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On CO_2 efficiency and trade-offs between safety and sustainability in concrete bridge management

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ABSTRACT: Roadway transportation systems contribute significantly to global Green House Gas (GHG) emissions. Although there has been significant progress in identifying how to reduce embedded GHG in construction, we do not know how efficient our decisions are in creating sustainable welfare. To achieve this knowledge, it is necessary to investigate how structures contribute to economic growth, life safety, resilience and sustainability, relative to their associated embedded GHG emissions. In the present paper a framework is provided on how the GHG efficiency of different strategies for roadway bridge design and integrity management may be modelled and quantified. The application of the framework is illustrated on an example considering typical design decisions for ordinary concrete highway bridges and it is shown that optimal decision in this respect have the potential to reduce embedded GHG emissions by a factor of two.

1 INTRODUCTION

The urgency to mitigate climate change has made the reduction of carbon emissions a global imperative, particularly in the short to mid-term. Civil structures and building structures play a big role in global greenhouse gas emissions. The global embodied GHG emissions from construction amounts to nearly 20% of global emissions caused by human activities (Faber, 2020). At the same time, infrastructure is expanding rapidly across the globe, driven by economic growth and increasing urbanization. This expansion brings significant environmental challenges. As critical elements of infrastructure, the construction, maintenance, and operation of civil structures, hereunder concrete bridges are significant contributors to global greenhouse gas emissions, particularly CO_2 emissions. This necessitates a focused effort to understand and mitigate the carbon footprint associated with the lifecycle of concrete bridges– as one example. To enable the construction industry to engage effectively in redesigning best practices, it is necessary to shift the focus of leading principles. These principles should be grounded in achieving the desired functionality of the built environment with maximum efficiency, especially in terms of minimizing environmental impacts like CO_2e emissions (all greenhouse gas emissions converted to the equivalent effect of CO2 on climate change), rather than relative to costs alone. To redesign best practices in this regard, however, necessitates that we are able to:

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- Assess the efficiency of structural designs and strategies for structural integrity management in providing the desired functionality relative to associated effects on impacts to the environment, reliability/safety and economy.
- Understand the trade-offs between life safety, economy and reductions in impacts to the environment (at global and local scale) under different strategies for the development of societal infrastructure with respect to quality and quantity.

Presently, knowledge on these two points is very sparse; in fact no previous study of such nature has been identified by the authors.

The present paper focuses on the modeling of the relationship between bridge construction and integrity management decisions and their impact on associated life-cycle costs and embedded CO_2e emissions. Bridge structures made by reinforced concrete are addressed in the present paper but the general approach presented may be easily adapted to structures made of other materials. To investigate how different strategies for design affect the life-cycle cost and embedded CO_2e emissions, different design scenarios are explored by altering the cross section, material type, target reliability, and cover depth. Our analysis aims to support decisions for design of concrete bridges, contribute to decision making at political, regulatory, and operational levels on how to ensure and optimize sustainable and affordably safe development of infrastructure.

2 DECISION SUPPORT FRAMEWORK FOR BRIDGE MANAGEMENT

2.1 *Brief introduction of the decision support framework*

This framework is established based on previous research (Nishijima & Faber, 2009) in which optimal strategies for the development of infrastructure systems was addressed from the context of socio-economic optimization. In the present paper, focus is on the modeling of the relationships between the decisions related to the quality and quantity of the bridges and the consequences in terms of life-cycle cost and embedded CO_2e emissions during the life-cycle of the structures. In this framework, the quality of the structures is considered as the reliability/safety and durability of the structures and the quantity of the structures are considered as the material consumption such as the consumption of concrete and steel. There are trade-offs between the decisions on the quality and quantity of the structures considering the life-cycle cost and embedded CO_2e emissions as consequences. Decisions which may improve the reliability/safety level of the structures could lead to higher material consumption. Opting for higher reliability/safety in structural design reduces the probability of failures, thereby decreasing the expected embedded CO2e emissions from replacements or repairs caused by failures, but the higher material consumption may also at the same time be associated with a higher emissions.

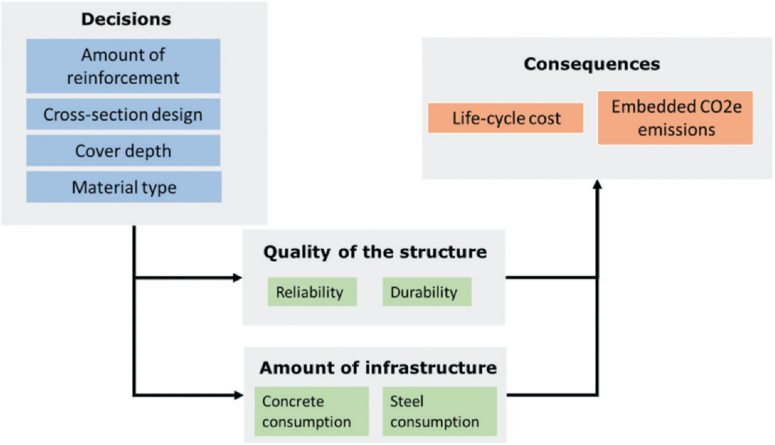

Figure 1. Principal relationships between decisions on the quality and quantity of bridges and consequences with respect to embedded CO_2e emissions and life-cycle cost.

2.2 *Modeling of failure events*

2.2.1 *Failures due to extreme operational loads*

The approach utilized for calibrating design codes, as demonstrated by Faber & Sorensen (2003), is adapted to model the failures due to extreme operational loads. In this way, instead of modeling structures in detail, only the failure modes relating to different types of materials and load cases are considered.

For purposes of simplicity, and without loss of practical relevance, it is assumed in the design process of the bridge girder cross section that the pre-stress reinforcement is designed to carry all the dead load. As a consequence the event of failure of the cross section is modelled as the event that the tensile force from the live loads in the mild reinforcement is larger than the yield capacity, which is expressed as:

$$g(z) = z \times F_{\mathrm{y}} - F_{\mathrm{load,l}} \tag{1}$$

where $F_y = f_y \times A_{\mathrm{s}}$ represents the tensile capacity of mild reinforcement, f_y is the yield strength of the mild reinforcement and A_{s} is the area of the longitudinal reinforcement; $F_{\mathrm{load,\,l}}$ is the tensile force from the live loads; z is the design parameter (e.g., cross-section parameter) which is adjusted such that the annual probability of failure is equal to a given target value $P_{\mathrm{f}}^{\mathrm{T}}$.

It is acknowledged that pre-stressing cables possess additional capacity which, under realistic conditions, would contribute to the ultimate capacity of the structure in response to live loads. However, in the present paper, we adopt this simplification to facilitate straightforward, preliminary estimates of the environmental impact, specifically in terms of CO2 emissions, associated with varying levels of safety. More detailed model of the limit state should be introduced in the future work.

The probabilistic model for the parameters entering Equation (1) are given in Table 1.

Table 1. Uncertainty model for the considered failure mode.

Basic variable	Distribution	Mean	CoV
Tensile capacity (F_y)	Log-normal	1	0.07
Tensile force from the live loads ($F_{\mathrm{load,l}}$)	Gumbel	1	0.3

2.2.2 *Modeling of degradation*

Research into the probabilistic modeling of deterioration processes has received considerable attention. The report by Duracrete (1999) provides a comprehensive review of the current understanding as it pertains to reinforced concrete (RC) structures compromised by chloride-induced reinforcement corrosion. Different limit state functions describe different condition states, which are related to the serviceability and the safety of the structure.

In the present paper, a simplified model is utilized to describe the ingress of chlorides into concrete (Malioka,2009), which is expressed as:

$$C(z,t) = C_s\left[1 - erf\left(\frac{z}{2\sqrt{tD}}\right)\right] \tag{2}$$

where $C(z,\, t)$ represents the chloride concentration at a distance z from the concrete surface at time t, C_s represents the the surface chloride concentration, D represents the chloride diffusion coefficient and $erf(\cdot)$ is the error function.

Corrosion will essentially begin when the chloride level at the depth of the reinforcement will exceed a critical threshold level, C_{CR}. Assuming both the surface chloride concentration and the diffusion coefficient as constant, the time till corrosion initiation, T_{CI}, at the first layer of reinforcement may be determined as follows:

$$T_{CI} = \frac{d^2}{4D}\left(erf^{-1}\left(1 - \frac{C_{CR}}{C_S}\right)\right)^{-2} \tag{3}$$

where d is the cover depth, which replace z in Equation (2), $erf(\cdot)$ is the inverse of the error function and can be expressed for computational purposes as:

$$erf^{-1}(\cdot) = \frac{\Phi^{-1}(\cdot)}{\sqrt{2}} \tag{4}$$

The limit state function for visible corrosion at time t can be expressed as:

$$g_{CV}(t, \mathbf{X}) \;=\; T_{CI}(\mathbf{X}) + T_V - t \tag{5}$$

where $\boldsymbol{X}$ is a vector that includes all the stochastic variables in the limit state function, T_V represents the time from corrosion initiation to visible corrosion. As suggested by Johnsen et.al. (Johnsen et.al., 2003), T_V is estimated as 10 years.

The deterioration of concrete structures is a random phenomenon that shows significant spatial variability. In the present paper, the model proposed by Straub et.al. (Straub et.al., 2009) is utilized. To model the spatial variability in concrete structures, areas with similar characteristics are grouped into zones. It is assumed that there is no interdependency between different zones. Then the zones are further discretized into elements. To assess the size of these elements, as well as their dependency structure, a study of the correlation length or radius of the parameters governing the degradation process must be carried out. In Straub (2009), the correlation length is identified as 80 cm.

Table 2. Uncertainty model for the degradation model.

Basic variable	Unit	Distribution	Mean	Std. dev.
d	mm	Log-normal	45/50/55	8/9/10
D	mm²/ year	Log-normal	μ_D	24
C_s	Weight-% of concrete	Log-normal	μ_{C_s}	0.04
C_{CR}	Weight-% of concrete	Normal	0.1	0.03
μ_D	mm²/ year	Normal	30	3
μ_{C_s}	Weight-% of concrete	Normal	0.24	0.02

2.3 *Life-cycle analysis*

Life-cycle assessment (LCA) is extensively utilized to evaluate the energy and environmental impacts throughout the lifespan of products and services. This is particularly relevant in the context of civil structures, which encompasses various stages such as material production, construction, maintenance, operation, and end-of-life (ISO 14040, 2006). These stages correspond to the A1 to C4 categorization in Life Cycle Assessment, see Figure 2.

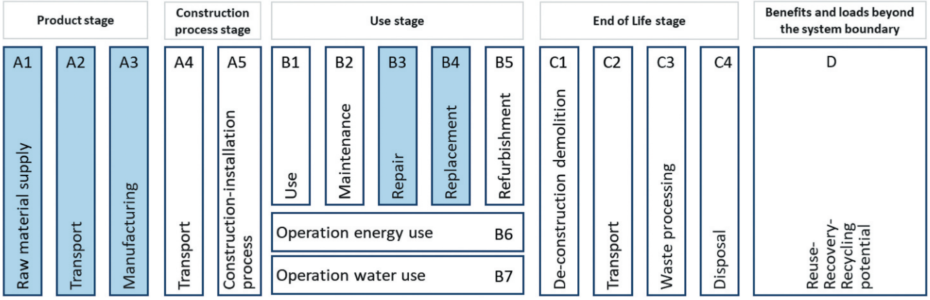

Figure 2. Life-cycle stages (ISO 14040, 2006).

2.4 *Life-cycle cost and embedded CO_2e emissions*

Considering different decisions related to the design and integrity management of the bridges, the life-cycle cost $E[C_T]$ can be expressed as:

$$E[C_{\mathrm{T}}\ (\mathbf{a})] = E[C_{\mathrm{C}}\ (\mathbf{a})] + E\left[C_{\mathrm{Repair}(\mathbf{a})}\right] + E\left[C_{\mathrm{Replacement}}\ (\mathbf{a})\right] \tag{6}$$

where **a** is the vector that represents the decision variables, $E[C_{\mathrm{C}}\ (\mathbf{a})]$ is the initial cost depending on the design decisions which lead to different material consumption and construction cost; $E\left[C_{\mathrm{Repair}(\mathbf{a})}\right]$ represents the repair cost, which depends on the decisions related to the degradation process of the structures such as cover depth and inspection and repair plan; $E\left[C_{\mathrm{Replacement}}\ (\mathbf{a})\right]$ represents the replacement cost which depends on the reliability of the structures.

The life-cycle embedded CO_2e emissions can be expressed as:

$$E[E_{\mathrm{T}}\ (\mathbf{a})] = E[E_{\mathrm{C}}\ (\mathbf{a})] + E\left[E_{\mathrm{Repair}(\mathbf{a})}\right] + E\left[E_{\mathrm{Replacement}}\ (\mathbf{a})\right] \tag{7}$$

where $E[E_{\mathrm{C}}\ (\mathbf{a})]$ is the embedded CO_2e emissions at the production phase (A1-A3), which also depends on the design decisions which lead to different material consumption; $E\left[E_{\mathrm{Repair}(\mathbf{a})}\right]$ represents embedded CO_2e emissions from the repairs (B3) (assuming embedded CO2e from inspection being minimal and somewhat similar for all scenarios) and $E\left[C_{\mathrm{Replacement}}\ (\mathbf{a})\right]$ (B4) represents the emissions from replacement. The considered stages in the life-cycle analysis are highlighted in Figure 2. It should be noted that the emissions calculated here are all expected values, which are the results after taking into account the uncertainty of the system. They are not directly calculated emissions in a given scenario.

3 ILLUSTRATIVE EXAMPLE

3.1 *Introduction of the example bridge*

The example bridge is a two-span continuous bridge, see Figure 3, and the detailed superstructure cross-section for the basic case is shown in Figure 4.

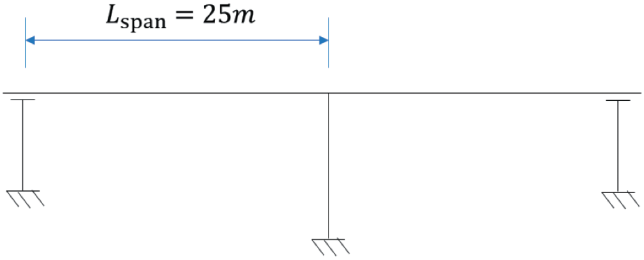

Figure 3. Two-span continuous bridge.

In the following, only the superstructure of the bridge is being considered.

3.2 *Design scenarios*

In the example, various design scenarios are explored by altering the cross section, material type, target reliability, and cover depth. Consequently, 18 distinct design scenarios are examined. Scenario 1 is the basic case shown in Figure 4. More scenarios could be investigated, but some of the most obvious are investigated here. These scenarios are indeed possible and reasonable, but some of them ar not allowed due to existing codes and guidelines. Even though these scenarios are not all currently implemented in practice, their inherent potential emphasize the needs for changing these regulations.

The first group of scenarios encompasses those with a reliability/safety level equivalent to the basic case, characterized by a failure probability, $P_f^T = 10^{-6}$. These scenarios are introduced as follows:

- Using a new type of cement, “FUTURECEM”, which is a more sustainable cement based on the LC3 technology, can possibly reduce the CO_2e emissions significantly while

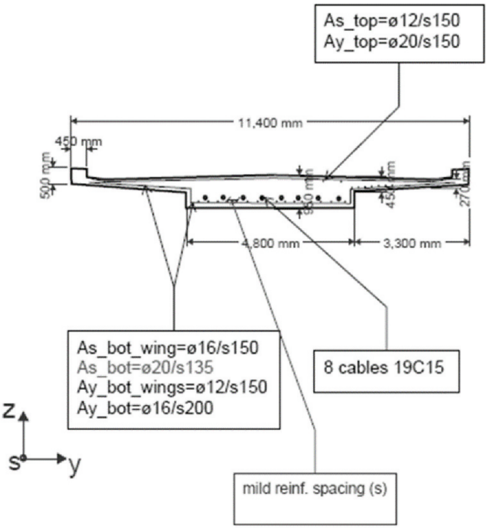

Figure 4. Cross-section for the basic case.

maintaining high performance, and is currently being implemented in various construction projects (Scenario 8).

- Using LC3 (Limestone Calcined Clay Cement), which is an environmentally friendly concrete technology that combines calcined clay and limestone to reduce clinker content, thereby lowering CO_2e emissions while possibly maintaining or enhancing the performance of traditional Portland cement (Scenario 9).
- Cut outs in the cross section, a technique involving intentional voids or openings in structural elements, effectively reduces concrete consumption. To maintain the bending capacity, this scenario necessitates an approximate 10% increase in the consumption of mild reinforcement (Scenario 10).
- Using lower strength concrete, C30. To preserve the bending capacity in this scenario, it's necessary to increase the consumption of mild reinforcement by about 5% (Scenario 11).
- Using recycled concrete. By repurposing concrete from the demolished structures, the aggregate and clinker in the concrete can be substituted by the recycled This approach reduces the consumption of raw materials and lowers CO_2e emissions (Scenario 12).
- Reduce the cross-section height with 10cm. To maintain the capacity, this scenario necessitates an approximate 30% increase in the consumption of mild reinforcement (Scenario 13).
- Reduce the cross-section height with 20cm. To maintain the capacity, this scenario requires an approximate 75% increase in the consumption of mild reinforcement (Scenario 14).
- Reduce the cross-section height with 20cm and using high-strength mild reinforcement (700 Mpa). To maintain the capacity, this scenario requires an approximate 40% increase in the consumption of mild reinforcement (Scenario 15).

Then different reliability levels are considered, which are calibrated according to Equation (1). Scenarios related to lower reliability/safety level ($P_f^T = 10^{-5}$) are considered as follows:

- Reducing mild reinforcement based on the basic case (Scenario 2).
- Using low strength concrete (Scenario 3).
- Reduce the cross-section height with 10cm (Scenario 4).
- Reduce the cross-section height with 20cm (Scenario 5).
- Reduce the cross-section height with 20cm + 700 MPa reinf. (Scenario 6).
- LC3 concrete + Reduce the height of the cross section with 20cm + 700 MPa reinf. (Scenario 16).

Scenarios related to higher reliability/safety level ($P_f^T = 10^{-7}$) are considered as follows:

– Increasing mild reinforcement based on the basic case (Scenario 7).

Finally, to investigate the effect of cover depth, on basis the basic case (cover depth is 45mm), two other scenarios are considered by reducing or increasing the cover depth by 5 mm.

3.3 *Results*

Figure 5 shows the expected value of life-cycle total emissions. The emission factors utilized in the example come from InfraLCA, a tool developed by the Danish Road Authority (2021). The emission factors for the FUTURECEM and LC3 are assumed according to the research in Antoni et al. (2012) and the report from Aalborg Portland (2020).

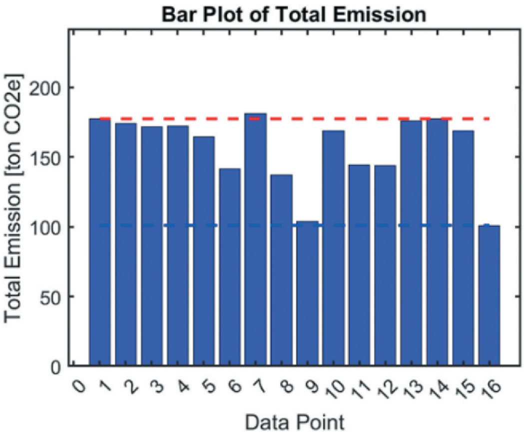

Figure 5. Expected value of life-cycle total emissions (A1-A3 + B4).

It is observed that all scenarios with lower reliability/safety levels have been observed to reduce embedded CO2e emissions when compared to the basic scenario, conversely, the scenario with higher reliability/safety level is associated with an increase in embedded CO_2e emissions compared to the basic scenario. Keeping the basic-case reliability/safety level, it is still possible to reduce emissions by utilizing low emission materials such as LC3 and FUTURECEM or utilizing high strength steel. Scenario 16 can reduce emissions by more than 40%. Additionally, there is a minimal difference in the total cost across the various scenarios.

By calculating the expected value of life-cycle total costs, it is found that there is a minimal difference in the total cost across the various scenarios - within a margin of 5%. The purpose of the calculation here is to estimate the cost difference due to changes in material type, material consumption, and reliability level. Since many materials are not yet available on the market, the results here are based on assumptions.

Table 3 shows the results about expected value of total embedded CO_2e emissions for different cover depths. It is observed that increasing the cover depth by 5mm can reduce the annual embedded CO_2e emissions (yearly emissions) by 20% compared with the basic case. It is important to understand that this does not imply a reduction of total emissions at the initial point.

Table 3. Expected value of CO_2e emission with different cover depth.

Cover depth	Emission (production (A1-A3)) [t CO_2e]	Expected value of emission from major repair (B3) [t CO_2e]	Expected value of total CO_2e emissions (A1-A3 + B3)	Life [yr]	Annual carbon emission [t CO_2e/yr]
40 mm	175.21	2.67	177.88	100	1.78
45 mm	177.36	3.88	181.24	135	1.35
50 mm	179.91	5.96	185.87	175	1.06

4 CONCLUSION

The efficiency of roadway bridge design and strategies for structural integrity management in providing the desired functionality relative to associated effects on impacts to the environment, safety and economy are assessed. This study demonstrates that there are multiple strategies to effectively reduce embedded CO_2e emissions in civil structures. The utilization of lower strength concrete (scenario 6 and 11), incorporation of high strength steel (scenario 5 and 15), and the use of low emission materials (scenario 8, 9, 12, and 16) have all shown promising results. Notably, these strategies have the potential to decrease emissions by more than 40%. Additionally, increasing the concrete cover thickness (the concrete outside the reinforcement), while also initially increasing the embedded CO_2e emissions during the production phase, has the long-term benefit of reducing the frequency of major repairs and extending the lifespan of structures, thereby reducing annual embedded CO_2e emissions. The findings of the present study emphasize the vital necessity for industries to expedite the qualification of new materials for various uses and exposures. It's imperative that this information is shared swiftly and incorporated into new policies, codes, standards, and guidelines.

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