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A harmonized method for automatable life cycle sustainability performance assessment and comparison of civil engineering works design concepts

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Abstract. The life cycle sustainability performance of civil engineering works is increasingly important. The possibility to influence the sustainability of a project design is larger in the conceptual stage than in later stages. Better-informed decisions regarding design choices' impact on sustainability can be made by comparing conceptual project designs based on an assessment of their life cycle sustainability performance. It is essential that concepts are assessed in a harmonized way and compared impartially. Current standards provide the general framework for the assessment of sustainability performance, but do not give detailed guidance on calculation of sustainability indicators and their aggregation. Since design in automated systems is becoming increasingly common, there is a growing need for machine-readable data and automatable assessment methods. Assessment methods which can be applied using open-access data is important to achieve fair competition. This paper aims to provide a method for life cycle sustainability performance assessment and comparison of civil engineering works design concepts, possible to apply using open-access Environmental Product Declarations (EPDs) and life cycle assessment (LCA) data. The purpose is to enable fair and automatable sustainability assessments of design concepts, to facilitate impartial comparisons of such assessments as a basis for choosing sustainable designs. A literature review of relevant standards and scientific papers on sustainability assessment of construction and civil engineering works was performed. A harmonized, fair and automatable method for life cycle sustainability assessment and comparison of civil engineering works design concepts, well-suited for optimization purposes, is presented. However, the aim currently limits categories and indicators possible to include. The proposed method includes guidance on the calculation of environmental, social and economic indicators, based on LCA, life cycle costing (LCC) and external costs, and aggregation using normalisation and weighting factors of the Product Environmental Footprint (PEF). The proposed method allows for an impartial comparison of the sustainability of design concepts, resulting in better-informed decisions.

1. Introduction

In civil engineering projects, life cycle environmental, social and economic sustainability performance is increasingly important, as reflected in the large number of standards on the subject in recent years [1–15]. To make better-informed decisions regarding design choices' impact on project sustainability,

sustainability performance assessment is recommended. It is important that assessments are performed in a harmonized way and compared impartially. Current standards provide the general framework for sustainability performance assessment of civil engineering works, but do not give detailed guidance on calculation of sustainability indicators and their aggregation. Since design in automated systems is becoming increasingly common, there is a growing need for machine-readable data and automatable assessment methods. To achieve fair competition, access to open-access data is also important.

The possibility to influence the sustainability of a design is larger in the conceptual stage of the design process than in later stages [16]. It is therefore important to define parameters that can support an iterative sustainability-driven design process from concept to final implementation. An automated set-based design (SBD) method was shown to be practical in formalizing sustainability assessment of design concepts [17]. However, the limited number of sustainability indicators used in the study was a limitation for a formalized implementation of the method in the design process. To achieve that, SBD must be complemented by a comprehensive sustainability assessment method. If the SBD method and the sustainability assessment method are data-driven and automated they are promising for training artificial intelligent agents that can perform isolated and/or global tasks in the design process [18].

To address the challenge of choosing sustainable designs, a formalized method enabling impartial, fair and automatable sustainability assessments and comparisons of design concepts is desired. This paper aims to provide a harmonized method for life cycle sustainability assessment and comparison of design concepts, which can be applied by using open-access Environmental Product Declarations (EPDs) and life cycle assessment (LCA) data. The method is intended to be used in the clients' or the contractors' planning, design and tender phase of civil engineering works projects.

A suite of international and European standards has been published in the field of sustainability assessment of civil engineering works and buildings, see Table 1.

Table 1. Overview of standards on sustainability of civil engineering works and buildings.

Standard number (publication year)	*Information about the standard*	*Ref.*
ISO 15392 (2008, updated 2019)	Provides general principles of sustainability related to buildings and other construction works and set out sustainability objectives.	[14]
EN 15643-1 (2010)	A general framework standard for sustainability assessment of buildings.	[1]
EN 15643-2 (2011)	A framework standard for the assessment of environmental performance of buildings.	[2]
EN 15643-3 (2012)	A framework standard for the assessment of social performance of buildings.	[6]
EN 15643-4 (2012)	A framework standard for the assessment of economic performance of buildings.	[7]
EN 15643-5 (2017)	Outlines specific principles and requirements for sustainability assessment of civil engineering works. Requires that environmental indicators are the same as EPD indicators in EN 15804. Suggests including LCC and external costs as indicators in the economic dimension.	[9]
EN 15804 (2012, updated 2019)	Provides a structure to ensure that EPDs of construction products, services and processes are derived, verified and presented in a harmonized way.	[13]
EN 15978 (2011)	Provides calculation rules for the assessment of the environmental performance of new and existing buildings. Requires that environmental indicators are the same as the EPD indicators in EN 15804.	[3]
EN 16309 (2014)	Provides calculation rules for the assessment of the social performance of buildings. Requires assessment of social aspects and impacts for the use stage only.	[4]
EN 16627 (2015)	Provides calculation rules for the assessment of the economic performance of buildings. Only requires calculation of the indicator life cycle costing (LCC).	[5]
ISO 21929-2 (2015)	Describes and gives guidelines for the development of sustainability indicators related to civil engineering works. Defines the aspects and impacts of civil engineering works to consider when developing systems of indicators.	[15]
ISO 21931-2 (2019)	Provides a framework for methods for the assessment of the sustainability performance of civil engineering works. The purpose is to improve quality and comparability of methods for assessing the contribution of civil engineering works to sustainable development based on a life cycle approach.	[11]

In addition, a European standard on calculation methods for sustainability assessment of civil engineering works, and an international standard on principles for the development and use of benchmarks in sustainability assessment of buildings and civil engineering works are currently under development.

The standards classify life cycle stages in so-called modules. Module A0 is the pre-construction stage, modules A1-A3 represent the product stage from raw material extraction to construction material manufacturing, A4-A5 represent the construction process stage, B1-B5 the use stage relating to maintenance, B6-B7 the use stage relating to operation, B8 the use stage relating to the user's utilization, C1-C4 the end-of-life stage and module D represents the benefits and loads beyond the system boundary.

Since 2013, the European Commission is developing and testing the multi-criteria measure Product Environmental Footprint (PEF); a joint European way of measuring the environmental performance of products [19]. Normalization and weighting are optional steps of PEF which may be used to better understand and compare results. Normalized results show the magnitude of the indicator relative to a reference unit. Thus, it reflects the contribution of the analyzed system to the total impact potential, not the severity or relevance of the respective total impact. Weighting factors reflect the regarded relative importance of the indicators considered. Weighted results of indicators may be summed to obtain a single overall score. The normalization and weighting factors within PEF are published by the Joint Research Centre (JRC) [20, 21]. Regulation (EU) 66/2010, which establishes the rules and conditions to develop Ecolabel criteria for products, prescribes that criteria shall be based on life cycle assessment (LCA) [22]. As the European Commission has adopted PEF, it will likely be the reference method for performing all new LCA studies for developing Ecolabel criteria. EN 15804 was updated in 2019 to be compatible with PEF.

The proposed method has a high scalability potential and can be used as-is in Europe. It may be used globally since it does not contradict ISO 21931-2, and because LCA datasets and EPDs representing all parts of the world are available. The number of international LCA datasets and EPDs within the construction sector are expected to increase and be adapted to the updated EN 15804 [13]. The innovativeness of the proposed method is high since it enables automation of sustainability assessments. This allows coupling the assessment to machine learning and artificial intelligence to optimize design concepts based on their contribution to sustainable development.

The proposed method contributes to Sustainable Development Goals (SDGs) 9 and 12; SDG 9 since it is intended to be used for design of sustainable infrastructure, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, and SDG 12 since it supports sustainable management and efficient use of natural resources and reducing waste generation and because it promotes sustainable public procurement practices. It also contributes to SDGs 3, 6, 7 and 8, since it supports healthy building materials, water-use efficiency, renewable energy use and energy efficiency and global resource efficiency in consumption and production.

2. Method

A literature review of relevant standards and scientific papers on sustainability assessment of construction and civil engineering works was performed. The literature search was made by searches on the word "sustainability" on the homepage of the Swedish Institute for Standards (SIS) and searches and mail alerts on the word combinations: sustainability AND (indicator OR criteria) AND (infrastructure OR "civil engineering"), social AND (criteria OR indicator) (infrastructure OR construction), and LCSA OR "life cycle" on Google Scholar.

3. Result

The proposed method follows the principles and requirements of methods for sustainability performance assessment given in the standards [9] and [11], although currently not all categories recommended by the standards are included. It can be used for assessment of the entire life cycle of a civil engineering works; from module A0 to module D. It is possible to use the proposed method in any stage of the project, from the early concept stages.

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3.1. Assessment steps

The mandatory steps in an assessment (as prescribed in ISO 21931-2) are presented in Table 2. For guidance on the assessment steps, see ISO 21931-2.

Table 2. Mandatory assessment steps in the proposed method.

1	Indicate the object of assessment
2	Indicate the intended use of the assessment
3	Indicate additional functions provided by the object of assessment (in addition to the client's primary brief)
4	Define and describe the functional equivalent: a) Type/use of the civil engineering works, b) Capacity, c) Period and pattern of use, d) Design life (required service life, RSL), e) User requirements
5	State the time of assessment in the life cycle
6	State which life cycle stages are assessed
7	Justify and explain any exclusion of life cycle stages (modules). All relevant modules shall be calculated.
8	Define area of influence for each sustainability dimension and life cycle stage
9	Indicate the energy and mass flows considered in the assessment
10	Define and describe general assumptions and scenarios used
11	Indicate the required service life (RSL) of the object of assessment
12	Indicate the reference study period
13	Describe the sources of data for the indicators
14	State for each data if it is specific or generic
15	State reference year of cost data
16	Document and explain the outcome

The assumptions that are predetermined in the proposed method are detailed below and further described in the following chapters:
Functional unit: The functional unit shall be the same as the functional unit in the PCR of the product group which the object of assessment belongs to. The PCR shall be from a program operator that is a member of Eco Platform.
Core set indicators: See Table 3.
Calculation methods used for indicators: Environmental and social indicators shall be the life cycle impact assessment (LCIA) indicators and the method of measurement shall be LCA, both according to [13]. LCC shall be calculated according to [10]. The external environmental cost shall be calculated in accordance with ISO 14008, for example using the EPS 2015dx assessment method [23].
Reference levels used: No reference levels are used.
Aggregation method: Environmental and social indicators shall be aggregated by using the normalization and weighting factors used within PEF. See further details in chapter 3.4.
Sources and types of data for the indicators: See chapter 3.3.
Weighting process, weighting factors and evaluation approach: See chapters 3.4-3.6.

3.2. Core set indicators

The core set of indicators and categories included in the proposed method has been chosen based on requirements in standards [3–5, 9, 11, 15]. All indicators can be assessed in all life cycle stages. The indicators are presented in Table 3.

Table 3. Core set indicators per dimension and category, and their unit of measurement.

Dimension	*Category*	*Indicators (core set)*	*Unit of measurement*
Environ-mental	Acidification	Acidification potential (AP)	mol H^+ eq
	Biodiversity	Eco-toxicity (freshwater)	CTUe
		Potential soil quality index (SQP)	Dimensionless
	Climate change (total)	Global warming potential total (GWP-total) (fossil+biogenic+land use and land use change)	kg CO_2 eq
	Depletion of abiotic resources - minerals & 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 (EP-freshwater)	kg P eq
		Eutrophication potential (EP-marine)	kg N eq
		Eutrophication potential (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	Ionizing radiation, human health (PIR)	kBq U235 eq
		Human toxicity, cancer effects (HTP c)	CTUh
		Human toxicity, 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	Direct life cycle costs (LCC) and incomes	e.g. Euro
	External cost	Environmental externalities	e.g. Euro

3.3. Data sources
A life cycle inventory (LCI) is a prerequisite for the calculation of LCIA indicators. LCI is an inventory of energy and material resources needed and emissions and waste generated in the project, expressed in quantities. LCIs may be in the form of Bill of Materials (BoMs) or can be calculated using SBD. To increase precision and accuracy of the calculations it needs to be detailed on resource level. In early design stages however, the detail level is allowed to be low. For the LCC, costs from the LCI are needed.

For each of the resources used, EPDs, PEFs and/or open-access LCA datasets are necessary. For the calculation of external environmental costs, results for the environmental indicators are used. The results are translated to costs by using for example the open-access EPS 2015dx method [23].

Realistic and representative scenarios of the resource consumption and costs in modules B-D need to be developed for each design concept. They can be developed in collaboration with experts and collected from open national statistics databases. Future EPDs following the updated EN 15804 standard will also in most cases include data on modules C and D.

3.4. Aggregation method
Current standards do not give guidance on aggregation of indicators. The proposed method suggests using normalization and weighting factors used in PEF for aggregation of environmental and social indicators since they have been agreed upon in a large European collaboration, see Table 4. PEF will also likely be the reference method for performing all new LCA studies needed for developing Ecolabel criteria. The normalization factors (NF) are the "global NF for EF per person", based on the EF 2017 method [20] and updated in 2019 [24]. The weighting factors are from the JRC report by Sala et al. [21].

In the proposed method, some indicators are categorized into the environmental dimension and some into the social dimension. In the PEF system, the 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. Table 4 presents the NF and weighting factors used in the proposed method.

Table 4. Unit, NF and weighting factors for environmental & social indicators, adapted from [21, 24].

Indicator	*Unit*	*Normalization factor (NF)*	*Weighting factor (%)*
<u>*Environmental dimension*</u>			
Global warming potential total (GWP-total)	kg CO_2 eq	8 096	28,63
Ozone depletion potential (ODP)	kg CFC 11 eq	0,0536	8,58
Photochemical ozone creation potential (POCP)	kg NMVOC eq	40,6	6,50
Acidification potential (AP)	mol H^+ eq	55,6	8,43
Eutrophication potential (EP-terrestrial)	mol N eq	177	5,04
Eutrophication potential (EP-freshwater)	kg P eq	1,61	3,81
Eutrophication potential (EP-marine)	kg N eq	19,5	4,02
Eco-toxicity (freshwater)	CTUe	42 683	2,61
Potential soil quality index (SQP)	dimensionless	819 498	10,80
Abiotic depletion potential for non-fossil resources (ADPE)	kg Sb eq	0,0636	10,27
Abiotic depletion potential for fossil resources (ADPF)	MJ, net calorific value	65 004	11,31
<u>*Social dimension*</u>			
Human toxicity, cancer effects (HTP c)	CTUh	0,0000169	8,05
Human toxicity, non-cancer effects (HTPnc)	CTUh	0,00023	6,96
Particulate matter emissions (PM)	Disease incidence	0,000595	33,88
Ionizing radiation, human health (PIR)	kBq U235 eq	4 220	18,94
Water user deprivation potential (WDP)	m^3 world deprived eq	11 469	32,17

The normalized and weighted result for each environmental and social indicator is obtained by dividing the indicator result in its measured unit by its NF and multiplying it by its weight.

3.5. *Result presentation per design concept*

Results shall be presented for the functional unit and reference service life (RSL), and per cost and income/indicator/category and life cycle stage as prescribed by the standards, see presentation layout in Table 5. The proposed method allows summarizing the life cycle stages A-C, which is not prescribed by the standards. The result for the LCIA indicators shall be presented in their measured units (see Table 3). Normalized and weighted results for each of the LCIA indicators shall be presented in a second table. Normalized and weighted results for all environmental and social indicators may be aggregated by addition on dimension level while the two economic indicators shall be presented separately (adding costs and incomes/benefits), see Table 5. This is in line with standards' requirements.

Table 5. Example of normalized and weighted results and summarized results presentation layout, aggregated on dimension level for the functional unit and RSL.

Dimension	Indicator *(unit)*	A0	A1-A3	A4-A5	B1-B5	B6-B7	B8	C1-C4	*A-C*	D
Environmental	All *(dimensionless)*									
Social	All *(dimensionless)*									
Economic	LCC and incomes *(Currency)*									
	Environmental externalities *(Currency)*									

3.6. *Comparison of design concept results*

The proposed method suggests a procedure for comparison of design concept results. Design concepts may only be compared on dimension level and for any of the life cycle stages. Inter-dimensional comparison is not possible. To compare concepts over the whole life cycle, the aggregated result for life cycle stages A-C shall be used. It is required that all modules are calculated within each life cycle stage when comparing aggregated results of life cycle stages. The result for module D may not be included in the comparison over the whole life cycle but may be compared separately. For the environmental and social dimensions, only the normalized and weighted results shall be used for the comparison.

An example of a comparison of three hypothetical design concepts for the whole life cycle (modules A-C) and for the future re-use, recovery and recycling potential (module D), aggregated on dimension level, is shown in Table 6.

Table 6. Example of a comparison of three design concepts for modules A-C and for module D, aggregated on dimension level for the functional unit and RSL.

	Concept 1		Concept 2		Concept 3	
Dimension, indicator *(unit)*	*A-C*	*D*	*A-C*	*D*	*A-C*	*D*
Environmental, all *(dimensionless)*	-90	30	-80	40	-70	20
Social, all *(dimensionless)*	-40	10	-60	20	-50	25
Economic, LCC and incomes *(Currency)*	-800	300	-400	100	-1 100	200
Economic, Environmental externalities *(Currency)*	-200	30	-250	10	-300	150

4. Discussion

The aim for a harmonized method that can be applied using open-access data currently limits the categories and indicators possible to include in the proposed method. Indicators reflecting impacts on for example landscape, biodiversity, several social categories and social externalities are lacking. In summary, the social dimension is not as well represented as the environmental and economic dimension in the proposed method. In addition, EPDs made according to the previous version of EN 15804 do not present results for all indicators used in the proposed method. This currently limits its application during a transition period. On the other hand, the proposed method formalizes sustainability assessment and facilitates impartial comparison of design concepts.

Since the method is based on standardized indicators and aggregation methods, it can easily be developed when new or updated indicators are published. The future standard for calculation methods for sustainability assessment of civil engineering works shall then be used.

The method can be complemented by qualitative or semi-quantitative social indicators for the construction and use stage for specific civil engineering works types. The indicators could be aggregated using a multi-criteria decision analysis (MCDA) method into a separate social dimension score.

With the proposed method, the result of a design concept is not dependent on the results of other design concepts included in the comparison. This allows additional concepts to be added to the comparison without affecting the results of the concepts originally included.

5. Conclusion

The proposed method is formalized and well-suited for use in automated comparative sustainability assessments. This is because data sources are becoming increasingly machine-readable, indicators are quantitative, and normalization and weighting are performed with recognized, standardized factors and not on varying value judgements. When more data and indicators are made available, the method can be further developed. In addition, results are not dependent on each other in the comparison. This together with the automation potential and open-access data being enough for application, are the main advantages of the proposed method. A limitation of the proposed method is the small number of social indicators. To further promote fair competition and a higher level of accuracy in the results, an increase of the extent and availability of open-access machine-readable EPDs and LCA data is welcomed.

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