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LIFETIME ANALYSIS OF HIGHWAY COMPOSITE BRIDGE

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ABSTRACT

Highway bridges are important assets in every infrastructure network. The cost of construction and operation of highway bridges are key issues for bridge engineers. However, in the near future the design of bridges and other infrastructures will require more than compiling with safety requirements according to safety standards and economic constraints. The multidimensional perspective of sustainability requires the combination of current design criteria with other important aspects such as society and environment, usually considering a life cycle approach.

In this work, a framework for an integrated life cycle design of bridges is presented. Specific indicators characterising several aspects of sustainability in bridge design are chosen: (i) environmental impacts, (ii) initial and future costs, and (iii) impacts on users. These indicators are quantified over the complete life cycle of the bridge in a probabilistic based approach. Furthermore, the purpose of this paper is to apply the proposed methodology to a steel-composite highway bridge in order to enhance the unique features of this kind of structures in the pursuit of a sustainable construction system.

Keywords: Life-cycle, environmental impacts, economical impacts, social impacts, uncertainties

INTRODUCTION

The design of bridges and other infrastructures requires a life cycle approach that combines safety requirements, environmental and social aspects.

The life cycle analysis framework was described in Gervásio and Simões da Silva (2008) and entails the assessment of the environmental, economical and social performances of a bridge over its life cycle, following the International Life Cycle Analysis framework defined in ISO standards 14040 (2006) and 14044 (2006). Although this set of standards addresses only the environmental criterion, the same framework is used for the evaluation of economical and social criteria. Thus, the impact assessment stage of the three criteria is made separately but all the criteria share the same goal and scope and they are based on the same inventory analysis.

The goal of the life cycle analysis is to evaluate which processes, over the bridge life cycle, contribute with a major share to environmental, economical and social impacts. The object of assessment, the functional unit, is a composite bridge designed for a service life of 100 years

In a life cycle approach uncertainties are unavoidable. In this work two types of uncertainty were taken into account: parameter uncertainty and uncertainty in choices. In the analysis presented in this paper, parameter uncertainty in the inventory stage and uncertainty in the choice of the allocation procedure for the end-of-life stage were considered.

Parameter uncertainty is considered by the assignment of probabilistic distributions to the main parameters in each analysis (environmental, economical and social) and running Monte-Carlo simulations.

For the choice of the allocation procedure, two end-of-life scenarios for recycling of steel are defined, as described in the following paragraphs.

In Scenario 1 it is considered that the recycling process of steel avoids the production of new steel via the primary route, thus all environmental burdens associated with this route may be deducted from the analysis. This approach is known as "substitution method" or "avoided burden method". This closed material loop recycling approach is the methodology adopted by the Worldsteel organization, former International Iron and Steel Institute (IISI) (2002).

In scenario 2 it is also considered that the recycling process of steel avoids the production of new steel via the primary route, however, all credits and/or burdens due to the recycling process are simply "cut-off" from the system.

These two scenarios will be evaluated under environmental, economical and social criteria.

LIFE-CYCLE ENVIRONMENTAL ANALYSIS

The environmental life cycle analysis is performed according to the CML methodology (2001) and the SimaPro (2008) software program. An environmental life cycle analysis entails the quantification of all environmental burdens from the production of the raw materials to the final destination of the products. For each process it is necessary to quantify all the input flows (materials, energy, etc) and output flows (emissions to air, water, soil; waste; etc).

Collection of data and the impact assessment analysis were considered as described in Gervásio and Simões da Silva (2008).

Allocation procedure

The closed-loop recycling process avoids the production of new steel via the primary route, thus all environmental burdens associated with this route may be deducted from the analysis. Assuming X_{pr} to be the LCI for the BF route, and X_{re} the LCI for the EAF route, then the environmental burden (LCI) for scrap is given by equation (1) (IISI, 2002):.

$$\text{LCI allocation for scrap} = Y(X_{pr}-X_{re}) \qquad (1)$$

where, Y is the metallic yield, which represents the fact that the recycling process is not 100% efficient.

Considering the production of steel via the primary route, and assuming that the scrap recovered for recycling at the end of life is RR, then the LCI for primary manufacture with the credit for the scrap produced is given by

$$\text{LCI for 1 kg of steel including end of life} = X_{pr} - RR \times Y(X_{pr}-X_{re}) \qquad (2)$$

In the case study, it was assumed that 1.05 kg of scrap is required to produce 1 kg of secondary steel, thus Y = 1/1.05 = 0.952, and RR = 80%.

LIFE-CYCLE ECONOMICAL ANALYSIS

The life cycle economical analysis entails all the cost occurring over the bridge life cycle. These costs are usually borne by the agency responsible for the bridge. Hence, three main groups of costs were considered: (i) the construction costs (*CC*), (ii) the operation costs (*OC*), and (iii) the end-of-life cost (*EC*), as expressed by:

$$LCC = CC + OC + EC \tag{3}$$

where, OC includes the costs of maintenance and rehabilitation of the bridge over the lifetime; and EC includes the costs of demolition minus the residual value of the structure at the time of decommission.

In this approach future costs occurring over the life cycle of the bridge are discounted to present-value cost by using expression (4):

$$PVLCC = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t} = CC + \sum_t \frac{OC}{(1+d)^t} + \frac{(DC - RC)}{(1+d)^t} \tag{4}$$

where, C_t is the sum of all relevant costs, less any positive cash flows, occurring in year t; N is the number of years in the study period; and d is the discount rate used to adjust cash flows to present value.

LIFE-CYCLE SOCIO ANALYSIS

The life cycle social analysis addresses all the cost borne by the users of the bridge. Three types of costs are quantified, as described in the following paragraphs. These costs are calculated based on their difference from the baseline condition of non-construction traffic disturbance.

The cost of the time lost by a driver while travelling through a work zone is here denominated as driver's delay cost (DDC). This cost is given by the difference between the cost of the time lost by a driver while travelling at normal speed and the time lost while travelling at a reduced speed due to construction works on the same length of the motorway. Thus, based on expression (5),

$$DDC = \left(\frac{L}{S_a} - \frac{L}{S_n} \right) \times N \times ADT \times \sum_{i=1}^{4} \left(DTC_i \times p_i \right) \tag{5}$$

where, L is the length of affected motorway (in km), S_a is the traffic speed during work activity (km/h), S_n is the normal traffic speed (km/h), N is the number of days of road work, ADT is the average daily traffic (no.cars/day), DTC_i is the cost per hour of a driver's time of a class i vehicle and p_i is the percentage of class i vehicles in total traffic flow.

Vehicle operating costs due to roadwork-related traffic include four main parcels: fuel consumption, the cost of tires, the cost of maintenance and the cost of depreciation of vehicles. These costs are calculated by,

$$VOC = S_a \times \left(\frac{L}{S_a} - \frac{L}{S_n} \right) \times N \times ADT \times \sum_{i=1}^{4} \left(VOC_i \times p_i \right) \tag{6}$$

where, S_a is the traffic speed during bridge work activity (km/h), S_n is the normal traffic speed (km/h), L is the length of affected roadway (km), N is the number of days of road work, ADT is the average daily traffic (no.cars/day), VOC_i is the operation cost of class i vehicle and p_i is the percentage of class i vehicles in total traffic flow.

Accident costs due to roadwork-related traffic, which are calculated using the following expression,

$$AC = L \times ADT \times N \times \left(A_a - A_n \right) \times C_a \tag{7}$$

where, L is the length of affected roadway, ADT is the average daily traffic (no.cars/day), N is the number of days of road work, A_a and A_n are the accident rates during construction and normal periods, respectively (per vehicle-kilometre), and C_a is the cost per accident. The cost per accident takes into account the severity of the accident, the type of road and the volume of traffic.

DESCRIPTION OF THE CASE STUDY

The case study analysed in this paper is the composite viaduct, represented in Figure 1, with 3 spans of 18.5 m + 40.8 m + 18.5 m. This viaduct was built in 2008 near Porto, Portugal. The deck is composite defined by two longitudinal steel girders and a concrete slab. The main frame is made of steel grade S355, with two built-up girders, which are laterally restrained by IPE profiles. Apart from the connections between the transverse beams and the longitudinal girders, which are bolted, all the other connections are welded. The main girders are made of steel welded plates, with variable thickness on the flanges and web in order to optimize the design of the structure.

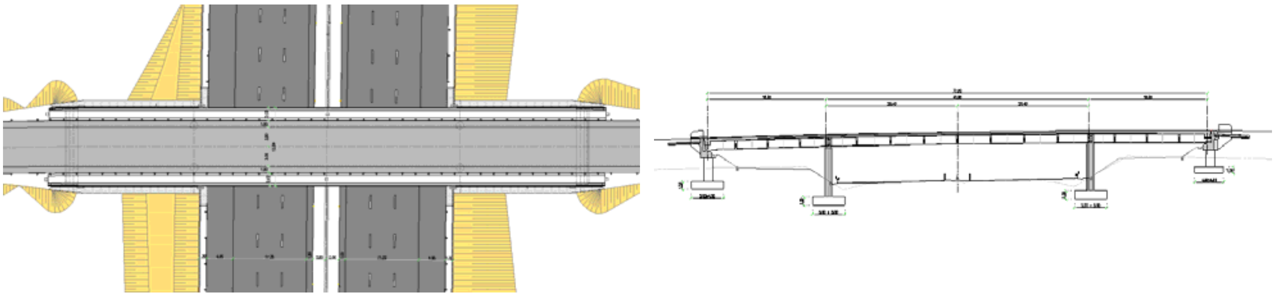


Figure 1. Plan and elevation views of the composite bridge

Material production and Construction stages

All the data from the design project and for the construction of the bridge were kindly provided the the Portuguese concessionaire BRISA.

For the construction of the viaduct a total of about 146 ton of structural steel were necessary. The bill of the main materials and respective costs are indicated in Table 1.

Table 1. Bill of main materials

Structural element	*Class/grade*		
Foundations	Concrete C25/30	223 m^3	58 €/m^3
Abutments	Concrete C30/37	123 m^3	63 €/m^3
Piers	Concrete C30/37	33 m^3	63 €/m^3
Deck – “in situ” concrete slab	Concrete C35/45	164 m^3	71 €/m^3
Deck – precast concrete slab	Concrete C35/45	161 m^3	58 €/m^3
Steel reinforcement	Steel A500	75 459 kg	0.65 €/kg
Structural steel	Steel S355	145 678 kg	1.20 €/kg
Alkyd Paint	------	1 296 m^2	11 €/m^2

The construction of the bridge took a total of 87 days. The list of equipment used during construction was provided by the contractor. The time used per equipment was estimated based on the detailed construction plan provided by the contractor.

In-service stage

This period of time starts when the viaduct comes into service and ends when the viaduct reaches the end of its functionality. During this period procedures to estimate the service life of viaduct components, together with cost information, are necessary to prioritize and optimize a management system with budgetary constraints. These procedures are, however, outside the scope of this paper. In this work a plan for maintenance and rehabilitation of the bridge was considered based on the estimated service life of each bridge component and current practice in BRISA.

Table 2. Maintenance and rehabilitation plan

Activity	First intervention	Interval of time	Unit cost
Periodic inspections	2	2	1 000 €
Main inspection	5	5	2 000 €
Cleaning of expansion joints	1	1	200 €
Replacing of expansion joints	25	25	13 500 €
Surfacing (asphalt)	15	15	11 000 €
Replacing edge beam	25	25	11 000 €
Replacing railings	25	25	4 500 €
Replacing bearings	25	25	6 000 €
Coating of steel beams	25	25	300 €/m
Maintenance of concrete structure	25	25	50 €/m^2
Rehabilitation of deck	50	-	100 €/m^2

Moreover, it is further assumed that the concrete structure needs a major rehabilitation after 50 years since it is opened to the traffic.

End-of-life stage

At the end-of-life stage it was assumed that the bridge is demolished. Data for the demolition of the structure was based on the demolition project of a real concrete bridge, provided by BRISA, and in direct information received from contractors. It was further estimated that a total of 23 days were needed.

According to current European and National legislation it is mandatory to sort the materials in the construction site or in a sorting plant (if sorting in the construction site is not possible). After sorting the materials are sent to different places according to its characteristics and potential for recycling. Steel is assumed to be recycled at a location 100 km away from the construction site. All the remaining materials are assumed to be transported to a landfill (travelling distance of 50 km).

RESULTS OF THE ENVIRONMENTAL ANALYSIS

Deterministic analysis

In Figure 2, the results of the deterministic life cycle analysis are shown for scenario 1 (closed-loop recycling approach). The contribution of each life cycle stage to each impact category is represented in the graph of Figure 2. The material production stage contributes with a minimum share of 4.8% in the impact category ozone layer depletion, to a maximum of 62.9% in the impact category global warming. The construction stage contributes with a minimum share of 9.2% and a maximum share of 19.5%, respectively for the impact categories of human toxicity and photochemical oxidation. The operation stage contributes with a minimum share of 29.5% in the impact category terrestrial ecotoxicity, to a maximum of 53.6% in the impact category photochemical oxidation. Finally, the last stage contributes with a minimum of -7.1 % in the impact category global warming, and a maximum of 15.3% in ozone layer depletion.

All stages, apart from the material production, include the use of construction equipment and traffic congestion caused by construction activity. In all cases, the impacts due to traffic congestion overrides the remaining processes, even in the end-of-life stage, although with lower values. The use of equipment also contributes with high values in all stages, particularly in the impact categories of acidification, eutrophication and global warming.

The result of the life cycle analysis considering the “cut-off” approach in the end-of-life stage leads to very similar results in all impact categories except in global warming. In this case, the material production stage has a major share of 55.3%, followed by the operation stage with 30.5%, the construction stage with 8.3% and the end-of-life stage with 5.9%.

Due to the long time span of bridges, the results described in the previous paragraphs are subjected to a high degree of uncertainties and therefore a more accurate analysis is needed to deal with this problem. To overcome some of the uncertainties inherent to such analysis, a probabilistic analysis was performed as described in the following section.

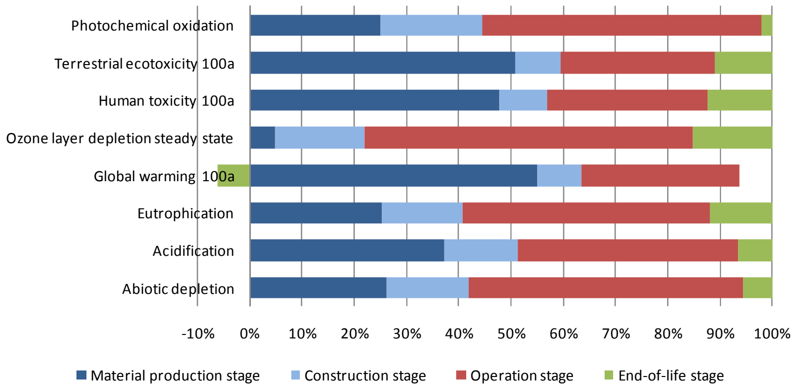
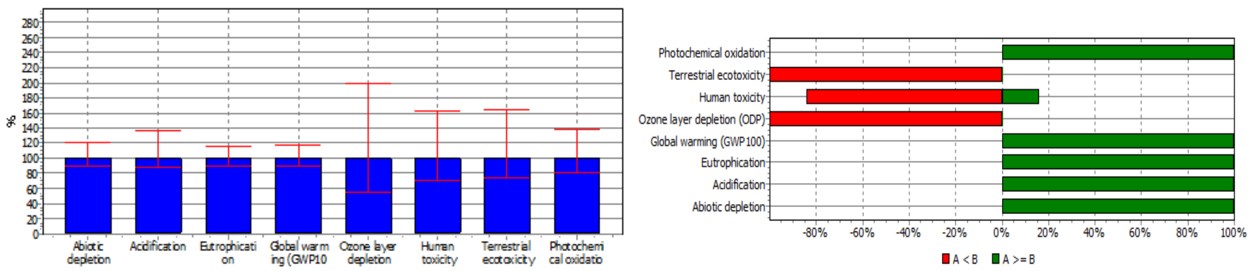


Figure 2. Contribution analysis of life cycle stages

Results of the probabilistic analysis

Although parameter uncertainty occurs in each parameter used in the life cycle analysis, in the present analysis, only the uncertainty in input data is considered. Thus, lognormal distributions were assigned to all input values in all unit processes.

The probabilistic analysis was carried out by a Monte Carlo simulations and the Simapro software. The results of the probabilistic life cycle analysis are presented in the Figure 3a. For each impact category, the median value is represented, together with the 95% confidence interval. The impact category with a lower uncertainty are eutrophication and global warming, while the impact categories with the highest uncertainties are ozone layer depletion, human toxicity and terrestrial ecotoxicity.



(a) (b)

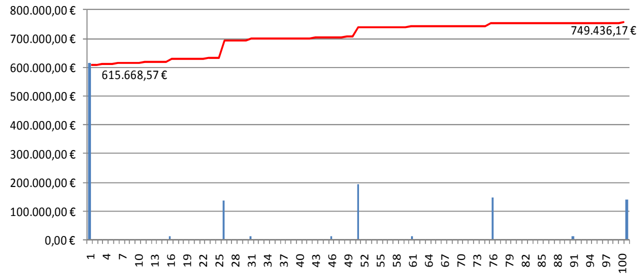
Figure 3. Probabilistic life cycle environmental analysis

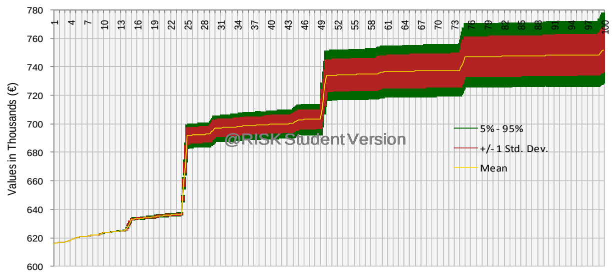
In order to compare the probabilistic analysis of the life cycle analysis with both end-of-life scenarios, the software has a feature that allows to count the number of comparison runs in which one system is larger than the other. The graph in Figure 3b represents the difference between both systems: system A is the life cycle analysis with the “cut-off” approach and system B the life cycle analysis with the “closed-loop” approach. Thus, system A has a larger impact than system B in most categories, except terrestrial ecotoxicity, human toxicity and ozone layer depletion, which are the impact categories with higher uncertainties, as referred in the previous paragraph.

RESULTS OF THE ECONOMICAL ANALYSIS

Deterministic analysis

The compilation of the life cycle costs lead to the total present value life cycle cost of 749 436.00 €, which represents a cost of 800.00 €/m^2. The costs per year and the accumulated present value cost of the bridge are illustrated in Figure 4a. In terms of life cycle cost, there is no significant difference between the two scenarios for end-of-life allocation. The only difference is that by the use of the "cut-off" rule the revenue due to scrap recovered in the end-of-life stage is not taken into account. In this case the life cycle cost would be 749 794.00€





(a) (b)

Figure 4. Cumulative present value of life cycle cost of the bridge: (a) deterministic and (b) probabilistic

Results of the probabilistic analysis

After a sensitivity analysis four main parameter were identified as being determinant for the result of the life cycle analysis. These parameters are: (i) the discount rate; (ii) the cost of the maintenance of the concrete structure; (iii) the cost of rehabilitation of the concrete structure; and (iv) the cost of maintenance of the steel structure. Thus, a probabilistic distribution was assigned to each one of these variables as follows: for the cost of maintenance and rehabilitation of the concrete and steel structure a normal distribution was assigned with mean value equal to the value given in Table 2 and a standard deviation of 10%; for the discount rate a triangular distribution was assigned with a mean value of 3.8%, a minimum value of 3.0% and a maximum value of 4.5%. The results obtained from the probabilistic analysis by running a Monte-Carlo simulation are provided in the graph represented in Figure 4b.

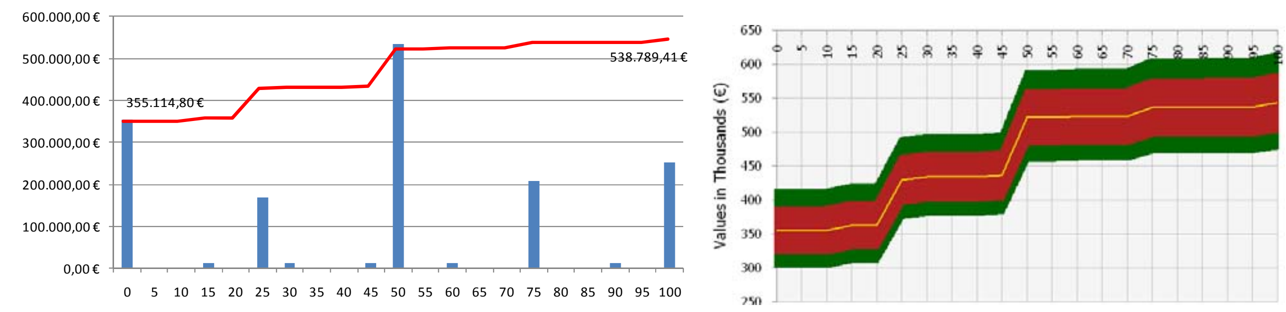
The total life cycle cost of the bridge has a mean value of 752 850€ and a 90% confidence interval between 728 700€ and 779 400€. It is noted from the previous graph that the range of uncertainty increases with time.

RESULTS OF THE SOCIAL ANALYSIS

Deterministic analysis

The compilation of the life cycle social costs lead to the total present value life cycle cost of 538 789.00 €, which represents a cost of 575.00 €/m^2. The costs per year and the accumulated present value cost of the bridge are illustrated in Figure 5a. This cost is about 70% of the life cycle cost of the structure as indicated in the previous sections. This analysis took into account the users of bridge (traffic over the bridge) and the users of the motorway (traffic below the bridge). For the construction stage only the traffic on the motorway was considered, as before the bridge construction there was no bridge. Also, for the end-of-life stage it was assumed that traffic over the bridge would be diverted to an alternative route, as thus no impacts were considered.

The results of the life cycle social analysis do not depend of the end-of-life allocation procedure.



(a) (b)

Figure 5. Cumulative present value of life cycle social cost of the bridge: (a) deterministic and (b) probabilistic

Results of the probabilistic analysis

In the probabilistic analysis a triangular distribution was assigned to the discount rate with a mean value of 3.8%, a minimum value of 3.0% and a maximum value of 4.5%. For the social costs a normal distribution was assigned with mean value equal to the value calculated in the previous section and a standard deviation of 10%. The results obtained from the probabilistic analysis by running a Monte-Carlo simulation are provided in the graph represented in Figure 5b.

The total life cycle cost of the bridge has a mean value of 543 132.00 € and a 90% confidence interval between 474 000,00 € and 617 400.0 €.

CONCLUSION

There are two major environmental and economical impacts over the bridge life cycle, the use of construction equipment and the traffic congestion caused by a work zone.

Composite bridges allow shorter periods of time for construction and minimize the need for maintenance, contributing to a better life cycle performance.

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