are presented per indicator in Figure 4 (only module B8) and Figure 5 (excluding module B8). Figure 6 shows the share of contribution of each resource to the total

impact over the life cycle (modules A–C excluding B8) in the environmental dimension and the social dimension respectively, for the resources with the greatest contributions.
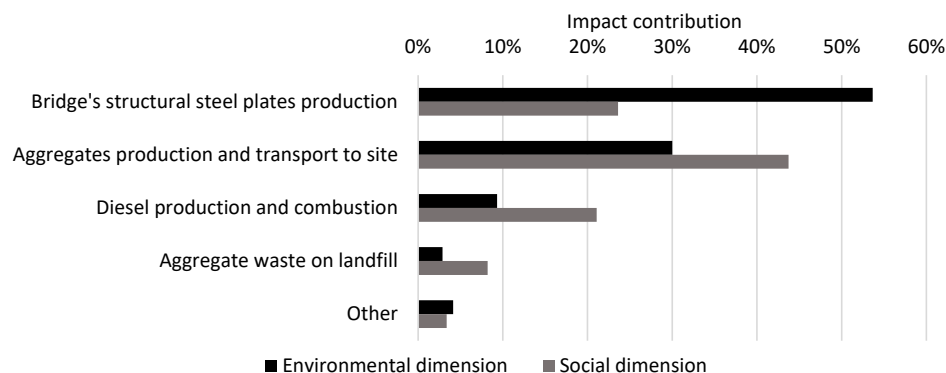
In the environmental dimension, 72% of the total impact for life cycle stages A–C (excluding module B8) occurs in the production stage (modules A1–A3), followed by the construction stage (20%, modules A4–A5). If module B8 was included, it would contribute to 38% of the total impact for life cycle stages A–C. Module D has the potential to reduce the future environmental impact (by future re-use or recycling) by 31% for life cycle stages A–C (excluding module B8). The main contribution to the environmental impact over the life cycle (modules A–C, excluding B8) is accounted for by the indicators "abiotic depletion potential for non-fossil resources" (35% of the total impact), "global warming potential" (30% of the total impact), and "abiotic depletion potential for fossil resources" (19% of the total impact). Practically all (99.6%) of the abiotic depletion potential for non-fossil resources and 36% of the global warming potential are caused by the production of structural steel for the bridge. Forty-seven percent of the global warming potential is caused by the production and transport of aggregates. The production of structural steel for the bridge contributes to 54% and the production and transport of aggregates contributes to 30% of the total environmental impact over the life cycle (see Figure 6).

Figure 5. Normalized and weighted results for the SSC bridge design concept per life cycle stage in (**a**) the environmental dimension and (**b**) the social dimension per indicator and for the functional unit. Module B8 is not included. See Figure 4 for module B8. Note that the ozone depletion potential indicator bar cannot be seen in the figure since it is very small.

In the social dimension, 64% of the total impact of life cycle stages A–C (excluding module B8) occurs in the production stage, followed by the construction stage (25%). If module B8 was included, it would contribute to 73% of the total impact for life cycle stages A–C. Module D presents the potential to reduce the future social impact by 56% for life cycle stages A–C (excluding module B8). The main contributor to the social impact over the life cycle (modules A–C excluding B8) is

accounted for by the indicators "particulate matter emissions" (66% of the total impact) and "human toxicity—non-cancer effects" (11% of the total impact). The largest portion of the particulate matter emissions is caused equally by the production of aggregates and the production and combustion of diesel used for the construction, maintenance, and deconstruction of the bridge over the life cycle (each 36%), followed by the production of structural steel (23%). Over the life cycle, the production and transport of aggregates contributes to 44%, the production of structural steel for the bridge contributes to 26% and the production and combustion of diesel used for the construction, maintenance, and deconstruction of the bridge over the life cycle contributes to 21% of the total social impact (see Figure 6).

Figure 6. Contribution of resources to the total impact over the life cycle (modules A–C, excluding B8) for the SSC bridge design concept in the environmental and social dimensions.

In the economic dimension, 70% of the total net cost for the indicator "LCC and incomes" in life cycle in stages A–C (excluding module B8) occurs in the production stage, and 24% occurs in the construction stage (see Table 6). If module B8 was included, it would contribute to 17% of the total net cost for life cycle stages A–C. Module D presents the potential to reduce the future net cost (by future re-use or recycling) by 0.2% for life cycle stages A–C (excluding module B8). The greatest contributor (39%) to the cost of the LCC and incomes over the life cycle is the production of structural steel for the bridge. For the indicator environmental externalities, 68% of the total external cost in life cycle stages A–C (excluding module B8) occurs in the production stage. Ninety percent of the environmental externalities are caused by the production of structural steel for the bridge. If module B8 was included, it would contribute to 3% of the total external costs for life cycle stages A–C. Module D presents the potential to reduce the future external costs by 1% for life cycle stages A–C (excluding module B8).

3.2.1. Modules A1–A3

In the production stage, the abiotic depletion potential for non-fossil resources has the largest impact in the environmental dimension (see Figure 5). This indicator has 48% of the total impact in this life cycle stage. Almost all (99.7%) of the depletion is caused by the production of 40 tons of structural steel. The second largest contributor is the global warming potential; this constitutes 26% of the total environmental impact. Fifty-seven percent of this indicator is accounted for by the production of structural steel plates for the bridge and 42% by the production of aggregates. The abiotic depletion potential for fossil resources also has a significant impact (16% of the total environmental impact).

Particulate matter emissions have the largest impact in the social dimension (60%). Fifty-eight of this originates from the production of aggregates and 40% comes from the production of bridge steel.

In the economic dimension, for the indicator "LCC and incomes", 67% of the total cost is for structural steel and 28% is for aggregates. There is no income. For the indicator "environmental externalities", 96% of the cost is for the production of structural steel.

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3.2.2. Modules A4–A5

In the construction stage, greenhouse gas emissions have the largest impact in the environmental dimension (see Figure 5). The global warming potential contributes to 41% of the total impact in this life cycle stage. Seventy-three percent of this originates from the transport of aggregates to the construction site. Nineteen percent originates from the production and combustion of diesel used in construction machines on the construction site. The second largest impact comes from the abiotic depletion potential for fossil resources, causing 27% of the total environmental impact. Seventy-two percent of this is caused by the transport of aggregates to the site. The three eutrophication potential indicators make a significant contribution, together contributing to 9% of the total environmental impact. The production and combustion of diesel used at the construction site contributes to 71% of the total eutrophication potential.

In the social dimension, particulate matter emissions have the largest impact by far (86%). Eighty-seven percent of these emissions are caused by the production and combustion of diesel used at the construction site.

In the economic dimension, for the indicator "LCC and incomes", 32% of the total cost is for the transport of aggregates, 28% is for the construction workers, and 20% is for transport of the bridge's structural steel plates. There is no income. For the indicator "environmental externalities", 66% of the total cost is for the transport of aggregates and 27% is for the production and combustion of diesel used at the construction site.

3.2.3. Modules B1–B7

In the use stage, greenhouse gas emissions have the largest impact in the environmental dimension (42%), followed by the depletion of fossil resources (33%) (see Figure 5). Seventy-three percent of the global warming potential is caused by the production of 1.4 tons of steel racks and 16% is caused by the production of 10.5 tons of asphalt. Fifty percent of the abiotic depletion potential of fossil resources is caused by the production of asphalt and 41% is caused by the production of steel racks.

In the social dimension, particulate matter emissions have the greatest impact (59% of the total impact), followed by 16% each from the indicators "human toxicity—cancer effects" and "human toxicity—non-cancer effects". Seventy-six percent of particulate matter emissions comes from the production of steel racks. The production of steel racks contributes to 87% of the factor "human toxicity—cancer effects" and 55% of "human toxicity—non-cancer effects". The production of asphalt contributes to 31% of "human toxicity—non-cancer effects".

In the economic dimension, for the indicator "LCC and incomes", 50% of the total cost is for steel racks. The installation of steel racks accounts for 23% of the total cost. There is no income. For the indicator "environmental externalities", 81% of the total cost is for the production of steel racks.

3.2.4. Module B8

The environmental impact of module B8, the stage relating to the user's utilization, is 38% lower than the environmental impact of all other modules together (excluding module D) for the SSC bridge, see Table 6. The social impact of module B8 is almost three times larger. The net cost for LCC and incomes is 80% lower for module B8 than for all other modules together (excluding module D). The "environmental externalities" indicator is 97% lower for module B8 than for all other modules together (excluding module D). For other aspects of module B8 that do not depend on the bridge type, see Section 3.1.4.

3.2.5. Modules C1–C4

In the end-of-life stage, global warming potential has the largest impact in the environmental dimension (34%), followed by the abiotic depletion potential for fossil resources (22%), the three eutrophication potential indicators together (14%), and the photochemical ozone creation potential

(12%), see Figure 5. Fifty-one percent of both the global warming potential and the abiotic depletion potential for fossil resources is caused by the landfilling of 683 tons of aggregate waste. Thirty-three percent of the global warming potential is caused by the production and combustion of diesel used for deconstruction. Thirty-four percent of the abiotic depletion potential for fossil resources is caused by the production of diesel used for deconstruction.

In the social dimension, particulate matter emissions have the greatest impact (56% of the total impact), followed by the indicator "human toxicity—non-cancer effects" (35%). Seventy-seven percent of particulate matter emissions and 90% of human toxicity—non-cancer effects are caused by the landfilling of aggregate waste.

In the economic dimension, for the indicator "LCC and incomes", 90% of the total cost is for deconstruction workers. There is no income. For the indicator "environmental externalities", the largest portion of the cost (55%) comes from the landfilling of aggregate waste and the second largest portion (33%) comes from the production and combustion of diesel used for deconstruction.

3.2.6. Module D

Regarding the benefits and loads beyond the system boundary, the largest potential future benefit in the environmental dimension is the avoidance of contributing to global warming potential (51% of the total benefit) and the avoidance of abiotic depletion for fossil resources (30%), see Figure 5. The main factors involved in the avoidance of contributing to global warming potential are the potential recycling of bridge steel (52%) and the potential re-use of aggregates (45%).

Table 8. Comparison of the design concepts for modules A–C and for module D for the functional unit. The results are aggregated at the dimension level for the environmental and social dimensions and at the indicator level for the economic dimension. The results for the environmental and social dimensions are normalized and weighted, while the results for the economic dimension are summarized. Module B8 is not included in the comparison. The best options are highlighted in grey.

Dimension, Indicator *(unit)*	CSF Bridge		SSC Bridge	
	A–C	D	A–C	D
Environmental, all *(dimensionless)*	4.4	−1.5	7.0	−2.1
Social, all *(dimensionless)*	3.5	−1.2	2.5	−1.4
Economic, LCC and incomes *(Euro)*	526	−1.1	421	−0.8
Economic, Environmental externalities *(Euro)*	182	−7.9	1 142	−14

The greatest potential future benefits in the social dimension are the avoidance of particulate matter emissions (61%) and the avoidance of ionising radiation—human health (14%). The main factors involved in the avoidance of particulate matter emissions are the potential re-use of aggregates (59%) and the potential recycling of bridge steel (39%).

In the economic dimension, for the indicator "LCC and incomes", 94% of the total income comes from the potential recycling of the bridge's structural steel plates. For the indicator "environmental externalities", the largest benefit comes from the potential recycling of the bridge's structural steel plates (70%).
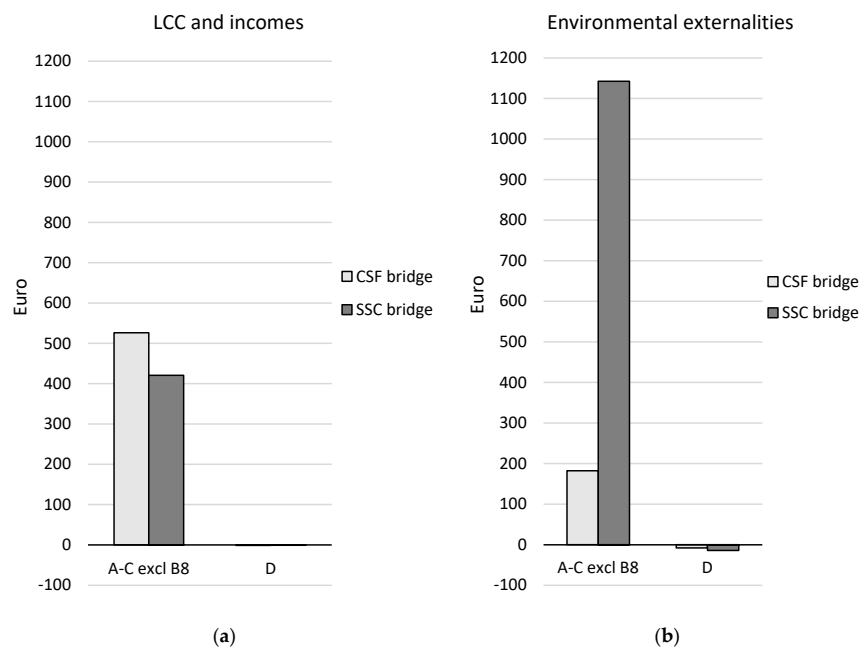
3.3. Comparison of the Design Concepts

A comparison of the two design concepts over the life cycle (modules A–C excluding module B8) and in terms of the future re-use, recovery, and recycling potential (module D) is presented in Table 8 and Figures 7–9. The results are aggregated on the dimension level for the environmental and social dimensions and on the indicator level for the economic dimension. The results for the environmental and social dimensions are normalized and weighted, and the results for the economic dimension are summarized. The results for the environmental and social dimensions per life cycle stage for the two concepts are presented in Figure 10, and the summarized results for the economic indicators are presented in Figure 11 (excluding module B8).
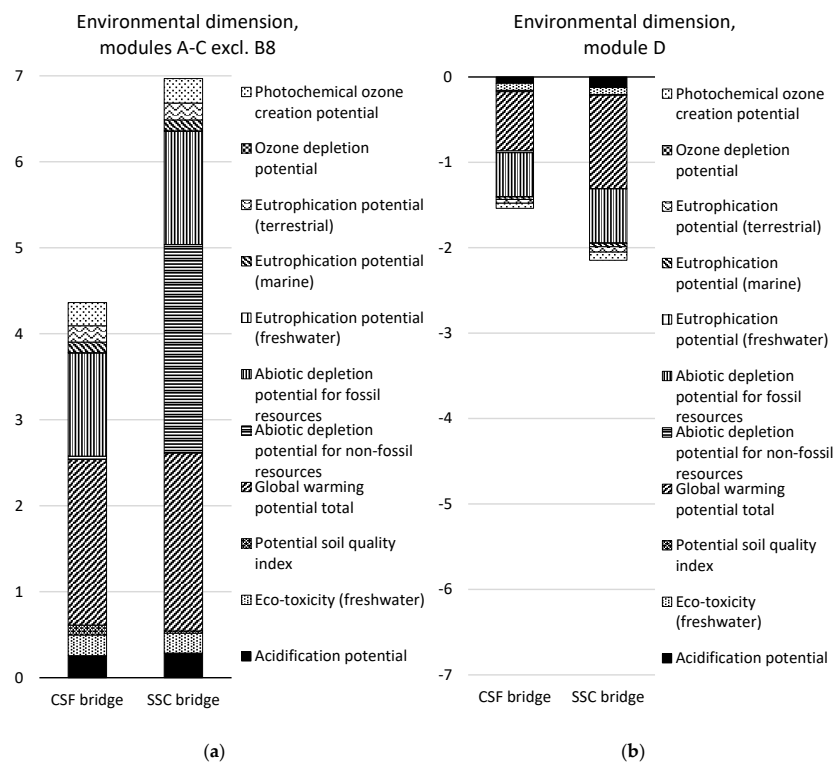
Figure 7. Comparison of the design concepts in the environmental dimension for (**a**) life cycle stages A–C excluding module B8 and (**b**) module D per indicator and for the functional unit. Note that the ozone depletion potential indicator bar cannot be seen in the figure since it is very small.
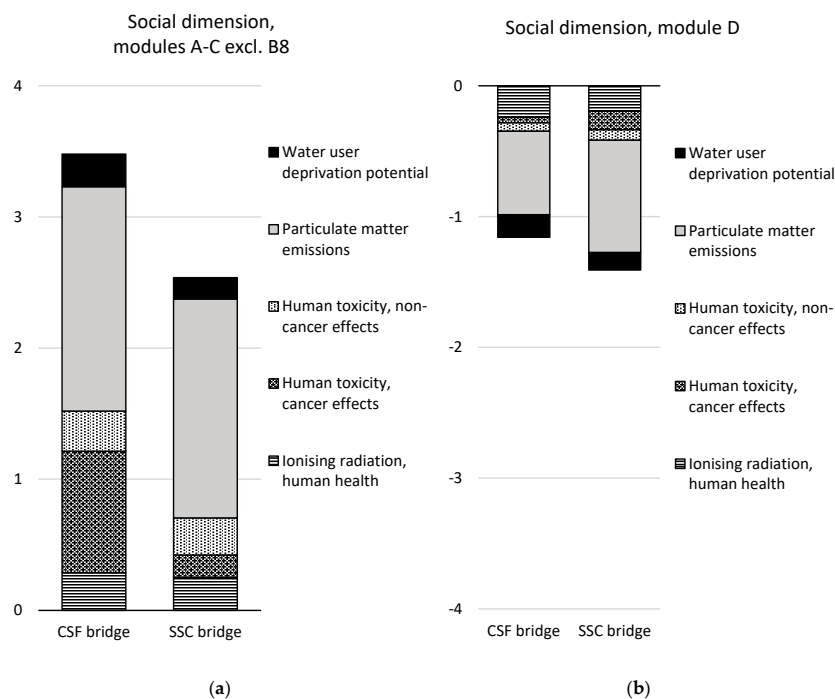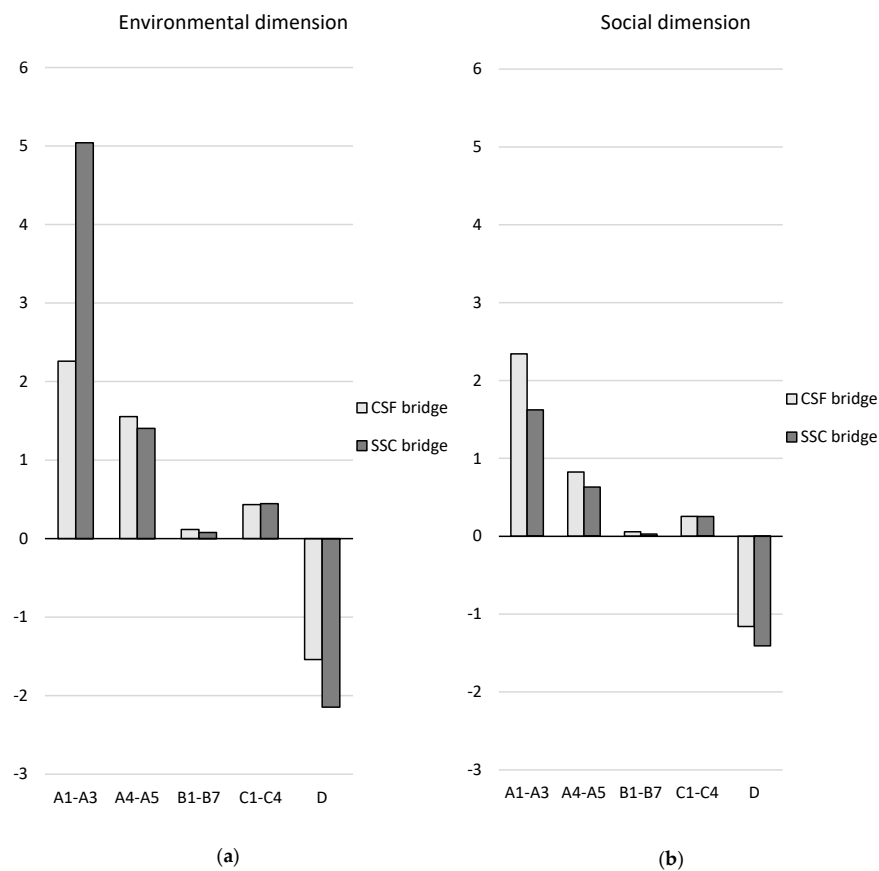

Figure 8. Comparison of the design concepts in the social dimension for (**a**) life cycle stages A–C excluding module B8 and (**b**) module D per indicator and for the functional unit.

Figure 9. Comparison of the design concepts per life cycle stage for (**a**) the LCC and incomes and (**b**) the environmental externalities; presented in Euros for the functional unit. Module B8 is not included in the comparison.
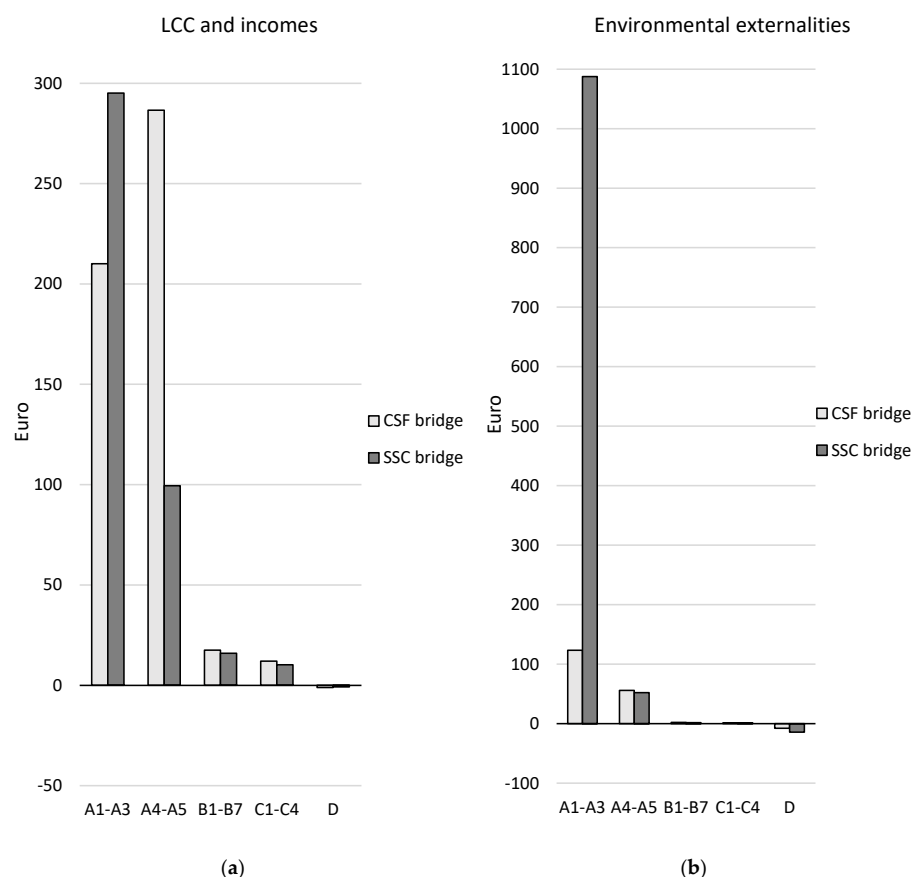

Figure 10. Comparison of the design concepts per life cycle stage in (**a**) the environmental dimension and (**b**) the social dimension for the functional unit. Module B8 is not included in the comparison.

In the environmental dimension, the CSF bridge performs better than the SSC bridge over the life cycle (see Table 8 and Figure 7). The environmental impact of the CSF bridge is approximately one-third lower than that of the SSC bridge. After the end-of-life stage (in module D), the potential avoidance of a negative environmental impact is 39% greater for the SSC bridge.

In the social dimension, the SSC bridge performs better than the CSF bridge over the life cycle (see Table 8 and Figure 8). The social impact of the SSC bridge is 27% lower than that of the CSF bridge. After the end-of-life stage (in module D), the potential avoidance of negative social impact is 22% greater for the SSC bridge.

In the economic dimension, the SSC bridge performs better than the CSF bridge over the life cycle for the indicator "LCC and incomes", but it has a significantly worse performance than the CSF bridge for the indicator "environmental externalities" (see Table 8 and Figure 9). The net cost of the SSC bridge is 20% lower than that of the CSF bridge when it comes to the indicator "LCC and incomes". In contrast, the impact of the factor "environmental externalities" is six times greater for the SSC bridge than for the CSF bridge. After the end-of-life stage (in module D), the potential income and the avoidance of environmental externalities have very small impacts for both concepts.

Considering the different life cycle stages, the SSC bridge has double the environmental impact in the material production phase (modules A1–A3) compared with the CSF bridge (see Figure 10). This is mainly due to the abiotic depletion potential of non-fossil resources caused by the manufacture of structural steel plates for the SSC bridge. This indicator contributes to almost half of the total environmental impact of the SSC bridge in the production stage (see Figure 7). The indicator global warming potential contributes to one-quarter of the environmental impact of the SSC bridge in the production stage.

Figure 11. Comparison of the design concepts per life cycle stage for (**a**) the LCC and incomes and for (**b**) the environmental externalities presented in Euros for the functional unit. Module B8 is not included in the comparison. Note the different y-axis scales in the charts.

The CSF bridge has a 44% larger social impact in the material production phase than the SSC bridge (see Figure 10). This is primarily due to "human toxicity—cancer effects", which are mainly caused by production of stainless-steel reinforcement, and the particulate matter emissions, which are mainly caused by the production of aggregates.

In the production stage, the impact of the environmental externalities of the SSC bridge is almost nine times greater than that of the CSF bridge (see Figure 11). This is due to the use of non-renewable elements in the production of the bridge's structural steel plates. In the construction stage, the net cost for LCC and incomes is almost three times larger for the CSF bridge. This is because of the larger cost for construction workers for the CSF bridge compared with the SSC bridge.

4. Discussion

In the environmental dimension, the CSF bridge was found to perform better than the SSC bridge over the life cycle (see Table 8 and Figure 7). The environmental impact of the CSF bridge was 37% lower than that of the SSC bridge. Similar results were demonstrated in an LCA study comparing a steel box girder bridge and a concrete box girder bridge, where the concrete bridge alternative performed best environmentally overall [22]. However, another LCA study on four CSF bridges and four SSC bridges showed the opposite result: the SSC bridges performed better than the CSF bridges over the life cycle [23]. This is partly because only 54–74% of the structural steel mass was used in three of the SSC bridges in the study by [23], compared with the SSC bridge in this case study. It is also partly because 37% of the structural steel plates were assumed to be secondary steel produced in an electric arc furnace (EAF) route in [23], while in this case study, all of the structural steel plates are from primary steel produced through a blast furnace (BF) route.

In the social dimension, the SSC bridge was found to perform better than the CSF bridge over the life cycle (see Table 8 and Figure 8). The social impact of the SSC bridge was 27% lower than that of the CSF bridge. A similar result was demonstrated by [23], where particulate matter emissions were slightly lower for three of the SSC bridges compared with the CSF bridges.

In the economic dimension, the SSC bridge was found to perform better than the CSF bridge over the life cycle for the indicator LCC and incomes, but it performed significantly worse than the CSF bridge for the indicator environmental externalities (see Table 8 and Figure 9). The opposite result was shown for environmental externalities in [23]. Using the Ecotax02 and Ecovalue08 monetary weighting methods updated with the Ecovalue12 method indicators [24,25], the SSC bridges performed better than the CSF bridges. This might be explained by the fact that the depletion of abiotic resources indicator was not included in the calculation of environmental externalities in [23], even though it is part of both the Ecotax02 and the Ecovalue08 and Ecovalue12 methods. Non-renewable elements and non-renewable energy resources were found to be the major contributors contribute to the environmental externalities in this case study.

For both design concepts, the majority of the negative impact on sustainability was found to occur in the production stage (modules A1–A3). This was also shown in [23], where between 55% and 92% of the environmental impact occurred in the production stage, depending on the indicator. An LCA study of a steel box girder bridge and a concrete box girder bridge similarly showed that the production of materials for the bridge superstructure and the abutments accounted for the main share of the environmental impact, with a limited number of materials being important [22].

Furthermore, the case study demonstrated that 36% of the life-cycle environmental impact for the CSF bridge and 20% for the SSC bridge occurred in the construction stage (modules A4–A5). In [23], it was also shown that the environmental impact of the construction stage is significant; causing up to 34% of the life cycle impact for some indicators. However, in [22], the construction phase accounted for a relatively small part of the impact, and the use phase contributed more significantly, which is contrary to the results of this case study. A main difference between the two concepts in this case study is that a large part of the economic impact (LCC and incomes) was found to occur in the construction stage for the CSF bridge, and this was mainly due to the cost of construction workers.

Module B8 was found to contribute to 50% and 38% of the total environmental impact and 66% and 73% of the total social impact over the life cycle (modules A–C) for the CSF bridge and SSC bridge, respectively. This demonstrates that the environmental and social impacts of the bridge itself are, in fact, significant in comparison to the impact from traffic on the bridge. This was even more obvious for the economic impacts, as module B8 was shown to only contribute to between 3% and 17% for the two economic indicators considered for both bridge types.

The main contribution to the environmental impact over the life cycle (modules A–C excluding B8) was shown to come from the indicator abiotic depletion potential for non-fossil resources for the SSC bridge (35%) and the indicator global warming potential for the CSF bridge (44%). Similar results were demonstrated in an LCA study of a concrete box girder bridge and a steel box girder bridge where global warming, abiotic depletion, and acidification were found to be the indicators with the greatest contributions [22]. In [23], on the contrary, it was shown that the SSC bridges performed better than the CSF bridges regarding the indicator global warming potential. This was partly because less structural steel was used in the SSC bridges and because 37% of the structural steel plates were assumed to be secondary steel produced via an EAF route in [23] (see further explanation above). If only the indicator "global warming potential" had been considered in this case study, the SSC bridge would have performed only 7% worse than the CSF bridge in the environmental dimension. When considering all environmental indicators, the SSC bridge was found to perform 60% worse in the environmental dimension. This demonstrates the importance of including more indicators than only global warming potential, as shown in previous studies [26]. This is an important observation, as today, it is common practice to solely consider global warming potential (or one other indicator such as embodied energy) in assessments of environmental performance [9,26,27].

The main contributor to the social impact over the life cycle (modules A–C excluding B8) was shown to be the indicator particulate matter emissions for both concepts. This is, in part, because of the large weight given to this indicator, but also because construction activities are significant sources of particulate matter emissions, for example, when crushing aggregates [28,29]. For the CSF bridge, the indicator "human toxicity—cancer effects" was also shown to contribute to a large portion of the social impact. For the CSF bridge, it was shown that approximately one-third of the particulate matter emissions were caused by the production of aggregates and their transport to the construction site, and one-third were caused by the production and combustion of diesel used at the construction site. For the SSC bridge, it was shown that one-third of the particulate matter emissions were caused by the production of aggregates; one-third by the production and combustion of diesel used for the construction, maintenance, and deconstruction of the bridge over the life cycle; and one-quarter by the production of structural steel.

The net cost for the LCC and incomes indicator was found to be 25% higher for the CSF bridge than the SSC bridge over the life cycle. For the CSF bridge, the main costs came from cost for workers during construction, and the production and transport of aggregates, concrete, and reinforcement steel. For the SSC bridge, the main contributor to the cost of the LCC and incomes was the cost for the production of structural steel. The environmental externalities of the SSC bridge was six times greater than that of the CSF bridge over the life cycle because of the use of non-renewable elements in the production of the bridge's structural steel plates.

The production of aggregates and their transport to the construction site was shown to be the main factor in the environmental and social impacts of the CSF bridge and the social impact of the SSC bridge. It was also shown to be the second greatest factor in the environmental impact of the SSC bridge. Hence, there is great potential to reduce environmental and social impacts by re-using aggregates on site in the next life cycle to avoid the production of virgin aggregates and their transport to the construction site. The production of the bridge's structural steel plates plays the largest role in the environmental impact as well as the impact on environmental externalities for the SSC bridge due to the depletion of metals. Thus, there is great potential to reduce the impact by using steel produced from recycled steel. Regarding the LCC and incomes over the life cycle, the results show that costs can be reduced

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by lowering the work costs as well as the material costs for the materials purchased in large quantities, such as aggregates, steel and concrete.

It is important to keep in mind that the environmental and social impact results are highly dependent on the LCA datasets chosen for the calculations. It is possible to apply the method using generic licensed datasets or generic datasets from open online LCA databases or Environmental Product Declarations (EPDs), provided they follow the EN15804 + A2 standard. The use of supplier EPDs instead of generic datasets further increases the accuracy of the environmental and social assessment results, since EPDs contain supplier-specific declarations, while generic datasets may not be fully representative of the actual materials supplied in an assessed civil engineering works project. In this case study, only generic datasets were used. They are not completely representative of the resources purchased for the object of assessment. For example, the generic dataset used for aggregates differed from the aggregates purchased, especially regarding the distance between the mining site and crushing plant (10 km in the generic dataset, a few hundred metres for the actual supplier). Generic datasets were used because supplier specific EPDs that follow the EN15804 + A2 standard are not yet available.

As shown from the examination of results, this method allows the sustainability performance of design concepts to be compared at the life cycle stage and construction component level in the early design and planning stages. The data available in these early stages are sufficient for assessment. Through the examination possibilities made available by the transparency of the method, it is possible to identify the critical elements in a civil engineering works project with the greatest impacts on sustainability. This allows necessary adjustments to be made to achieve more sustainable design concepts. Due to its general character, the method can be applied to other types of civil engineering works, not only bridges.

For the social dimension, in particular, but also for the environmental dimension, further research is needed to define appropriate indicators for civil engineering projects. The sustainability dimensions could also be further aggregated using a multi-criteria decision analysis (MCDA) method to obtain an overall sustainability score [30–32]. Furthermore, scenarios for the construction, use, and end-of-life stages may be improved by collecting data from ongoing projects [5]. It is recommended that future studies carry out a sensitivity analysis to assess the influences of different scenarios and datasets whose uncertainty is considered important for the evaluated impacts.

5. Conclusions

The case study demonstrates that our method can be used to carry out comparable and transparent life cycle sustainability performance assessments in the early design and planning stages of a civil engineering works project. It allows the sustainability performance of design concepts to be compared at the life cycle stage and construction component level. The method enables the identification of critical indicators with the greatest impacts on sustainability at the different life cycle stages and for the critical elements. The method is transparent, because the underlying BOMs, scenarios, and datasets used for the assessment are clearly described, and the results can be evaluated down to the building material level. Since the method is based on quantitative indicators and fixed factors, the calculation process used in the assessment is automatable.

The use of supplier EPDs instead of generic datasets will further increase the accuracy of the environmental and social assessment results, since EPDs are supplier-specific declarations, while generic datasets may not be fully representative of the actual materials supplied in an assessed civil engineering works project.

The case study demonstrates the importance of including more indicators than global warming potential in environmental assessments. Environmental and sustainability performance is clearly dependent on several indicators, and care should be exercised when generalising results obtained in assessments that only take into account only one or a few indicators.

The method used in the case study includes state-of-the-art indicators according to current standard specifications and can be complemented with additional indicators. For the social dimension, in particular, but also for the environmental dimension, further research is needed to define appropriate indicators for civil engineering projects.

The results of the case study show the importance of the production stage (modules A1–A3) and the construction stage (modules A4–A5) on the sustainability performance over the life cycle. Production of structural steel for the SSC bridge has the greatest environmental impact and accounts for almost all of the environmental externalities, which explains the poorer performance of this bridge in the environmental dimension. However, the CSF bridge was shown to perform worse than the SSC bridge in the social dimension with a higher LCC. The former point can be mainly explained by the large global warming potential of the CSF bridge due to concrete production, and the latter point can be explained by higher costs during construction due to being more labour-intensive. The production and transport of aggregates have large negative environmental and social impacts for both bridge types.

In summary, the examination of the case study assessment results provides important knowledge on the indicators and life cycle stages associated with large sustainability impacts for each of the bridge concepts investigated. We conclude that to reduce the overall negative impact on sustainability, mitigation measures should primarily address the production and construction stages. Our findings contribute to the development of a better understanding of the sustainability impact of civil engineering works through the identification of elements with the greatest impacts. A special focus and adaptations of identified elements (e.g., origin and type of materials, equipment used, structural optimization) could significantly improve the sustainability performance of the design concepts. After necessary adaptations have been applied to a design concept, the assessment can be re-performed to assess the new conditions. If the assessment is automated, this step could be iterated until the most sustainable alternative is found.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The life cycle inventory (LCI) database provides the life cycle inventory data. The datasets used in the life cycle assessment (LCA) modelling are presented in Table A1.

Table A1. Assignments of inputs and outputs to LCIs from the GaBi database for the LCA.

Inventory	Description	Assumption	GaBi Dataset	Country	Source
Acetylene	Acetylene	-	Ethine (acetylene)	DE	Generic dataset from Sphera
Aggregate waste treatment	Aggregate and macadam waste	90% is re-used as aggregates on site, 10% is transported to landfill	Crushed stone grain 2–15 mm (undried) (EN15804 A1–A3)	EU-28	"
			Inert matter (Construction waste) on landfill	DE	"
Aggregates 0/16 and 0/90 mm	Crushed aggregates 0/16 and 0/90 from igneous rock in Sweden	European limestone 2/15 mm crushed stone	Crushed stone grain 2–15 mm (undried) (EN15804 A1–A3)	EU-28	"

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Table A1. *Cont.*

Inventory	Description	Assumption	GaBi Dataset	Country	Source
Asphalt ABb	ABb asphalt from Sweden	European average supporting layer asphalt	Asphalt supporting layer (EN15804 A1–A3)	EU-28	"
Asphalt ABT	ABT asphalt from Sweden	European average asphalt pavement	Asphalt pavement (EN15804 A1–A3)	EU-28	"
Asphalt recycling	Recycling of ABb, ABT, and Viacogrip asphalt	0.7 kWh of Swedish grid mix electricity used per ton of recycled asphalt (crushing). 1000 kg of recycled asphalt replaces 740 kg of virgin aggregates and 60 kg of virgin bitumen.	Crushed stone grain 2–15 mm (undried) (EN15804 A1–A3)	DE	"
			Bitumen (Eurobitume LCI report 2019) w infrastructure	EU-28	Generic dataset based on Eurobitume report 2019 [33]
Asphalt ViacoGrip	ViacoGrip asphalt from Sweden	European average SMA asphalt	Stone mastic asphalt SMA (EN15804 A1–A3)	EU-28	Generic dataset from Sphera
Average electricity/diesel driven train	-	-	Rail transport cargo—average, average train, gross tonne weight 1000 t/726 t payload capacity	GLO	"
Bitumen sealant			Bitumen emulsion (EN 15804 A1–A3)	DE	"
Bitumen sheet	Icopal Membrane 5BRO (YEP 6500)	Produced in Germany	Bitumen sheets PYE-PV 200 S5 ns (slated) (EN15804 A1–A3)	DE	"
Bitumen sheet waste	Incineration in Swedish district heating plant (Jönköping)	Incineration of average municipal solid waste (MSW) in Germany	Commercial waste in municipal waste incineration plant	DE	"
Bituprimer	Degadur®112	-	Methacrylate resin products, highly-filled, flow coatings—Deutsche Bauchemie e.V. (DBC) (A1–A3)	DE	"
Carbon steel reinforcement recycling	-	Average German production	Recycling potential steel profile (D)	DE	"
Concrete elements	Concrete kerbstone	Bricks of concrete C20/25	Concrete bricks (EN15804 A1–A3)	DE	"
Concrete waste treatment	-	0.7 kWh of Swedish grid mix electricity used per ton of recycled concrete (crushing). 1 kg of recycled concrete replaces 1 kg of virgin aggregates.	Crushed stone grain 2–15 mm (undried) (EN15804 A1–A3)	DE	"
Container ship	-	-	Container ship, 5000 to 200,000 dwt payload capacity, ocean going	GLO	"
Diesel	Diesel 7% bioblend	Diesel 6,4% bioblend	Diesel mix at filling station	EU-28	"
Diesel combustion	Diesel combustion	Combustion of diesel (modified for diesel 7% bioblend)	Diesel combustion in construction machine	GLO	"
Electricity	Swedish grid mix electricity	-	Electricity grid mix	SE	"
Electricity generation from waste incineration	Electricity generation from incineration wood, particle board, plywood, plastic, bitumen sheet, and hazardous waste	Swedish grid mix electricity	Electricity grid mix	SE	"
Epoxy sealant	NM Försegling 62F Tix	Primer for exterior applications	Powder coating based on epoxy resin (EN15804 A1–A3)	DE	"
Form oil	Form oil	From crude oil	Lubricants at refinery	EU-28	"

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Table A1. *Cont.*

Inventory	Description	Assumption	GaBi Dataset	Country	Source
Geotextile	Drefon ST 550 (polypropylene fibre geotextile)	Approximated by woven cotton fibre fabric	Textile Manufacturing —Woven Fabric	GLO	Generic dataset from CottonInc
Graffiti protection	Graffiti Shield wax emulsion	From crude oil	Wax/Paraffins at refinery	DE	Generic dataset from Sphera
Hazardous waste treatment	-	Incineration	Hazardous waste in waste incineration plant	SE	"
HDG steel racks	Birsta W, single sided safety barrier (HDG)	Produced by blast furnace (BF) route, average European production	Steel forged component (EN15804 A1–A3)	EU-28	"
HDG steel recycling	-	Average German production	Recycling potential steel sheet galvanised (EN15804 D)	DE	"
HDG structural steel plates	SSAB Hot-rolled coils S355MC, produced in a blast furnace (BF) route in Sweden and galvanized in Poland	Produced through a BF route and galvanized, German average	Steel sheet HDG (EN 15804 A1–A3)	DE	"
HVO combustion	HVO combustion	Approximated by a combination of biomass/regular diesel combustion	HVO combustion in car	GLO	Dataset based on CO2e emission data from the Swedish EPA 2018, combustion of "Other biomass", other emissions (SO2, NOx, PM etc.) based on data for regular diesel
Hydrogenated Vegetable Oil (HVO)	HVO combustion	Approximated by RME	Rapeseed Methyl Ester (RME)	DE	"
Impregnation (direct emissions)	SILRES® BS 1701	Silicate emulsion primer	Primer silicate emulsion (building, exterior, white) (EN15804 A5)	DE	"
Impregnation (production) Liquified Petroleum Gas (LPG)	SILRES® BS 1701 Liquified Petroleum Gas	Silicate emulsion prime coat average European production	Primer silicate emulsion (building, exterior, white) (EN15804 A1–A3)	DE	"
			Thermal energy from LPG	EU-28	"
Macadam 8/16 mm	Crushed macadam 8/16 from igneous rock in Sweden	European limestone 16/32 mm crushed rock	Crushed rock 16–32 mm (undried) (EN15804 A1–A3)	EU-28	"
Mortar	Fine concrete K40 and expander concrete EXM 702	Average European production	Normal mortar (A1–A3)	EU-28	"
Particle board	Form board from Sweden	Average European P2 (Standard FPY)	Particle board	EU-28	"
Plastic film	-	-	Plastic Film (PE, PP, PVC)	GLO	"
Plastic waste treatment	Incineration in Swedish district heating plant (Jönköping)	Incineration in average European waste incineration plant	Plastic packaging in municipal waste incineration plant	EU-28	"
Plywood	Formply from Sweden	Pine plywood produced in Germany	Plywood board (EN15804 A1–A3)	DE	"
Plywood and particleboard waste treatment	Incineration in Swedish district heating plant (Jönköping)	Incineration in German waste incineration plant	Particle board in municipal waste incineration plant	DE	"
Polyethylene foam	Concrete carpet	Consisting of polyethylene foam	Polyethylene foam (EN15804 A1–A3)	DE	"
Polypropylene pipe	PP road drum	PP pipe produced in Germany	Polypropylene pipe (PP) (EN15804 A1–A3)	DE	"

Table A1. *Cont.*

Inventory	Description	Assumption	GaBi Dataset	Country	Source
PVC tube	PVC drain hose	PVC drain pipe produced in Germany	Rain drain pipe (PVC pipe) (EN15804 A1–A3)	DE	"
PVC waste treatment	PVC waste incineration in Swedish district heating plant (Jönköping)	Incineration in German waste incineration plant	Polyvinyl chloride (PVC) in waste incineration plant	DE	"
Ready-mix concrete C35/45	Betongindustri concrete C35/45 vct = 0,40	Average European production	Concrete C35/45 (Ready-mix concrete) (EN15804 A1–A3)	EU-28	"
Recovery of heat for district heating	Heat recovery from wood, particle board, plywood, plastic, bitumen sheet, and hazardous waste	District heating produced by plant in Jönköping	District heating mix Jönköping 2019	SE	Specific dataset based on fuel use for Jönköping district heating plant
Reinforcement (carbon steel)	B500B	Produced by the electric arc furnace (EAF) route, average European production	Reinforced steel (wire) (EN15804 A1–A3)	EU-28	Generic dataset from Sphera
Reinforcement (stainless steel)	LDX2101	Produced from 100% alloyed stainless steel scrap	Fixing material screws stainless steel (EN15804 A1–A3)	DE	"
Road salt	-	From rock salt	Sodium chloride (rock salt)	DE	"
Stainless steel reinforcement recycling	-	Average German production	Recycling potential stainless steel sheet (EN15804 D)	DE	"
Tap water	Tap water	Swedish tap water produced from groundwater	Tap water from groundwater (for regionalization)	GLO (SE chosen in dummy)	"
Truck, Euro 6	-	-	Truck, Euro 6, 20–26 t gross weight/17.3 t payload capacity	GLO	"
Untreated wood	Spruce wood from Sweden	Coniferous wood produced in Germany	Solid construction timber (softwood) (EN15804 A1–A3)	DE	"
Wood waste treatment	Wood waste incineration in Swedish district heating plant (Jönköping)	Incineration in German waste incineration plant	Wood (natural) in waste incineration plant	DE	"

" denotes 'Same as above'.

Appendix B

Table A2. Bill of materials (BOM) for the design concepts for each module. Amounts are representative of the required service life (RSL) and for the bridges as a whole. The amounts for modules B1–B8, C1–C4 and D were calculated based on the scenarios presented in Tables A3–A5.

Concept	Module	Resource/Waste	Amount	Unit
		Aggregates 0/16 and 0/90 mm	6,820,600	kg
		Macadam 8/16 mm	12,000	kg
	A1–A3	Asphalt Abb	6983	kg
		Asphalt ABT	4364	kg
		Asphalt ViacoGrip	5237	kg
		Concrete elements	8100	kg

Table A2. *Cont.*

Concept	Module	Resource/Waste	Amount	Unit
		Hot-dip galvanized (HDG) steel racks	250	kg
		Polypropylene pipe	106	kg
		Geotextile	17	kg
	A5	Electricity (Swedish grid mix)	4560	kWh
		Tap water	1500	liters
		PVC tube	105	kg
		PVC waste	105	kg
	B1	Zinc to fresh water	0.55	kg
		PAH to fresh water	0.112	kg
	B2	Tap water	400	liters
		Road salt	65	kg
	B3	HDG steel racks	692	kg
		HDG steel racks waste for recycling	692	kg
		HDG steel racks	692	kg
	B4	Asphalt	10,500	kg
		Diesel 7% bioblend	17	liters
		Tap water	10,000	liters
		HDG steel racks waste for recycling	692	kg
	B5	N/A	-	
	B6	N/A	-	
	B7	N/A	-	
	B8	Diesel 7% bioblend	11,797	liters
		Hydrogenated Vegetable Oil (HVO)	41,611	liters
		Electricity (Swedish grid mix)	357,209	kWh
		Particles to fresh water	10,950	kg
		Micro plastics to soil	131	kg
	C1	Diesel 7% bioblend	39	liters
	C2	See Table A6	-	
	C3	Aggregates for re-use	6,149,340	Kg
		Asphalt waste for recycling	16,580	Kg
		Polypropylene plastic waste for incineration	106	Kg
	C4	Aggregates on inert landfill	683,260	Kg
	D	Electricity (Swedish grid mix)	19	kWh
	A1–A3	Ready-mix concrete C35/45	463,700	Kg
		Reinforcement (carbon steel)	22,680	Kg
		Reinforcement (stainless steel)	553	kg
		Bitumen sheet	380	kg
		Mortar	180	kg
		Epoxy sealant	77	kg
		Bituprimer	35	kg
		Impregnation	19	liters
		Graffiti protection	19	liters
		Bitumen sealant	10	kg
		Polyethylene foam	5	kg
CSF bridge	A5	Untreated wood	5400	kg
		Diesel 7% bioblend	5280	liters
		Particle board	1600	kg
		Plywood	1000	kg
		Form oil	130	kg
		Plastic film	22	kg
		Concrete waste for recycling	23,185	kg
		Wood waste for incineration	5400	kg
		Plywood and particleboard waste for incineration	2600	kg

Table A2. *Cont.*

| Concept	Module	Resource/Waste	Amount	Unit
		Reinforcement waste (carbon steel) for recycling	1134	kg
		Plastic waste for incineration	22	kg
		Bitumen sheet waste for incineration	19	kg
	B1	CO$_2$ uptake	1139	kg
		Zinc oxide to air	0.55	kg
	B2	Diesel 7% bioblend	70	liters
		Tap water	29,400	liters
		Graffiti shield	15	liters
	B3	Concrete C35/45	1344	kg
		Tap water	1000	liters
		Concrete waste	1411	kg
	B4	Concrete C35/45	12,600	kg
		Diesel 7% bioblend	27	liters
		Bitumen sealant	10	kg
		Bitumen sheet	380	kg
		Bituprimer	35	kg
		Epoxy sealant	77	kg
		Bitumen sealant waste for incineration	10	kg
		Bitumen sheet waste for incineration	380	kg
		Bituprimer waste for incineration	35	kg
		Epoxy sealant waste for incineration	77	kg
	C1	Diesel 7% bioblend	1453	liters
		Tap water	386,000	liters
	C2	See Table A6	-	
	C3	Concrete for recycling	448,615	kg
		HDG steel for recycling	250	kg
		Carbon steel reinforcement for recycling	22,680	kg
		Stainless steel reinforcement for recycling	553	kg
		Bitumen sealant waste for incineration	10	kg
		Bitumen sheet waste for incineration	380	kg
		Bituprimer waste for incineration	35	kg
		Epoxy sealant waste for incineration	77	kg
	C4	N/A	-	
	D	Electricity (Swedish grid mix)	340	kWh
SSC bridge	A1–A3	HDG structural steel plates incl. bolts and nuts	40,653	kg
	A5	Diesel 7% bioblend	5230	liters
	B1	Zinc oxide to air	3.35	kg
	B2	Diesel 7% bioblend	52	liters
		Tap water	26,200	liters
	B3	N/A	-	
	B4	N/A	-	
	C1	Acetylene	8300	liters
		Diesel 7% bioblend	2339	liters
	C2	See Table A6	-	
	C3	HDG structural steel plates incl. bolt and nuts for recycling	40,653	kg
	C4	N/A	-	
	D	N/A	-	

Appendix C

Common scenarios for both design concepts are presented in Table A3. Specific scenarios for the CSF bridge and the SSC bridge design concepts are presented in Tables A4 and A5, respectively.

Table A3. Common scenarios for both design concepts for each module (B–D).

Module		Scenario
B1	(1)	Zinc in steel racks oxidizes and is released to air and water. The amount of zinc released from galvanized steel racks on a highway was calculated to be 0.95 kg/year/km [34]. It is assumed that 50% of this is released as zinc oxide particles to air and 50% is released in soluble form to water, giving a total of 0.55 kg of zinc released from the bridge to water and air respectively over 80 years.
	(2)	Bitumen in asphalt is degraded and PAH leaches into the local environment at a rate of 0.5 mg PAH/m^2 asphalt over 25 years [35], giving a total of 112 mg of PAH is released from the bridge to soil over 80 years.
B2	(1)	Washing of steel racks with drinking water occurs twice a year. Approximately 25 L is used per 100 m rack according to expertise within the Swedish Transport Administration, giving 400 L of water consumed over 80 years. The work cost is negligible and therefore was not included.
	(2)	A total of 0.8 kg of salt is administered per year across the whole road surface of the bridge [36], giving 65 kg over 80 years. The work cost is negligible and therefore was not included.
	(3)	A total of 0.07 h is needed for snow removal per km of lane per year [36]. The bridge has 3 lanes, and we assumed the use of a diesel-driven vehicle of 100 kW, giving 1.3 L of diesel over 80 years, which is considered negligible and was therefore not included.
B3		10% of the steel rack mass is repaired every second year, giving 692 kg over 80 years. The cost for this amount of steel is 8650 Euros. The energy used for the repairs is estimated to be negligible and was therefore not included. The work cost was calculated assuming 1 h of work per occasion and a salary of 60 Euros/h, giving 2400 Euros.
B4	(1)	Steel racks are replaced completely every 20 years, giving 692 kg over 80 years. The cost for this amount of steel is 8650 Euro of which the work cost is 2 400 Euro.
	(2)	A depth of 30 mm of the top asphalt layer is replaced every 40 years, giving 10,500 kg of asphalt over 80 years. The amount of diesel used for milling is 1.6 L/ton asphalt milled, giving 17 L over 80 years. The work cost is negligible and was therefore not included.
B5		No refurbishment needed
B6		No energy consumption
B7		No water consumption
B8	(1)	Energy consumption of passing vehicles: It is estimated that the mean daily traffic on the bridge per year over the RSL will increase, as illustrated in Figure A1. It is assumed that 50% of the vehicles will be diesel-driven and 50% will be electric up until 2030; 20% will be diesel-driven, 20% will be HVO-driven, and 60% will be electric in 2030–2045; and 30% will be HVO-driven and 70% electric from 2045 onwards. The diesel and HVO consumption is assumed to 0,06 L/km and the electricity consumption is assumed to be 0.2 kWh/km, giving 11,797 L of diesel, 41,611 L of HVO, and 357,209 kWh of electricity over 80 years.
	(2)	A total of 760 kg of asphalt is abraded per 100 m lane/year (at AADT 15,000, 100 km/h according to [37], giving 10,950 kg particles (of diameter 50–1000 μm) over 80 years.
	(3)	Tires are abraded by 0.05 g/km and vehicles [38], giving 131 kg of microplastic over 80 years (25% styrene and 75% butadiene).
C1	(1)	Steel racks are lifted away using a diesel-driven crane. It is estimated that 1 h is needed for 14 m of racks using a crane that consumes 12 L/h [39], giving 12 L of diesel. The work cost is negligible and was therefore not included.
	(2)	Asphalt is milled using a machine that consumes 1.6 L of diesel/ton asphalt milled, giving 27 L. The work cost was calculated assuming 16 h of work and a salary of 60 Euros/h, giving 1000 Euro.

Table A3. *Cont.*

Module	Scenario
C2	(1) Steel racks are transported by truck to a storage facility. (2) Asphalt is transported by truck to recycling. (3) A total of 90% of the aggregates are not moved, and 10% are transported 39 km by truck to landfill.
C3	N/A, end-of-waste is reached for asphalt and steel racks before waste treatment takes place.
C4	A total of 10% of the aggregates are disposed on an inert landfill = 683,260 kg. The cost for landfilling is 30 Euros/ton.
D	(1) 100% of the steel racks are recycled. The selling price is 0.1 Euro/kg steel. (2) 100% of the asphalt is recycled. Crushing of the recycled asphalt is done with an electric crusher using 0.7 kWh/ton, giving 19 kWh in total. The selling price is 5 Euros/ton asphalt. (3) A total of 90% of the aggregates are not moved and are re-used as filling material on site.
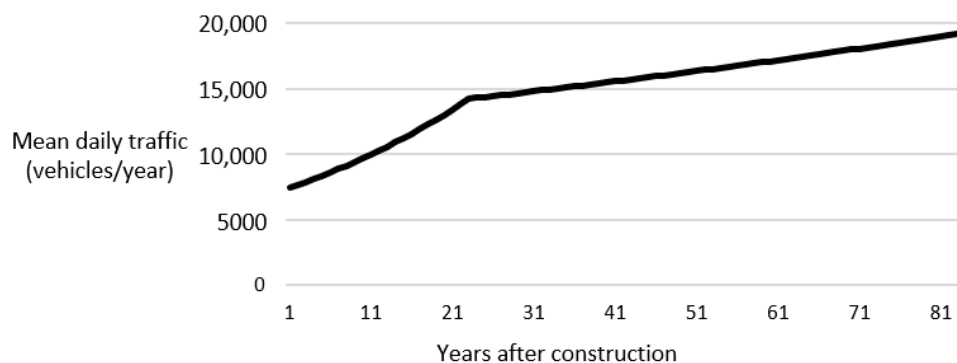
Figure A1. Estimated mean daily traffic on the bridge per year over the RSL (up to 80 years after construction).

Table A4. Specific scenarios for the CSF bridge design concept for each module (B–D).

Module	Scenario
B1	Carbonation of the concrete surfaces was calculated according to [40] with the following assumptions: • Area exposed to rain: 55 m² • Area protected from rain: 210 m² • Area in ground: 300 m² giving that 1139 kg CO_2 is taken up by the bridge over 80 years.
B2	Graffiti removal is done every 10 years by washing with hot water under high pressure. After washing, new graffiti protection is applied. It is assumed that 10% of the available surface area of 170 m² is covered by graffiti over 10 years, giving 17 m². It is estimated that it takes 15 min to wash 1 m², giving 4 h to wash in total per occasion. The equipment consumes 2.15 L of diesel/h, giving 70 L over 80 years. It consumes 15 L of drinking water/minute, giving 29.4 m³ in total over 80 years. Graffiti protection of 10% of the surface, giving 15 L over 80 years. The work cost was calculated assuming 32 h of work and a salary of 60 Euros/h, giving 1 920 Euro.

Table A4. *Cont.*

Module	Scenario
B3	Minor repairs in the concrete parts are needed every 10 years. A 1 m^2 layer of concrete with a thickness of 70 mm is repaired per occasion, giving 1344 kg concrete repaired over 80 years. A total of 2000 L of water is used per m^3 of concrete repaired, giving 1000 L over 80 years. The amount of diesel consumed is negligible and was therefore not included. The work cost was calculated assuming 14 h of work and a salary of 60 Euros/h, giving 840 Euros.
B4	Replacement of edge beams is done every 40 years. The two edge beams are 400 mm wide, 500 mm high, and 6 m long, giving 5 m^3 of concrete is replaced over 80 years. The equipment has a diesel consumption of 5.3 L/h, and 1 m^3 concrete is removed/h, giving 27 L over 80 years. It also consumes 2000 L of drinking water/h [41], giving 10 m^3 in total over 80 years. The bridge insulation is totally replaced every 40 years, giving 77 kg of epoxy sealant, 10 kg of bitumen sealant, 35 kg of bituprimer, and 380 kg of bitumen sheet over 80 years. The work cost was calculated assuming 16 h of work and a salary of 60 Euros/h, giving 1000 Euro. The cost for 1 day of scaffolding rent is estimated to be 100 Euros.
C1	(1) Concrete is demolished using equipment that consumes 2000 L of drinking water and 5.3 L of diesel per m^3 of concrete, giving 386 m^3 water and 1023 L of diesel in total. The work cost was calculated assuming 193 h of work and a salary of 60 Euros/h, giving 11,600 Euros. (2) A total of 90% of the aggregates is not handled at all, and 10% is excavated using an excavator consuming 1.5 L/m^3 of excavated material, giving 430 L of diesel. The work cost was calculated assuming 290 h of work and a cost of 100 Euros/h, giving 29,000 Euros.
C2	(1) Reinforcement steel is transported by truck to a storage facility. (2) Concrete is transported by truck to a recycling facility.
C3	N/A, end-of-waste is reached for concrete and reinforcement steel before waste treatment takes place.
C4	N/A, no waste is disposed.
D	(1) All of the concrete is recycled into filling material. Crushing of the recycled concrete is done with an electric crusher using 0.7 kWh/ton, giving 340 kWh in total. The selling price is 5.3 Euro/ton concrete. (2) All of the reinforcement steel is recycled into reinforcement steel. The selling price is 0.1 Euro/kg of carbon steel and 0.9 Euro/kg of stainless steel.

Table A5. Specific scenarios for the SSC bridge design concept for each module (B–D).

Module	Scenario
B1	Zinc oxidizes on the bridge's structural steel plates into a powder which is assumed to disperse into the surrounding air (since the steel surface is protected from rain). Conservatively, it is assumed that 0.5 g of Zn is dispersed per m^2 plate and year [34,42]. The area is 70 m^2, giving 2.8 kg of Zn is released to air over 80 years.
B2	(1) Graffiti removal is done every 10 years by washing with hot water under high pressure. No graffiti protection is needed on steel. It was assumed that 10% of the available surface area of 126 m^2 is covered by graffiti over 10 years, giving 13 m^2. It was estimated that it takes 15 min to wash 1 m^2, giving 3 h to wash in total per occasion. The equipment consumes 2.15 L of diesel/h, giving 52 L over 80 years. It consumes 15 L of drinking water/minute, giving 22.4 m^3 in total over 80 years.

Table A5. *Cont.*

Module	Scenario
	The work cost was calculated assuming 32 h of work and a salary of 60 Euros/h, giving 1 920 Euro.
	Washing of the bridge's structural steel plates surface of 95 m^2 is also done by using hot water under high pressure. It is done once a year using 0.5 L of drinking water/m^2, giving 3800 L over 80 years.
B3	No repairs are needed.
B4	No replacements are needed.
C1	(1) Masses covering the bridge's steel construction are excavated. A total of 4600 m^3 is excavated using an excavator with a capacity of 40 m^3/h using 20 L of diesel/h, giving 2300 L of diesel. (2) Steel plates are cut with a cutting torch consuming 0.3 m^3 acethylene/h to cut 36 m of steel plate/h [43], giving 8.3 L/m. A length of 1000 m was assumed to be cut, giving 8300 L used over 80 years (corresponding to 9 kg of ethine). The work cost was calculated assuming 16 h of work and a salary of 80 Euros/h, giving 1280 Euros.
C2	The bridge's structural steel plates are transported by truck to a storage facility.
C3	N/A, end-of-waste is reached before waste treatment takes place.
C4	N/A, no waste is disposed.
D	All of the bridge's structural steel plates are recycled. The selling price is 0.1 Euro/kg steel.

Appendix D

Table A6. Transport modes and distances travelled for the resources (applicable for modules A4, A5, B1–B4 and C2).

Concept	Resource	Transport Mode	Distance (km)
Both	Aggregates (crushed rock), asphalt	Truck, Euro 6, 20–26 t gross weight/17.3 t payload capacity, 55% utilisation	39
	Concrete elements	"	66
	Diesel 7% bioblend	"	100
	Steel racks	"	646
	Aggregate waste, Asphalt waste, Concrete waste	"	39
	Steel waste (racks, reinforcement steel, stainless steel)	"	50
	Plastic waste	"	38
CSF bridge	Ready-mix concrete C35/45	"	40
	Reinforcement (carbon steel)	Average electricity/diesel driven train, gross tonne weight 1000 t/726 t payload capacity, 40% utilisation Truck Euro 6, 20–26 t gross weight/17.3 t payload capacity, 55% utilisation	1510 198
	Reinforcement (stainless steel)	Container ship, 5000 to 200,000 dwt payload capacity, ocean going, 70% utilisation Truck Euro 6, 20–26 t gross weight/17.3 t payload capacity, 55% utilisation	49 1045
	Untreated wood, particle board, plywood	Truck Euro 6, 20–26 t gross weight/17.3 t payload capacity, 55% utilisation	20

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Table A6. *Cont.*

Concept	Resource	Transport Mode	Distance (km)
	Bitumen sheet waste, wood waste	"	38
	Hazardous waste	"	200
SSC bridge	Structural steel plates	Container ship, 5000 to 200,000 dwt payload capacity, ocean going, 70% utilisation Truck Euro 6, 20–26 t gross weight/17.3 t payload capacity, 55% utilisation	360 2027
	Steel waste (structural steel plates)	Truck Euro 6, 20–26 t gross weight/17.3 t payload capacity, 55% utilisation	50

" denotes 'Same as above'.

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