Sustainability potential of risk-informed decisions in structural design

Ramon Hingorani  
Post-Doc Researcher, Dept. of Structural Engineering, Norwegian University of Science and Technology, Trondheim, Norway

Jochen Köhler  
Professor, Dept. of Structural Engineering, Norwegian University of Science and Technology, Trondheim, Norway

ABSTRACT: Structural design codes feature safety concepts that are highly generalized to make them simple and applicable to a large variety of structures at the same time. This leads to structures that are sufficiently safe but where structural material is not utilized in an optimal manner. For a sustainable future, this is not good enough. We need to unlock the potential offered by advanced risk and reliability-based methods in order to utilize our resources as efficient as possible. The paper illustrates this potential in the context of a case-study: the design of building floor structures with steel beams and hollow-core slabs. Assuming different member geometries, material properties and load scenarios, a representative set of such systems is defined and designed according to the partial factor method in the Eurocodes. The significant benefit of risk-informed decision approaches compared to these standardised design rules is demonstrated and quantified in terms of costs, material consumption and CO$_2$ emissions.

1. INTRODUCTION

Many current and future challenges are related to the efficient management of (limited) financial and natural resources or the appropriate mitigation of consequences due to climate change. Engineering structures play a fundamental role in this regard since they consume large amounts of raw materials and contribute significantly to greenhouse gas emissions worldwide. As the challenges will become bigger, the demand for innovative and sustainable solutions well beyond traditional structural engineering practice will increase.

Structural design codes and standards play a fundamental role in this regard. They contain the compulsory decision rules for the detailed design of structures and their constitutive members and connections. These rules implicitly prescribe the flow of structural materials throughout our entire built environment. Their careful formulation is hence an essential means for addressing sustainable development. The Eurocodes (CEN, 2002), for instance, provide specific decision rules for verifying compliance with requirements to safety, serviceability and durability. The major objective that has been followed in their development, was the provision of sufficient safety, and the observed, relatively low failure rates, do proof success in this regard. However, the necessary simplifications and generalisations introduced in the formulation of these rules with the aim to enable their user-friendly application, come at the cost of inefficient material consumption and an unnecessary associated environmental impact. For assuring an optimal and sustainable structural performance in terms of both economical and the environmental indicators, well-defined adjustments to the current decision rules for structural design are imperative (GLOBE, 2022). Conveniently, such developments should be based on risk-informed approaches, which due to their
high level of detail regarding the representation of both uncertainties and consequences involved in structural limit state problems, contribute to resource efficient decision making, e.g. (Rackwitz et al., 2005).

After a brief introduction to risk-informed decision making in section 2, this paper illustrates the sustainability potential of risk-informed decision approaches in structural design procedures by means of a case study (sections 3-5). A representative set of steel beams supporting hollow-core slabs in office buildings is defined. The optimum beam design to resist bending moments is identified based on both an economic and environmental objective function, the latter in terms of embodied greenhouse gas emissions. The results are compared to a standardised structural design according to the Eurocodes.

2. RISK-BASED OPTIMISATION

2.1. Cost-based approach

Economic optimisation has been identified as a powerful approach for consistent decision making related to the design of structures, e.g. (Rackwitz, 2000; Rackwitz et al., 2005; Köhler and Baravalle, 2019). Supported by standardized guidance ISO (2015), these developments facilitate optimized solutions such that a balance is achieved between the associated costs and benefits. Normally, the benefits may be considered independent of the decision parameter $p$ (e.g. a cross-section dimension) and the optimization problem simplifies to the determination of $p = p_{\text{opt}}$ which minimizes the expected total costs $C_{\text{tot}}$ associated with a specific decision, as expressed by Eq.(1) and illustrated in Fig.1. The total cost $C_{\text{tot}}$ is constituted by the sum of the expected safety- ($C_s$) and failure- ($C_f$) cost (Fig.1). The former are defined as the sum of the construction cost $C_c$ and the expected obsolescence cost, $C_o$.

$$p_{\text{opt}} = \arg \min_p [C_{\text{tot}}] = \arg \min_p [C_c + C_f + C_o]$$

(1)

$$C_c = C_0 + C_1p$$

(2)

$$C_f = (C_c + H_C) \frac{\lambda P_f(p)}{i}$$

(3)

In Eq.(2), the construction cost $C_c$ are defined as the sum of $C_1p$, that is proportional to the decision parameter $p$, and $C_0$, that is independent of $p$. The expected failure cost $C_f$ (Eq.(3)) and the expected obsolescence cost $C_o$ (Eq.(4)) are estimated based on the assumption that structures are continuously renewed either after failure of after becoming obsolete respectively. A discussion and justification of this assumption can be found in Rackwitz (2000).

The expected yearly failure costs are defined as the sum of reconstruction costs $C_c$ and indirect failure cost $H_C$ independent of $p$, multiplied by the yearly failure rate $\lambda P_f(p)$. Conditional obsolescence costs (reconstruction cost $C_c$ plus demolition costs $D$) are multiplied by the yearly obsolescence-rate $\omega$ resulting in the expected yearly obsolescence costs. The net present value of the sum of annual expectations with the annual interest rate $i$ is computed by utilizing the asymptotic solution: $\sum_{\tau=1}^{\infty} \frac{1}{(1+i)^\tau} = \frac{1}{i}$.

$$C_o = (C_c + D) \frac{\omega}{i}$$

(4)

While the objective function given by Eq.(1) ensures that resources are expended optimally from the financial point of view, it does not guarantee that this optimum ($p_{\text{opt}}$) is consistent with the societal preferences in regard to life safety investments. This can be considered by imposing a corresponding acceptance criterion $p_{\text{opt}} > p_{\text{acc}}$ (Fig.1),
e.g. based on the marginal life saving costs principle (ISO, 2015).

The described framework allows for identification of optimal decisions in terms of expected costs. The corresponding saving potential in relation to the sub-optimal decisions based on the standardised design rules defined in structural codes and standards is illustrated in Fig.1. By definition, these sub-optimal decisions, represented by the dots, entail a certain deviation, in terms of expected total costs, \( \delta_{C_{\text{tot}}} \), from their respective optimum, \( C_{\text{tot},\min} \) (normalised to 100%). In regard to sustainable development, it is further of interest, how the sub-optimal solutions deviate from the optimum in terms of the decision parameter \( p \), which is representative of the material consumption and associated embodied greenhouse gas emissions at the design stage. In contrast to \( \delta_{C_{\text{tot}}} \), this deviation \( \delta_p \) can occur on both sides of the optimum \( p_{\text{opt}} \), see Fig.1.

### 2.2. Emission-based approach

In analogy to the described economic optimisation framework, it is possible to define the objective function in terms of environmental performance indicators, such as (embodied) carbon emissions (CE). Such a function is given by Eq. (5), where construction, failure and obsolescence-related CE are defined equivalent to Eqs. (2) to (4), under replacement of costs \( C \) by carbon emissions \( CE \). In addition to \( \delta_p \), this representation allows for quantification of the saving potential \( \delta_{CE_{\text{tot}}} \) in terms of the expected total emissions \( CE_{\text{tot}} \). Also here, the optimum design parameter \( p_{\text{opt}} \) must exceed the life-safety boundary condition \( p_{\text{acc}} \).

\[
p_{\text{opt}} = \arg\min_p [CE_{\text{tot}}] = \arg\min_p [CE_c + CE_f + CE_o]
\]

(5)

### 3. METHODS AND ASSUMPTIONS

#### 3.1. Overview

A risk-based optimisation of steel beams in office buildings is conducted in this study, in terms of both costs (Eq. (1)) and embodied CE (Eq. (5)). The results are compared to the findings of a design based on the Partial Factor Method according to CEN (2002, 2005).

#### 3.2. Structural system and loads

The case study assumes simply supported steel beams of span \( L \), which provide support to pre-stressed hollow-core slabs (HCS) spanning over length \( D \) in the direction perpendicular to the beam orientation (Fig.2).

![Figure 2: Sketch of the analysed floor system consisting of steel beams supporting one-way hollow-core slabs](image)

Permanent loads \( g \) acting on the beams include the self weight of both the beams, \( g_b \), and the HCS, \( g_{\text{hcs}} \), as well as the weight of non-structural permanent loads, \( g_{\text{nst}} \), including the flooring and roofing system (Fig.2). In addition, the beams sustain a uniformly distributed imposed load \( q \).

#### 3.3. Limit state function and decision parameter

Bending failure at mid-span of the beams is investigated. The limit state function (LSF) is given by Eq. (6), representing equilibrium between acting and resisting bending moments at mid-span of the beams, where \( \theta_E \) and \( \theta_R \) denote the corresponding model uncertainties. Variable \( \theta_q \) represents the uncertainties associated with the imposed load model and \( f_y \) the steel yield strength.

\[
\theta_E \frac{(g + \theta_q)DL^2}{8} = \theta_R f_y
\]

(6)
Decision parameter \( p \) is represented by the plastic cross-section modulus \( W_{pl} \) - assuming class 1 or 2 cross-sections (CEN, 2005). Note that \( p \) is functionally related to the beam’s material volume \( V \). Eq.(7) provides a close estimate of the relationship between \( V \) and \( p \), where \( h \) represents the cross-section depth of rolled steel profiles with I or H cross-section \((h = L/25 \) is assumed\).

\[
V \approx 2.5L \frac{p}{h} \tag{7}
\]

### 3.4. Characteristic values and probabil. models

With the aim to define a representative set of design situations, the parameters most relevant to the design of the steel beams are varied within reasonable ranges.

Three spans \((L)\) are distinguished \((6, 12 \) and \(18 \) m) in addition to four different spacings \(D\) between members \((L1, L2, L3, L4)\) (Fig.2). Steel grades S235 \((f_{yk} = 235 \text{ N/mm}^2)\) and S355 \((f_{yk} = 355 \text{ N/mm}^2)\) are assumed.

In line with EN1991-1-1, a characteristic value of the imposed load of \( q_k = 3 \text{ kN/m}^2 \) is adopted. A wide range of ratios \( a_q \) of variable \((q_k)\) to total loads \((g_k+q_k)\) between 0.05 and 0.95 is considered, with an interval size \( \Delta a_q=0.05 \). In addition, three ratios \( a_g \) of self weight \((g_{sw})\) to total permanent loads \((g_{sw,k}+g_{nsl,k})\), ranging between 0.6 and 1.0 are adopted \((a_g=0.2)\). Based on these assumptions, the characteristic values of the permanent loads \( g_{sw,k} \) and \( g_{nsl,k} \) are computed. The self-weight, \( g_{sw,k} \), can be further broken down into the contribution of the beam \((g_b,k)\) and of the HCS \((g_{hcs,k})\). The depth of the latter, \( h_{hcs} \), is then inferred under the assumption of a typical density \( \rho_{hcs}=1414 \text{ kg/m}^3 \) (IBU, 2020). In order to ensure only practically relevant design situations to be included in the study, maximum and minimum ratios of the HCS depth \( h_{hcs} \) to span \( D \), of respectively, 1/35 and 1/60, are imposed in addition to a typical minimum depth of \( h_{hcs} = 150 \text{ mm} \) (Mones and Brena, 2013). By imposing these constraints, the number of design situations is limited to 50 cases, distributed within \( a_{q,min}=0.2 \) and \( a_{q,max}=0.55 \).

The probabilistic models for the loads \((g_{sw}, g_{nsl}, q)\), material strength \((f_j)\) and model uncertainties \((\theta_E, \theta_R, \theta_q)\) are adopted from CEN (2022). All other variables in Eq.(6) \((L, D, p)\) are assumed as deterministic quantities.

### 3.5. Costs

#### 3.5.1. Construction costs

Construction costs \( C_c \) - see Eq. (8) - are based on an indicative price for steel frame structures with rolled profiles in Germany of \( c_{mat+fab+inst}=2 \text{ €/kg} \) Bauforumstahl (2021). This price accounts for the three primary components of the total installed cost of a steel frame, i.e. material \((\text{mat})\), fabrication \((\text{fab})\) and installation \((\text{inst})\) costs (Barg et al., 2018). For sake of simplicity, we assume a linear relationship between the construction costs and the structural mass of the beams \(M \equiv V \rho\), where \( \rho = 7850 \text{ kg/m}^3 \). While in reality fabrication and installation costs are not entirely proportional to \( M \) (Barg et al., 2018), this will be neglected here due to its little effect on the results.

Although current carbon emission pricing rates are generally low in comparison to the overall costs of the structure, they should principally not be ignored in economic optimisation frameworks. The present study considers a carbon emission price \( c_{ce} = 0.1 \text{€/kgCO}_2\text{eq}\), what corresponds to the 2022 maximum value according to the EU emissions trading system. See section 3.6.1 for the carbon emission intensity \((CEI_b)\) embodied in the beams.

\[
C_c = V \rho (c_{mat+fab+inst} + c_{ce}CEI_b) \tag{8}
\]

#### 3.5.2. Failure costs

The indirect costs of a beam failure \( HC \) (see Eq. (3)) include costs for material, re-fabrication and installation of the HCS and the flooring/roofing system after failure, as well as the corresponding monetized carbon emissions. However, in comparison to compensation costs for potential fatalities in case of member collapse, these costs are negligible. Regarding such compensation costs, the study follows the recommendation by Virguez and Faber (2011), see also Annex E of ISO 2394 ISO (2015), to adopt the Societal Value of a Statistical Life for assessing the monetary impact of loss of life in the context of economic optimisation frameworks. The present study considers a \( \text{SVSL} \) of 2.775E06 €, converted from the value indicated in (ISO, 2015)
for Germany (based on an annual discount rate $i = 3\%$) by adjusting the average GDP per capita from US$333668 in 2008 to 43292€ in 2021.

As illustrated by Eq.(9), the SVSL is then multiplied to the expected number of fatalities due to beam collapse ($N_{\text{col}}$), estimated as a function of the probability of occurrence of a fatal collapse event, $P_N = P(N_{\text{col}} > 0)$, the expected area affected by such a collapse, $A_{\text{col}}$, and the number of persons at risk $Ocu_{\text{col}}$ present on that area, which depends on the building use (for office buildings, $Ocu_{\text{col}}/A_{\text{col}}=0.075$ is assumed). In accordance with the definition of the structural system (Fig.2), the collapse of a beam is assumed to affect an area $A_{\text{col}} = 4LD$ (floor area supported and below the collapsing beam). See (Hingorani et al., 2020) for further details on the consequence model.

$$H_C = N_{\text{col}}(P_N, A_{\text{col}}, Ocu_{\text{col}}) \cdot SVSL \quad (9)$$

3.6. Carbon emissions

3.6.1. Construction-related emissions

Construction-related carbon emissions, $CE_c$, are given by Eq.(10) as the product of the mass $M$ ($V \rho$) of the beams and the carbon emission intensity $CEI_b = 1.13$ (kgCO$_2$/eq/kg), representative of structural steel products used at German construction sites IBU (2018). As all other CEI adopted in this study, this value reflects cradle-to-gate emissions and has been adopted or inferred from an Environmental Product Declaration (EPD) according to EN 15804, issued by the German Institute for Construction and Environment (IBU) (2023). The fact that the total cradle-to-gate emissions are not entirely proportional to the material amount is neglected, due to its small influence on the results.

$$CE_c = V \rho CEI_b \quad (10)$$

3.6.2. Failure-related emissions

The study considers carbon emissions in consequence of beam failure. In addition to those embodied in the reconstructed (after failure) beam itself - considered in Eq.(10) - indirect failure emissions $H_{CE}$ need to be considered. These are estimated based on Eq.(11), as the sum of the embodied $CE$ in the collapsed HCS, in the non-structural permanent loads $g_{nsl}$, i.e. the flooring and roofing systems, and in non-permanent building equipment, such as furniture or movable partitions. The latter is approximated as a function of the 5y mean value of the sustained load contribution, $q_s = 0.5$ kN/m$^2$ in office buildings according to CEN (2022).

$$H_{CE} = (g_{hcs}CEI_{hcs} + g_{nsl}CEI_{nsl} + q_s CEI_{q,s})A_{\text{col}} \quad (11)$$

The CEI for the HCS, $CEI_{hcs}$, is adopted from IBU (2020), whereas the value for non-structural permanent loads, $CEI_{nsl}$, represents an average out of 32 different configurations of such loads, comprising four different flooring (ceramic tiles+screed, laminate+screed, PEC floor+screed, raised floor) and roofing systems (suspended ceiling, plaster boards, mineral boards, metal ceiling, in all cases incl. metal ducts for ventilation or installations), respectively. Each of the system components is represented by two different EPDs retrieved from IBU (2023). This procedure leads to a weighted average value of $CEI_{nsl} = 1.13$ kgCO$_2$/eq/kg (weighted with regard to the contribution of each component to the total weight of flooring and roofing system).

The carbon emission intensity corresponding to non-permanent building equipment, $CEI_{q,s} = 1.65$kgCO$_2$/eq/kg, has been estimated as an average value of the CEI reflected in a variety of EPDs for different furniture types (e.g. office chair, desks, shelves, meeting tables), compiled in Jortveit Lauvland (2021).

3.7. Obsolescence and interest rate

The calculation of expected obsolescence costs $C_o$ and emissions $CE_o$ in Eqs. (1) and (5) assumes an annual obsolescence rate $\omega = 1/50$. The considered annual discount rate $i$ is 3% - see section 5.2 for a discussion on this assumption.

4. RESULTS

The saving potential of the economic optimisation is illustrated in Fig.3 depending on the ratio of variable to total loads $a_q$ (high $a_q$ indicate dominant variable loads / light structures). Fig.3a reveals a maximum difference $\delta_{C_{\text{tot}}}$ (see Fig.1) between total costs for, respectively, the optimised and the Eurocode (EC) solution of up to 31%, with an average
of around 4%. The potential reductions $\delta_V (= \delta_p)$ in material volume/emissions at the design stage, which have been determined under the assumption of constant cross-section dimensions (corresponding to the mid-span cross-section) along the longitudinal axis of the beams, are plotted in Fig.3b. For relatively small $a_q$ of 0.2, the $\delta_V$ attain maximum values of up to $\approx 11\%$. However, due to the comparatively large sensitivity of the EC reliability level $\beta_{EC}$ to $a_q$ (Fig.3c), the $\delta_V$ continuously decrease with increasing relative contribution of variable loads, attaining negative values for $a_q > 0.4$.

Figure 3: Saving potential $\delta$ of the cost optimisation in terms of: a) expected total costs $C_{tot}$ and b) material volume $V$ at design stage; c) reliability index ($T_r=1y$)

5. DISCUSSION

5.1. Saving potential

The results of the economic optimisation (Fig.3) appear to be generally plausible: Less investment of resources into structural safety performance than compared to current Eurocode practice, as represented by positive $\delta E_{(C_{tot})}$ and $\delta V$, entails comparatively lower structural reliability levels. However, with annual reliability indices $\beta_{opt}$ oscillating around an average of $\approx 4.8$ (Fig.3c), the economically optimal solutions are likely to be acceptable from the perspective of societal preferences for investments into life saving measures, i.e. $p_{opt} > p_{acc}$ (Fig.1). Moreover, the obtained $\beta_{opt}$ are close to or above the (overly conservative) nominal annual Eurocode target, $\beta_{EC,t} = 4.7$. Hence, the optimised solutions can by no means be judged as unsafe. They reflect a more efficient use of financial resources. However, the results reveal also certain limitations of the approach. Situations characterised by larger $a_q$ lead to only irrelevant or even negative savings $\delta_V$ of material volume required at the design stage. In other words, the economic optimum calls in many practically relevant situations for a higher material demand (and hence higher associated carbon emissions) than the design solution based on the Eurocodes.

This limitation can be overcome if the objective of the optimisation consists in minimizing expected carbon emissions instead of costs, for in this case the reductions $\delta$ appear to be less sensitive to variations in $a_q$. The reasons for this difference is to be sought in the failure cost and emission term, respectively. On one hand, the failure probability ($P_f$) generally tends to increase with rising $a_q$ due to the dominant influence of the comparatively uncertain variable load (see $\beta_{EC}$ in Fig.3/4c). On the other,
larger $P_f$ cause higher expected failure costs, which play a dominant role in the economic optimisation of the beams due to comparatively high (in relation to other costs), indirect costs, i.e. human fatality compensation costs. Higher failure costs, in turn, cause decision parameter $p$ to increase, hence the optimum $P_f$ to decrease. This balancing effect explains the almost constant, even slightly increasing, optimum reliability level ($\beta_{opt}$) visible in Fig. 3c. In the emission-based optimisation, however, the influence of the indirect failure term is less pronounced and, consequently, $\beta_{opt}$ is not only lower than in the cost-based case, but also decreases with rising $a_q$, although far less noticeable than compared to $\beta_{EC}$ (Fig. 4c). Important to stress is that the corresponding low decision parameters $p_{opt}$ are likely to fall below the human safety (minimum) threshold, $p_{acc}$ (Fig. 1). Hence, the effective material and emission reductions ($\delta$) are expected to be somewhat lower than those shown in Fig. 4a/b.

5.2. Interest rates

The cost-optimisation considers economic discounting for establishing the net present value of costs related to periodical structural renewal, as well as to potential structural failure, see Eqs. (4) and (3). As in this study, a constant discount rate, inferred from consumption surveys, is commonly used for this purpose, what might imply disproportional economic efforts by future generations. Existing proposals to circumvent this problem include time-declining discount rates Lee and Ellingwood (2015) or an equivalent discount rate, based on an equal weighting of the preferences of present and future decision makers, e.g. Faber and Rackwitz (2004); Nishijima et al. (2007). In comparison to the traditional discounting method, these approaches assign higher resource use and monetary efforts at the time the decision is made as compared to the costs which are postponed to the future. Such considerations should be included in the further development of standardised decision strategies and rules for sustainable structural design.

Since the discount rates commonly used in economic analysis tend to underestimate environmental damage progressively more distant in time, the use of comparatively lower, “ecological discount rates” has been proposed for the assessment of environmental objectives, e.g. Gollier (2010). In the context of decision analysis of structures, such dual discounting strategies have, with very few exceptions, e.g. Adhikari et al. (2020), not yet been explored. With the aim to gauge the influence of lower discount rates on the outcome of the emission-based optimisation, Fig. 5 shows the result when instead of $i=3\%$ an interest rate $i=1.5\%$ is employed. As expected, the benefits of the optimisation with respect to the Eurocode solution decrease (compare to Fig. 3). However, the difference is not significant and might be even irrelevant taking into account that the emission-based design is likely to be governed by human safety requirements (section 5.1).

6. CONCLUSIONS AND OUTLOOK

The decision rules in structural design codes, such as the Eurocodes, are highly generalised and simplified, as the “ease of use” was one of the most important criteria for their development. Moreover, these rules do not contain any account of objectives related to environmental sustainability. This translates into a lack of efficiency in regard to the desired optimal balance between structure-inherent safety levels and the resources allocated to this end.

Opposed to this risk-informed approaches, facilitate a consistent way to identify an optimum out of different decision alternatives. The performed case study has clearly illustrated this. The results underline the significant resource- and greenhouse gas emission saving potential of such approaches in structural design procedures. Future studies should
increase the scope of the study to a more comprehensive set of design situations, paving the way for a consistent risk-based calibration of the standardised decision rules. Such a calibration would allow for a broad implementation of sustainability principles in daily structural engineering practice.

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8. REFERENCES


