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Quantifying the Environmental Impact of Railway Bridges Using Life Cycle Assessment: A Case Study

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Abstract

As emission regulations in the EU are becoming stricter, the reduction of greenhouse gas emissions from the construction industry has become a pressing need. As part of the efforts related to this issue, it has been found that Environmental Life Cycle Analysis (LCA) approaches are required to optimize the design, construction, operation, and maintenance of buildings and infrastructure assets. In this paper, The Institution of Structural Engineers guidance on how to calculate the embodied carbon in structures is used as LCA model and evaluated in a case study. The guidance divides the structure´s life cycle into five stages (A1-A3: Product, A4-A5: Construction process, B1-B7: Use, C1-C4: End of live and D: Benefits and loads beyond the system boundary) and the environmental impact is measured in terms of carbon dioxide equivalent emissions (kgCo2e) or global warming potential (GWP). The model was applied to an existing reinforced concrete trough bridge, which is a structure type commonly used in Swedish railways. Results show that that the model was effective and simple for investigating the environmental impact of the studied structure.

Keywords: Life cycle analysis; Reinforced concrete; Railway Bridge, Embodied carbon, Global warming potential.

1 Introduction

Anthropogenic emissions of CO_2 and other greenhouse gases (GHGs) cause global warming. After the Paris Agreement, Governments of 190 countries have decided to keep global warming well below 2°C above pre-industrial levels [1]. In addition, the EU is aiming to reach net-zero carbon emissions by 2050 [2], although some countries are setting their own national targets. For instance, the national target of Sweden is to become carbon neutral by the year 2045 [3]. These efforts are aimed to guarantee sustainable environment for this and future generations [4], [5]. As buildings and construction presently account for about 40% of energy-related CO_2 emissions [4], deep changes are needed in the design, construction, use, and reuse of structures and infrastructure to reach those goals. This might not only lead to reducing the global warming impact of the construction industry but to significant economic benefits through a more efficient construction practice and use of buildings. These savings could influence 42% of total energy consumption, 35% of greenhouse gas emissions (GHG), 50% of the raw materials extracted in some regions, and save up to 30% of water in certain regions according to the Roadmap to a Resource Efficient Europe [3].

The European Commission concluded that Life Cycle Assessment (LCA) is currently the best tool for evaluating the environmental effects of a building during its life cycle [6]. In recent years, Nordic countries (i.e., Denmark, Finland, Norway, and Sweden) have shown increased interest in employing LCA for environmental performance in the building sector [6]. The need of LCA to enhance the possibilities of mitigation environmental impacts has also been pointed out by several researchers in fields different than construction industry [7], [8].

To significantly reduce the carbon footprint of the building stock, it is therefore necessary to make the environmental optimization of the building life cycle easily accessible during the design phases. However, environmental issues, such as pollution emissions, are hardly ever considered during design, that traditionally focus on safety and economic issues [9]. This can be attributed to the complexity of the LCA tools, lack of data and the need of expertise on the subject that can lead to an unacceptable increase in design costs. In addition, results may vary because of the different LCA approaches used [10].

As bridges are one of the most essential infrastructure assets, a significant reduction of construction emissions can be achieved through their more efficient construction, maintenance, and use. However, in addition to the challenges mentioned above, the use of LCA approaches in the bridge sector also deals with the long-life span of bridges (usually 100 years) that makes it difficult predicting the entire structure life cycle. Furthermore, although there are some carbon calculation and environmental assessment tools for bridges [11], [12], [13], there is still the lack of a standardized LCA model [9]. To spread the use of LCA, consultancy companies need to be provided with simple, user-friendly, and reliable tools at an acceptable cost.

In this paper, the methodology of the Institution of Structural Engineers (IStructE) on how to calculate embodied carbon [4] is used as an effective and simple LCA tool to investigate the environmental impact of a railway bridge. The type of structure selected corresponds to a reinforced concrete (RC) trough bridge, commonly used in Swedish railways. This study only deals with the carbon footprint assessment of this structure, and evaluation of economic and social aspects are out of the scope of the paper.

2 Methodology

The IStructE's guidance [4] evaluates the environmental impact of a structure in terms of the carbon dioxide equivalent emissions (kgCO_2e), also known as global warming potential (GWP). The inputs required depend on the module and include material or product quantities, embodied carbon factors (ECFs), distance and means of transportation of materials to site, life span, and end of life scenarios, among others. It computes the carbon factors using UK, European and global averages values, based on Environmental Product Declarations (EPDs). EDPs are defined in the guide as *"an independently verified and registered document that communicates transparent and comparable information about the life cycle environmental impact of products"*. They are a verified description of the environmental profile of any product, based on Life-cycle assessment calculations according to ISO 14040, ISO 14044 and EN 15804 standards for EU countries [14]. Advantages of the guidance are mainly its simplicity, clarity, high reliability, and time efficiency [4], [15].

The guidance divides the structure life cycle in 17 modules (named A, B, C, and D) and groups them in five stages: A1-A3: Product, A4-A5: Construction process, B1-B7: Use, C1-C4: End of live and D: Benefits and loads beyond the system boundary. The product stage considers raw material supply, transport and manufacturing and it is also known as "cradle to gate" stage. The construction process stage comprises modules A4 and A5 (transport and construction process). The use stage starts from the practical completion (end of module A5) and finishes before the end of life. It includes seven modules (B1-B7): use, maintenance, repair, replacement, refurbishment, operational energy use, and operational water use. The end-of-life stage contains four modules (C1-C4): de-construction, demolition, transport and disposal. When these four stages are considered, the LCA follows a "cradle to grave" approach. If the Benefits and loads beyond the system boundary stage is considered, the whole life embodied carbon can be computed. In this way, net kgCO_2e benefits beyond the project´s life cycle are considered and the approach is referred to as "cradle to cradle". This fifth stage comprises module D: Reuse/Recovery/Recycling potential.

Most of the embodied carbon is usually associated with lifecycle modules A1-A3. These emissions are also the easiest to calculate. According to the guidance, A1-A3 emissions (EC_{A13}, kgCO_2e) are calculated as:

$$EC_{A13} = \sum_{i=1}^{n}[Q_i(ECF_{A13,i})] \quad (1)$$

where:

Q_1 = Quantity of the material (kg)

$ECF_{A13,1}$ = Module A1-A3 embodied carbon factor for *i*th material ($kgCO_2e/kg$)

Additional carbon factors related to transport to site and material wastage on site are considered to compute the total A1-A5 emissions (see Eq. 2). According to the guidance, this should be the minimum extent of a structural embodied carbon calculation. Emissions associated to modules A4 and A5 include $kgCO_2e$ released during transport of materials/products to the site, energy usage because of activities on-site (site huts, machinery use etc.), and those associated with the production, transportation, and end-of-life processing of materials wasted on site.

$$EC_{A15} = EC_{A13} + \sum_{i=1}^{n}[Q_i(ECF_{A4,i} + ECF_{A5w,i})] + EC_{A5a} \quad (2)$$

where:

EC_{A15} = total embodied carbon for life cycle modules A1–A5 in $kgCO_2e$.

$ECF_{A4,i}$ = embodied carbon for life cycle module A4 for the *i*th material.

ECF_{A5w} = Embodied carbon factor for production, transportation, and disposal of wasted material for the *i*th material in $kgCO_2e$ (see Section 4.3).

EC_{A5a} = Emissions related to on-site electricity and fuel consumption (see Section 4.3). A precise, as-built embodied carbon calculation can be achieved if these emissions are monitored during construction. In the case of lack of data for a given project, EC_{A5a} emissions can be assessed prior to construction begins, using data available from previous studies or similar projects. The RICS guidance [16] recommends an average rate of 1400 $kgCO_2e$ per £100,000 of the project´s construction cost. Nevertheless, a value of 700 $kgCO_2e$ per £100,000 of the project cost will be used in this paper (see Section 4.3) as the IStructE´s guidance reports that initial calculations have shown that EC_{A5a} emissions of only substructure and superstructure can be equal to 50% of the value reported in the RICS guidance for the total construction.

Use stage (modules B1–B7) is generally insignificant for structural materials. However, it is hard to estimate as information regarding modules B2 and B3 (maintenance and repair), for instance, is not widely available. Operational modules (B6: Operational Energy Use and B7: Operational Water Use) are outside of the scope of the IStructE´s guidance. End of Life stage (modules C1–C4) considers the emissions released during decommissioning, stripping out, demolition, deconstruction, and transportation of materials away from the site, waste procession and disposal of materials. As new standards (e.g., BS En 15804) require Modules A1-A3 and C1-C4 EPDs to be declared, there is an increasing amount of information available to evaluate the embodied carbon emissions of these stages.

If a wider understanding of the structure environmental effect is required, stage D (Benefits and loads beyond the system boundary) needs to be assessed. In this way, $kgCO_2e$ benefits associated with recycling of the materials or energy recovered from them are evaluated, ensuring that future emissions and resource consumption are kept to a minimum. It is highlighted that if recycled construction materials are employed, the released $kgCO_2e$ is appraised in modules A1–A3. On the other hand, if source materials are recycled after the end of the life cycle, emissions are to be evaluated in Module D.

3. Case study

The Swedish railway net comprises approximately 15600 km of tracks, of which 14200 km are managed by the Swedish Transport Administration (Trafikverket). There are almost 4000 railway bridges managed by Trafikverket along the Swedish tracks. Around 20% of the existing Swedish bridge population (i.e., c.a. 800 bridges) corresponds to reinforced concrete (RC) trough bridges [17], [18].

Trough bridges are built up as a slab suspended between two longitudinal main beams that carry the loads towards the supports (see Figure 1). The structure typically forms a "U-shape" which allows for them to be filled with ballast to distribute loads from the sleepers, rails, and traffic appropriately. The traffic load is transferred to the ballast using sleepers on which the rail is fastened.

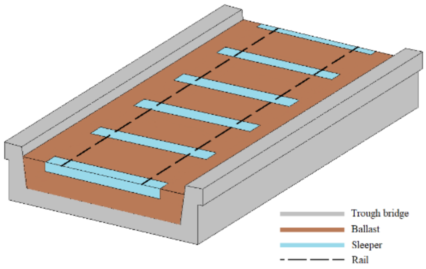

Figure 1. 3D-model of an RC trough bridge [14]

As trough bridges have proven to be quite efficient, they are nowadays also considered as a viable alternative during the construction of new railway lines or for the replacement of deteriorated bridges and/or those that have reached their design lifespan. Therefore, LCA is quite timely as it provides invaluable input for the selection of the most sustainable option for a given project.

In this paper, a typical RC trough bridge with a longitudinal span length of 7.2 m and a transverse length of 3.1 m. was studied.

4. LCA of Trough Bridge

4.1. Modules A1-A3

Material quantity for the studied trough bridge were calculated according to the geometry and reinforcement details found in [18].

The calculated volume of concrete is equal to 9.4 m^3. Assuming a concrete density of 2400 kg/m^3, the total concrete weight is equal to 22477 kg. For concrete with 25% ground granulated blast furnace cement replacement, A1–A3 embodied carbon factors ECF can be taken as 0.12 kgCO_2e/kg (Institution of Structural Engineers (Great Britain), n.d.).

The reinforcement weight amounts to 1859 kg, with reinforcement density equal 7850 kg/m^3. According to [4], average ECF worldwide is equal to 1.99 kgCO_2e/kg. However, lower values have also been reported. For example, the UK CARES sector average EPD reports a value of 0.76 kgCO_2e/kg [4]. Other steel European producers have reported values as low as 0.42–0.45 kg CO_2e/kg [19] for hot-rolled bar steel. In this paper, a value of 0.45 kg CO_2e/kg was used.

The estimated total area of wood formwork used is 53.56 m^2. Assuming a thickness of 15 mm and density 575 kg/m^3, the total formwork weight is 462 kg. For Swedish Plywood, ECF is taken as 0.229 kgCO_2e/kg.

For single rail ballasted and stationary slab tracks, Trafikverket uses continuously welded UIC60 profiles, which are the most widely used rail type in Europe [19]. For the case study, the weight of the rail is 60×2×7.2 = 864 kg.

According to Trafikverket, the most common sleeper type in Sweden is the concrete sleeper which is used for almost 71% of the railway tracks. For this case, sleepers with dimensions of 0.2×0.2×2.65 m with an edge-to-edge distance of 0.60 m are considered. For a total length of 7.2 m, a total of 13 sleepers are required, which account for a total weight of 3307 kg of ordinary concrete and 110 kg of reinforcement.

Crushed stone is selected as ballast material. The simplified volume of the ballast is computed assuming a rectangle 3.1 m wide by 0.6 m height. With a density of 20 kg/m^3, the ballast weight is 3.1×0.6×7.2×2000 =26784 kg. If the volume of the sleepers is subtracted (i.e., 0.2×0.2×2.65×13) the weight of the ballast is 24028 kg. Table 1 presents the ECFs and EC values for modules A1-A3 for the studied trough bridge, and the percentage of embodied carbon for each one of the bridge´s materials. Results show that superstructure (concrete + steel reinforcement) have the highest values of CO_2e, and account for up to 75% of the total embodied carbon.

Table 1. Module A1-A3 Embodied Carbon Calculation

Material	Quantity (kg)	ECF A1-A3	Embodied Carbon ($kgCO_2e$) A1-A3	
In situ Concrete	22477	0.12	2697	(57%)
Reinf. steel	1859	0.45	836	(18%)
Formwork	462	0.229	105	(2.3%)
Rail-steel	864	0.45	388	(8.2%)
Ballast	24028	0.004	96	(5.5%)
Concrete sleepers	3307	0.12	396	(8.0%)
Sleepers reinforcement	0.110	0.45	0.049	(1.5%)

4.2. Module A4

Module A4 $kgCO_2e$ emissions are mainly concerned with the transport of materials and products from factory to site, and typically constitute less than 10% of the total embodied carbon of a structure [4], [15]. Table 2 shows the transport emissions factors (TEF) used in the calculation of embodied carbon according to the IStructE´s guidance [4]. Table 3 presents the embodied carbon values of module A4 for the materials described in section 4.1 and the different transportation scenarios considered.

Table 2. Transport emissions factors (Institution of Structural Engineers (Great Britain), n.d.)

Mode TEFmode	TEFmode ($gCO_2e/kg/km$)
Road transport emissions, average laden	0.10650
Road transport emissions, fully laden	0.07524
Sea transport emissions	0.01614
Freight flight emissions	0.59943
Rail transport emission	0.02556

Table 3. Module A4 Embodied Carbon Calculation

Material	A4 transport scenario	ECF A4	Embodied Carbon $kgCO_2e$
In situ concrete	Locally 50 km	50×0.1065/1000= 0.005	112
Reinfrcement steel	Nationally 300 km	0.032	59
Concrete Sleepers	Locally 50 km	0.005	16
Formwork	Locally 50 km	0.005	2
Ballast	Locally 50 km	0.005	120
Rail-steel	European 1500 km	(1500×0.02556)/1000 = 0.03834	33

4.3. Module A5

Module A5 emissions are likely to account for a small but not insignificant percentage of the total structural embodied carbon over the lifecycle of a project [4]. On-site construction waste embodied carbon factor $ECF_{A5w,i}$ for the ith material is computed as:

$$ECF_{A5w,i} = WF_i\left(ECF_{A13,i} + ECF_{A4,i} + ECF_{C2,i} + ECF_{A34,i}\right) \quad (3)$$

where:

WF_i = waste factor for the ith material. It is based on the expected percentage waste rate of each material/product. Average values are shown in Table 4 [4].

$ECF_{A13,i}$ = Emissions for production of the wasted material, including sequestration factors for timber (see Table 1).

$ECF_{A4,i}$ = Emissions for transporting the wasted material to site (Table 3).

$ECF_{C2,i}$ = Considers the Transportation of the wasted material away from site. Assuming 50 km by road to the nearest reuse/recycling location, a value of 0.005 $kgCO_2e/kg$ of material can be used.

$ECF_{C34,i}$ = Emissions for processing and disposal of the waste material (Modules C3 and C4, see Section 4.5). In the absence of better data, 1.77 $kgCO_2e/kg$ for timber products and 0.013 $kgCO_2e/kg$ for all other materials can be assumed [4], [15].

Table 4. Module A5w (material wastage on site) Embodied Carbon Calculation

Material product WR	WR waste rate	WF waste factor	ECF A5w	Embodied Carbon $kgCO_2e$
Concrete situ	5%	0.053	0.008	170
Reinf. steel	5%	0.053	0.027	49
Con. sleepers	1%	0.010	0.001	4
Formwork	10%	0.111	0.031	14
Ballast stone	10%	0.111	0.003	72
Rail-steel	1%	0.010	0.005	4

Embodied carbon from construction site activities (EC_{A5a}) can be estimated based on industry studies or previous project data. EC_{A5a} is calculated based on the construction cost, as shown in Eq. 4 [4]:

$$EC_{A5a} = CAEF \times \frac{PC}{100{,}000} = 700 \times \frac{300{,}000}{100{,}000} = 2100 kgCO_2e \quad (4)$$

where:

PC = project cost, assumed as 300,000 £.

CAEF = construction activities emission factor of 700$kgCO_2e$/£100,000 for superstructure and substructure only (see Section 2).

4.4. Modules B1-B5

The use and maintenance phases include regular consumption of materials during the bridge's 100-year life cycle (usually 100 years). Quality of the original materials, surrounding environmental conditions, train loading and traffic conditions, and the quality and periodicity of control inspections dominate the requirements and frequency of maintenance interventions. Although it is impossible to predict these aspects accurately beforehand, it is critical to make reasonable assumptions for the maintenance scenarios and the corresponding intervals. Based on previous projects experience [9], a series of maintenance activities and repair intervals for the case study are presented in Table 5.

Table 5. The maintenance activity during the whole life cycle

Maintenance activity during 100 years' service life	Period years
Rail grinding	1 year
track direction	0.5 year
Ballast tamping	0.5 year
Rail replacement	25 years
Sleeper renewal	50 years
Fastener renewal	25 years
Ballast replacement	20 years

However, as module B1 accounts for sometimes negligible percentage of structural embodied carbon, and data for modules B2 (maintenance) and B3 (repair) is quite scarce, the guide focuses on the calculation of the embodied carbon associated to module B4 (Replacement). According to [4], the carbon factor for Module B4 is a product of the number of times a component is replaced in the asset's life cycle and the sum of ECF of modules A1-A5 and C2-C4:

$$ECF_{B4,i} = \left[\frac{RSP}{CL_i} - 1\right] \left(ECF_{A13,i} + ECF_{A4,i} + ECF_{A5w,i} + ECF_{C2,i} + ECF_{C34,i}\right) \quad (5)$$

where:

RSP = Estimated asset lifespan, assumed as 100 years.

Cl_i = Estimated component lifespan for the *ith* material (see Table 5).

Table 6 shows that the largest amount of embodied carbon for this module is associated to the ballast (2880 kg) which is repeated five times during the life of the bridge (see Table 5). Lower values of embodied carbon are generated by rail (1325 kg) and replacement of sleepers (727 kg).

Table 6. Module B4 Embodied Carbon calculation

Material	B4 - Embodied Carbon (kCO_2e)
Concrete in situ	0.00
Steel Reinf. [sleepers]	250
Concrete sleepers	477
Formwork	0.00
Ballast (stone)	2880
Rail-steel	1325

4.5. Modules C1-C4

As at the end of life (EOL) stage the bridge will be demolished, there are several scenarios for material waste processing and disposal. A value of embodied carbon for module C1 (demolition and deconstruction, EC_{C1}) around 9% of the value found during construction, as used by [20]. Module C2 (transportation, see Eq. 3) includes removing materials away from the site at EOL and is calculated in the same way as module A4. However, waste treatment or disposal facilities are likely to be local to the site, so transport distances should be shorter. Values for modules C3-C4 were discussed in Section 4.3 (see Eq. 3).

4.6. Module D

Reusing or recycling the original materials will benefit the structure´s environmental impact if treated properly, even if considerable energy consumption and transportation processes are usually involved in the waste treatment process.

Recycling is a popular strategy to reduce waste as it helps reducing the demand of new resources, cutting down transport and production energy and utilising waste which would otherwise be lost. Steel, for instance is recyclable and the scrap can be converted to the steel with the same, or even higher, quality. However, additional resources and reprocessing are required to turn waste into new products. Assessing Module D can contribute to a holistic quantification of the environmental impact and provide a measure of circularity of a project. It can be calculated in the same way as A1–A3 emissions, i.e., multiplying the material quantity by an emission factor. However, such calculation is out of the scope of this paper.

5. Discussion

Figure 2 shows the values of embodied carbon during of the bridge's lifecycle, as percentage of the total $kgCo_2e$ obtained for modules A to C. It can be seen that embodied carbon during production of materials (modules A1-5, stage product) are significantly larger than those computed in the remaining modules. Module B4 (replacement) had the second largest percentage of computed embodied carbon, mainly due to the replacement of the ballast, as mentioned before.

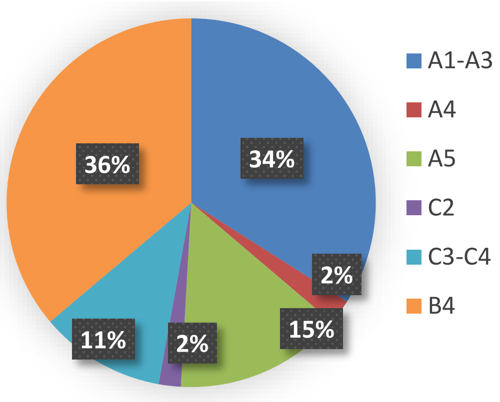

Figure 2. Embodied Carbon of modules A-C for a RC Trough bridge

Based on these results, it can be affirmed that the minimum scope of an embodied carbon assessments for bridge elements needs to include at least life cycle Modules A1–A5 (embodied carbon to practical completion).

Therefore, and considering that A1–A5 emissions will be released before 2050, it is important to understand how to minimise them to reach net-zero carbon emissions and reduce global warming. This implies that for improving the environmental design of bridges, LCA must be applied during the early design stages. In this way, changes that can have a significant impact on the project can be achieved at the lowest additional costs.

As concrete production represents a significant part of the embodied carbon of modules A1-A3, significant efforts need to be carried out to improve the sustainability of concrete production by, for example, the use of recycled materials. Extending the life span of existing bridges will also reduce the emissions as the embodied carbon of product and construction process could be avoided. This means that reliable data regarding the emissions of additional maintenance (B2) and repair (B3) are paramount. As ECF for these activities are usually not available, a huge research effort needs to be implemented in this area. Maintenance activities need also to be carefully planned to achieve a significant reduction of emissions with the associated environmental benefits. It is also important to consider transportation distances and traffic disruption during construction or maintenance, as they can represent a significant share of the environmental effects.

6. Conclusions

As demonstrated in this paper, the IStructE's guidance model is an effective and simple way for investigating the environmental impact of any given structure. For the case study, it allowed to assess the life cycle of the railway bridge easily and clearly from cradle to grave. Results show that most of the emissions (49%) calculated for the bridge are associated to Modules A1-A5 (raw material supply, transport, and manufacturing). Out of the materials considered, concrete production represented a 57% of the $kgCO_2e$ calculated for these modules, followed by the steel reinforcement (18%). Module B4 also had a significant impact on the emissions calculated. This was expected as parts of the track need to be replaced during the lifespan of the bridge. The highest influence the results was related to the replacement of the ballast that according to the available data, will need to be carried out five times in a period of 100 years (i.e., bridge lifespan).

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