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A novel framework to establish optimal failure probabilities for engineering structures

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The reliability of engineering structures in the built environment is of crucial importance for society. However, improving structural safety by building more robust structures also increases their monetary cost and environmental burden. This represents a trade-off between different aspects of sustainability, which is not fully considered in current literature and building codes such as ISO2394 and EN1990.
To address this, a novel framework is proposed to establish target reliabilities for structures, taking broad sustainability into account. This paper focuses on finding an acceptable failure probability value based on reaching a sufficient relative investment in life safety improvement. In current literature, this investment is quantified using a function for the lifetime monetary costs of structural safety, discounted to their net present value, without consideration of environmental effects. As part of the new framework, this paper proposes taking harmful emissions into account through a shadow-costing scheme, thereby establishing an augmented cost function and accompanying criterion for sufficient safety investment.
This proposed approach is tested on a typical structural design case study, where the augmented and conventional approaches have been compared. The augmented approach yields an acceptable failure probability around 50% larger than the conventional approach, though the difference is sensitive to the utilised shadow price of emissions. In general, the acceptable reliability of a structure is also sensitive to the number of potential fatalities occurring at structural failure, and the applied discount rate.

Keywords: Structural Safety, Sustainability, Optimal reliability, Acceptable reliability, Differential discounting.

1. Introduction

The reliability of engineering structures in the built environment, such as buildings and large infrastructure objects, is crucial to society. However, improving structural safety requires significant investment into additional material, which also causes additional embodied emissions. In many countries, the construction sector represents more than 10% of GDP, and more than 20% of carbon emissions (RILEM, 2022). When considering the desired safety of a structure (quantified through a target failure probability P_f or equivalent reliability index β), a balance should therefore be found between the societal value of safety and the economic and environmental burden required to achieve it. Current norms on structural safety define optimal reliability based on monetary optimisation of a total lifetime cost function, and acceptable reliability based on relative life-saving costs and the societal willingness to pay for life safety or SWTP (ISO, 2015; NEN-EN, 2025), with the most stringent value used as the target reliability. Carbon emissions are not currently accounted for, despite the significant contribution of the construction sector and the importance of reducing emissions to mitigate climate change.

Ideally, target reliabilities should be informed by *broad sustainability*, defined as a combination of economic, environmental, and social sustainability. These three 'pillars' are incorporated in the life cycle sustainability assessment (LCSA) method, itself a combination of economic life cycle costing (LCC), environmental life cycle assessment (E-LCA), and social life cycle assessment (S-LCA). The last of these three methods is not as mature as the other two; however, the current approach to establishing acceptable failure probabilities can contribute to its development, as life safety is a crucial social concern for assessment in the built environment NEN-EN (2021). The life quality index (LQI) used to establish the SWTP (Pandey and Nathwani, 2004; Fischer et al., 2012) can be viewed as an instrument for S-LCA. The monetary cost functions can be viewed as LCC, so if environmental concerns were also incorporated through E-LCA, all three pillars would be covered.

This is the aim of the novel framework presented in this paper: to establish target reliability values based on broad sustainability. The cost functions will be augmented with shadow-costed CO_2-emissions, and the LQI is proposed as an instrument for S-LCA. The next section describes the current status quo in this area, followed by the proposed improvements of the new framework, which is currently in development. Preliminary results of applying the framework in a typical structural design are then presented.

2. Current practice

Current leading norms on structural safety are the probabilistic model code by the Joint Committee on Structural Safety (JCSS, 2000), ISO-norm 2394 on structural reliability (ISO, 2015), and the Eurocode EN-1990 (NEN-EN, 2025). The target reliabilities in these documents are in turn based on the work of Rackwitz (Rackwitz, 2000, 2006, 2008), Fischer (Fischer et al., 2012, 2019), Pandey (Pandey and Nathwani, 2004; Pandey et al., 2024) and several other authors. This section briefly summarizes their work, thereby explaining the 'conventional' approach for finding target reliability values.

Optimal and acceptable reliabilities are currently derived from objective functions representing the monetary lifetime cost of a structure. A simple formulation is used in most literature, based on the infinite renewal model by Rackwitz:

$$C_{total} = C_0 + C_1 x + (C_0 + C_1 x)\frac{\omega}{\gamma} + (C_0 + C_1 x + C_H)\frac{P_f(x)}{\gamma} \quad (1)$$

Where C_{total} represents the total lifetime costs of a structure or component, C_0 the costs independent of the decision parameter x (representing e.g. the dimension of a beam), and C_1 the costs that do vary with this parameter. The term $C_0 + C_1 x$ thus represents the cost of a single realisation of the structure. In principle, non-linear formulations could be used for this term as well, though these are rarely encountered in literature.

One realisation is constructed at the beginning of the lifetime, and another every time the structure is replaced, either through obsolescence or structural failure. The former process is represented by the term $(C_0 + C_1 x)\frac{\omega}{\gamma}$, where ω is the expected yearly obsolescence rate, and γ is the discount rate converting the expected yearly obsolescence costs to the net present value over an infinite lifetime. Structural failure is represented by the term $(C_0 + C_1 x + C_H)\frac{P_f(x)}{\gamma}$, where C_H represents additional damage costs in case of failure, and $P_f(x)$ the failure probability, which also depends on the decision parameter x. In general, the failure probability decreases monotonically with increasing x, with a decreasing slope (i.e., its first derivative is negative and its second derivative is positive for any value of x).

To determine the optimal failure probability, the cost function is minimised to find an optimal value of x, denoted as x_{opt}, leading to the corresponding value of the failure probability

$P_{f,opt} = P_f(x_{opt})$, and the associated reliability index $\beta_{opt} = \Phi^{-1}(1 - P_{f,opt})$ (with Φ^{-1} the inverse cumulative distribution function of standard-normally distributed variable).

This value is especially sensitive to the cost parameters C_1 and C_H relative to the constant costs C_0, representing the relative cost of increased safety and the relative consequences of failure, respectively. In the probabilistic model code and ISO 2394, three categories for both of these parameters are defined, leading to nine different cases for optimal reliability, summarised below (reproduced from ISO (2015); JCSS (2000)):

Table 1. Conventional optimal failure probabilities, from (ISO, 2015))

Cost C_1/C_0		Consequence classes C_H/C_0 Minor	Moderate	Large
Large	β	3.1	3.3	3.7
	P_f	10^{-3}	$5 * 10^{-4}$	10^{-4}
Normal	β	3.7	4.2	4.4
	P_f	10^{-4}	10^{-5}	$5 * 10^{-6}$
Small	β	4.2	4.4	4.7
	P_f	10^{-5}	$5 * 10^{-6}$	10^{-6}

The two parameters C_1 and C_H form a 'push-pull' effect. A larger relative safety cost 'pushes' the optimal failure probability upwards, towards smaller corresponding values of x. A larger relative consequence of failure instead 'pulls' it downwards.

Aside from optimal reliabilities, minimum acceptable values are also defined, serving as a lower bound for the target reliability. To determine the minimum acceptable failure probability, the life quality index (Pandey and Nathwani, 2004) is used to establish a societal willingness to pay for safety (SWTP), which quantifies how much relative resources a society can commit to save one statistical life (Fischer et al., 2012):

$$SWTP = \frac{G}{q} \cdot C_x \tag{2}$$

Where G is the GDP per capita, q is the fraction of a person's lifetime spent working, and C_x is a demographic constant based on the distribution of life safety risk across the considered population (Rackwitz, 2006). The SWTP is used to form a constraint based on the marginal increase in life safety, along with the number of fatalities in case of structural failure, N_f, and a different cost function for the investment into life safety C_{safety}:

$$C_{safety} = C_0 + C_1 x + (C_0 + C_1 x)\frac{\omega}{\gamma} \tag{3}$$

These safety costs are essentially equal to C_{total} with the failure cost component disregarded. This is done because only direct investments into life safety are considered to affect the life quality index Fischer et al. (2013). Furthermore, from the perspective of distributive justice, a societal concern such as life safety should not be 'traded' for a reduction in expected damage costs, which forms a private benefit (van de Poel and Royakkers, 2011). The constraint is then formulated based on the derivatives of C_{safety} and $P_f(x)$ with respect to x, representing the marginal increase in costs and decrease in risk, respectively:

$$-\frac{dP_f}{dx} \leq \frac{\frac{d}{dx}C_{safety}}{SWTP \cdot \frac{N_f}{\gamma}} = \frac{C_1\,(\gamma + \omega)}{\frac{G}{q} \cdot C_x \cdot N_f} = K_1 \tag{4}$$

The value of x for which this inequality holds exactly is noted as x_{acc}, with the associated failure probability $P_{f,acc} = P_f(x_{acc})$ and accompanying β_{acc}. The constant K_1 is referred to as the relative life-saving cost and informs the acceptable reliability according to cost and risk aspects of the considered structure. Table 2 provides general values from Fischer et al. (2012), though note that these are dependent on the definition of the decision variable x.

Table 2. Conventional acceptable reliability indices, from (Fischer et al., 2012)

Life-saving costs	K_1 range	β_{acc}
Large	$10^{-3} \sim 10^{-2}$	3.1
Medium	$10^{-4} \sim 10^{-3}$	3.7
Small	$10^{-5} \sim 10^{-4}$	4.2

Smaller life-saving costs correspond to a smaller acceptable failure probability and a larger reliability index. Another 'push-pull' effect is at play here, now between the absolute value C_1 on

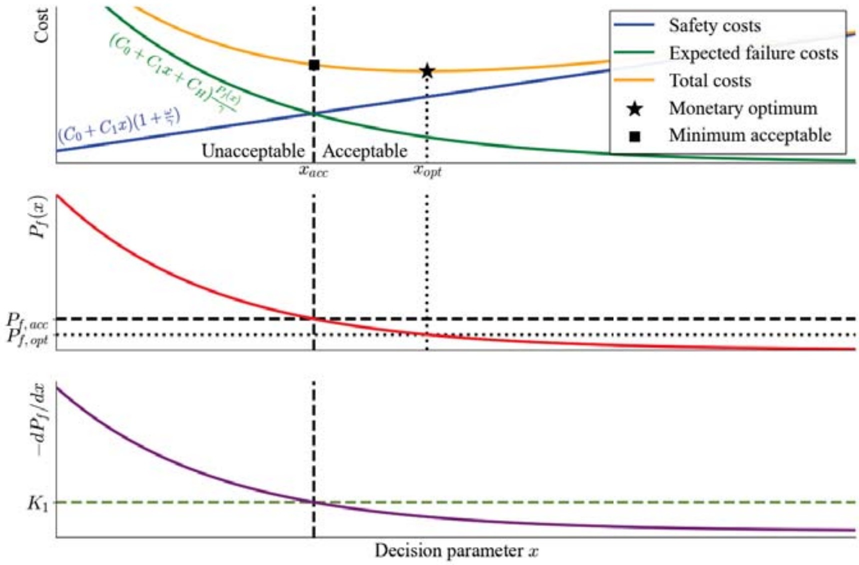

Fig. 1. Visual overview of the current approach towards optimal and acceptable failure probabilities.

one hand and the SWTP and number of fatalities on the other, representing the monetary cost of safety and societal consequences of failure, respectively.

Figure 1 provides a visual overview of the current approach. The top panel shows the total cost function, along with its two components C_{safety} and the failure costs. The middle panel shows the failure probability $P_f(x)$, and the bottom the negative of its derivative and the relative life-saving costs K_1.

3. Proposed Improvements

As stated, optimal and acceptable failure probabilities should be derived from the perspective of broad sustainability, combining social, economic and environmental aspects. This paper focuses on the acceptable value. The current approach covers economic aspects through the safety cost function C_{safety}, but environmental concerns are absent. An important social aspect, life safety, is incorporated in the SWTP derived from the LQI. By viewing this as a social mechanism, as described in the state-of-the-art literature on social life cycle assessment (UNEP et al., 2020; ISO, 2024), the role of social sustainability becomes more explicit. In turn, this concept can also contribute to the further development of S-LCA, where quantitative assessment methods are currently lacking (Larsen et al., 2022; Amini Toosi et al., 2021),

To involve environmental aspects, a simple model for CO_2-equivalent emissions is proposed, based on the infinite renewal process but using emissions instead of costs, and with the same decision parameter x and failure probability $P_f(x)$:

$$E_{total} = E_0 + E_1 x + (E_0 + E_1 x)\frac{\omega}{\gamma} + (E_0 + E_1 x + E_H)\frac{P_f(x)}{\gamma} \quad (5)$$

Where the different parameters represent similar aspects as in C_{total}: E_0 the emissions independent of x, E_1 the emissions varying with x, and E_H the additional emissions in case of failure. Similar models have been used in several papers by Hingorani and Köhler (Hingorani and Köhler,

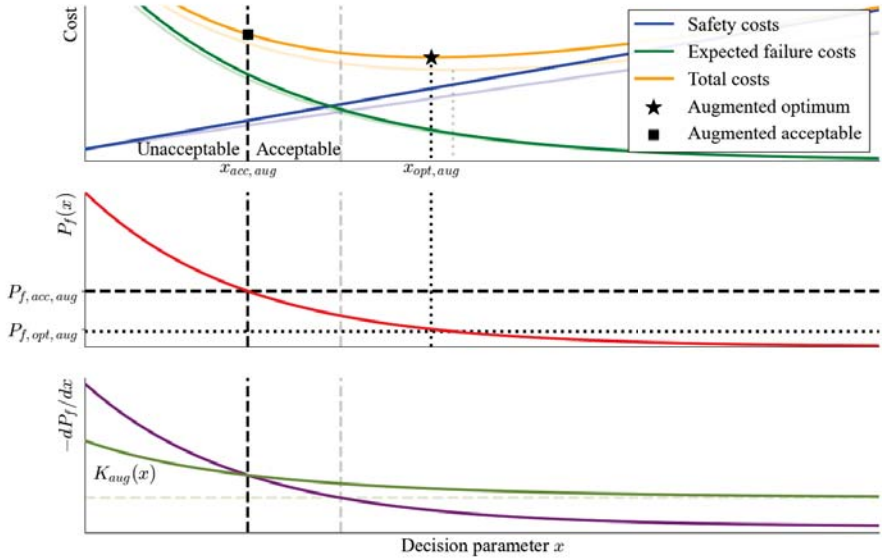

Fig. 2. Visual overview of the novel approach towards optimal and acceptable failure probabilities. The faded lines represent the conventional approach. The difference in result between the two approaches is indicative

2023a,b, 2025). This model can be considered as the output of E-LCA, and will be used to add environmental shadow costs to the cost functions of the current approach.

The complete lifetime emissions should be taken into account in the shadow costs, including those associated with structural failure, while the monetary failure costs are still disregarded. A reduction in failure costs benefits the owner, while a decrease in life safety risk benefits all of society, so these two aspects should not be commensurated when establishing a societally acceptable failure probability. At the same time, the owner cannot invest an infinite amount of resources into reducing this risk, so the costs they carry should be taken into account. Therefore, the costs of a reduction in failure probability $C_1(1+\frac{\omega}{\gamma})$ are weighed against the improvement in life safety; $\frac{dP_f}{dx} \cdot SWTP \cdot N_f$. The current formulation of K_1 reflects this.

Carbon emissions, as opposed to failure costs, affect the environment and climate. The consequences of this are undeniably a societal problem, so from the perspective of a fair distribution of costs, benefits and risk, emissions related to failure should be accounted for in establishing an acceptable failure probability in the new framework. This leads to the following expression for the augmented safety costs:

$$C_{safety,aug}(x) = C_{safety}(x) + c_e E_{total}(x) \quad (6)$$

Where c_e is the emission shadow price, expressed in monetary units per kilogram CO_2-equivalent emissions. The shadow price should represent the societal burden and may not necessarily be equal to a carbon tax, if one is applicable. Inserting this in Equation 4 yields the augmented constraint for the acceptable failure probability:

$$-\frac{dP_f}{dx} \leq \frac{\frac{d}{dx}(C_{safety} + c_e E_{total})}{SWTP \cdot \frac{N_f}{\gamma}} = \frac{C_1(\gamma+\omega) + c_e E_1(\gamma+\omega+P_f(x))}{\frac{G}{q}C_x \cdot N_f + c_e(E_0 + E_1 x + E_H)} = K_{aug}(x) \quad (7)$$

With the augmented relative life-saving costs $K_{aug}(x)$. Similar to before, the value $x_{acc,aug}$ for which the inequality holds exactly yields $P_{f,acc,aug}$ and $\beta_{acc,aug}$.

For finding optimal reliability in the new framework, a similar approach can be followed, whereby the total cost function C_{total} is augmented with the shadow-priced emissions functions. This augmented cost function is then minimised to find an optimal failure probability considering both monetary costs and emissions, leading to $x_{opt,aug}$ and $P_{f,opt,aug}$. Optimal reliability will be part of the final framework, but it is not within the scope of this paper. Figure 2 shows a visual overview of the novel approach compared to the conventional approach.

4. Case Study

The proposed framework for finding acceptable reliabilities has been applied on a typical case study based on the design of a steel beam in an office building. Real data was used as far as possible, including a model by Hingorani et al. (2020) to estimate the important parameter N_f, as well as databases for cost (Bauforum Stahl, 2025), environmental (Institut Bauen und Umwelt, 2025) and economic (World Bank, 2025) data. The acceptable reliability was determined with both the conventional and augmented approach, followed by a sensitivity analysis on several of the parameters in the cost, emission and failure probability model. A brief overview of the results is presented here.

The decision variable x was defined as the section modulus of the profile of the beam, which sets its moment resistance. The beam area, setting the volume and thereby the material costs and embodied emissions of the beam, was linked to the section modulus through a non-linear function $A_b(x)$ based on beam profile data. The cost of a single realisation of the beam can then be expressed as:

$$C_b(x) = C_0 + c_s \rho L * A_b(x) \tag{8}$$

And the emissions as:

$$E_b(x) = E_0 + e_s \rho L * A_b(x) \tag{9}$$

Where c_s represents the material cost of steel, given in monetary units per kilogram, and e_s represents the emission intensity, given in kilograms of CO_2-equivalent emissions per kilogram material. The terms L and ρ represent the length of the beam and the density of steel, respectively. These two terms replace the linear terms $C_0 + C_1 x$ and $E_0 + E_1 x$ in the cost and emission functions. The conventional criterion for acceptable reliability then becomes:

$$-\frac{dP_f}{dx} \leq \frac{\frac{d}{dx} C_b(\gamma + \omega)}{\frac{G}{q} C_x \cdot N_f} \tag{10}$$

And the augmented criterion:

$$-\frac{dP_f}{dx} \leq \frac{\frac{d}{dx} C_b(\gamma + \omega) + c_e \frac{d}{dx} E_b(\gamma + \omega + P_f)}{\frac{G}{q} C_x \cdot N_f + c_e(E_b + E_H)} \tag{11}$$

The value of a number of important parameters is given in Table 3. Not every parameter is included for the sake of brevity.

Table 3. Parameter values in the case study

Parameter	Value	Unit
c_s	2.00	€ / kg steel
e_s	1.89	kg CO_2eq / kg steel
c_e	0.50	€ / kg CO_2eq
$\frac{G}{q} C_x$	6,600,000	€ / person
N_f	0.217	person
γ	0.03	-
ω	0.02	-

The two criteria have been used to find the acceptable failure probability. The results are given in Table 4 as the 'baseline' scenario. To illustrate the importance of several variables in the problem, alternative scenarios have been considered, where one variable in question is either doubled or halved. This has been done for the number of fatalities N_f, the discount rate γ and the emissions shadow price c_e (all three are quantified for the baseline in Table 3). All three of these variables have a significant influence on the result, and can vary depending on the use and location of the building, and considered climate change mitigation policies (Lee and Ellingwood, 2015;

Yang et al., 2018; Hingorani et al., 2020; Kamali Saraji et al., 2024), so they are relevant to investigate. The approach of doubling or halving one variable per scenario was chosen to provide a brief overview of their influence on the resulting acceptable reliability values. The resulting values are given in the following rows of Table 4. A full factorial analysis was also performed, though the full results are not shown here, again for the sake of brevity.

Clearly, the difference between the acceptable failure probability found through the conventional or augmented approach is driven by the shadow price placed c_e. In the baseline scenario, the augmented approach yields a failure probability approximately 1.5 times larger than the conventional approach. For a doubled shadow price, this becomes a factor 2, while for a halved value, it becomes 1.25.

The influence of the number of fatalities N_f is also clear: both acceptable failure probabilities are approximately inversely correlated with N_f. This illustrates the downward 'pull' of the consequence of failure on the acceptable failure probability. This is also influenced by γ. As failure of the structure occurs in the future, a larger discount rate decreases its influence on the net present value, thereby increasing the acceptable failure probability. Hence, the full factorial analysis revealed a strong negative interaction effect between these two variables. Furthermore, a small positive interaction between c_e and γ could be seen, as both increase the augmented life-saving cost, as well as a small negative interaction between c_e and N_f, showing that c_e also contributes to the 'push'-effect.

In general, the acceptable reliability values found in this case study are more stringent than those appearing in the literature, especially compared to the values in Table 2 from Fischer et al. (2012). A possible cause could be the number of fatalities at failure, N_f. Fischer et al. used estimates for the order of magnitude of the number of fatalities per square meter of office floor, ranging from 0.001 to 0.1. The model used to estimate this parameter in this case study, from Hingorani et al. (2020), was based on a database of structural collapse of existing structures, and resulted in a value in the upper end of this range. A direct comparison is difficult, however, as Fischer et al. consider different example structures, though one is located in an office building as well, and use a different decision parameter and accompanying models for the cost and failure probability (and do not consider emissions).

5. Conclusions

This paper has presented a proposal for a novel framework to establish optimal and acceptable failure probabilities for engineering structures. This framework will be constructed from the perspective of *broad* sustainability, involving economic, environmental, and social aspects. An overview was given of the current approach in norms and literature, followed by proposed improvements to achieve all three pillars of sustainability. Finally, a case study was briefly presented in which a part of the framework, concerning acceptable reliability, was applied on a typical structural design. Compared to the conventional approach, the new framework resulted in an acceptable failure probability 50% larger than the conventional approach, sensitive to the shadow price of emissions, number of potential fatalities at structural failure and discount rate.

Table 4. Conventional and augmented acceptable yearly reliability values for a typical beam design

Scenario	$P_{f,acc}$ (β_{acc})	$P_{f,acc,aug}$ ($\beta_{acc,aug}$)
Double c_e	$6.1 \cdot 10^{-7}$ (4.85)	$1.2 \cdot 10^{-6}$ (4.72)
Half c_e	$6.1 \cdot 10^{-7}$ (4.85)	$7.5 \cdot 10^{-7}$ (4.81)
Baseline	$6.1 \cdot 10^{-7}$ (4.85)	$9.0 \cdot 10^{-7}$ (4.77)
Double N_f	$3.0 \cdot 10^{-7}$ (4.99)	$4.5 \cdot 10^{-7}$ (4.91)
Half N_f	$1.2 \cdot 10^{-6}$ (4.71)	$1.8 \cdot 10^{-6}$ (4.63)
Double γ	$9.8 \cdot 10^{-7}$ (4.76)	$1.4 \cdot 10^{-6}$ (4.68)
Half γ	$4.3 \cdot 10^{-7}$ (4.92)	$6.3 \cdot 10^{-7}$ (4.85)

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