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Augmented life quality index approach for social life cycle assessment in engineering structures: Societally and environmentally acceptable failure probabilities

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ABSTRACT

Life cycle assessment (LCA) is becoming increasingly important for structures in the built environment, but more development is still required. This paper proposes an augmented life quality index (LQI) for social and environmental life cycle assessment (S-LCA and E-LCA) of engineering structures. The original LQI has previously been applied in norms and literature on structural safety, but not yet in social life cycle assessment, nor with inclusion of environmental aspects. Its main application is to determine the societally acceptable failure probability of a structure by weighing costs and benefits of improvement in life safety, making the LQI an ideal candidate for further development of S-LCA and LCA in general.

This paper describes how the LQI can be used while adhering to state-of-the-art S-LCA guidelines and norms. A novel augmentation based on E-LCA is then proposed, where shadow costs of embodied emissions are added to the cost of structural safety, combining social, economic and environmental sustainability. This is demonstrated through a case study based on a typical structural design, showing that the LQI can be used in S-LCA to establish the acceptable failure probability of a structure, and that the E-LCA augmented LQI-based criterion allows the acceptable reliability index to be reduced by approximately 0.1 to 0.3. This reduction is dependent on the ratio of the shadow price and material costs.

1. Introduction

Life cycle assessment methods are becoming increasingly important in the built environment. These have generally focused on the environmental and economic impacts of buildings and structures until now, and less so on societal aspects such as safety (see [1] for more information). The safe functioning of structures is of great importance to society, but construction has environmental and economic impacts as well. In many countries, the built environment contributes more than 10% to GDP, [2], while construction is responsible for approximately 20% of global CO_2 emissions [3]. There is thus a strong need to optimise structural designs, taking into account safety, affordability and sustainability.

A crucial aspect of this design is the target reliability of a structure, as discussed in [4–7]. The ISO2394 code on structural safety [8] distinguishes *optimal* and *acceptable* reliability (appendix G.5, pages 105–109), as does the Eurocode EN 1990 [9] (paragraph C.3.4, pages 124–125). The former is based on monetary optimisation, where the optimal failure probability leads to the smallest lifetime cost of the structure. The latter determines the maximum allowable failure probability from a societal point of view, based on human life safety, placing a constraint on the optimisation. *This* paper focuses on acceptable reliability.

In general, the failure probability should be small enough to be societally acceptable, without needlessly hindering crucial developments such as housing and infrastructure. This can be viewed as a trade-off between the three 'pillars' of sustainability: environmental, economic, and social [10,11], together forming *broad sustainability*. Ideally, all three should be taken into account when making decisions about structures. A method that aims to achieve this is life cycle sustainability assessment (LCSA), which gives a comprehensive view of the sustainability of a product [12].

LCSA is commonly presented as a combination (or metaphorical summation) of three methods, one for each pillar:

$$\text{LCSA} = \text{E-LCA} + \text{LCC} + \text{S-LCA} \quad (1)$$

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Environmental life cycle assessment (E-LCA) is well-established and is supported by several ISO-norms [13,14]. In E-LCA, the environmental impact profile of a product or service is determined based on the flow of materials throughout its life cycle. Because E-LCA has been standardised, it often recommended by governments to be performed as part of large projects [15,16].

The second method, Life Cycle Costing (LCC), covers the economic pillar. It is also well-known, if not as formalised as E-LCA [17]. Monetary optimisation over the lifetime of a structure [8,9,18–21], can be considered an application of LCC.

The third method is social life cycle assessment (S-LCA), which is not as mature as the other two yet [1,22,23]. State-of-the-art literature includes the guidelines by the United Nations Environmental Programme [24] and the recently published ISO14075 norm [25]. These indicate that, while development of S-LCA is ongoing, several challenges still exist before it can be applied to the same extent as LCC and especially E-LCA. One of the main challenges in this development is choosing indicators and characterisation models for the social impact assessment phase of S-LCA, which links data gathered for a certain system or product to its effects on different societal stakeholder groups [10,26].

In structural engineering, three such stakeholder groups can generally be considered, represented by three 'actors': the environment, the owners or maintainers of a structure, and its users. These groups also represent the environmental, economic and social pillars, respectively, indicating that the three pillars and life cycle methods can be intertwined and that ultimately, these three actors have a shared interest in societal wellbeing. The distribution of costs, benefits and risks over these groups is an important aspect in determining the acceptable failure probability [27]. LCSA, and S-LCA specifically, can be a useful instrument for this, but a method is then needed to weigh improvements in safety for one group against costs for another.

Another key problem, which affects life cycle methods in general, is that guidelines generally do not prescribe whether the design of the considered product or system can be considered optimal or acceptable. Decision-making using LCA is therefore limited to comparing different alternatives [25]. For engineering structures, this could for example involve the choice of the structural system and the material types. However, whether the decision outcome can be judged to be 'sufficiently sustainable' or 'sufficiently safe' is not generally addressed in LCA, while this is needed to arrive at a usable design.

To address these issues, this study proposes an approach based on the life quality index (or LQI), along with an augmentation of this approach based on environmental emissions. The LQI has been applied in structural engineering, but not yet in S-LCA or LCSA [28]. It is a compound societal indicator, representing 'life quality' as a utility function of the resources and time available for consumption [29]. One of its main applications is to determine maximum acceptable failure probabilities for buildings and structures, by requiring any investment into life safety that lead to a larger LQI [8,30]. This can be viewed as a social characterisation model that links the design of a structure to its costs and structural safety, important impacts for different stakeholder groups, making it a promising candidate for use in the further development of S-LCA. In this study, this use of the LQI is compared to current guidelines on S-LCA [24]. Recent literature on the LQI suggest that environmental concerns should play a role in establishing target reliabilities as well [29,31]. The proposed augmentation of the LQI-based approach addresses this. The investment into life safety in this augmentation consists not only of monetary costs, but also environmental impacts across the structure of a structure, from both construction and structural failure. This makes the LQI an ideal instrument for use in both S-LCA and E-LCA in structures.

Sections 2 and 3 describe the current development of S-LCA in the built environment and the background of the LQI, with its current applications in structural engineering, respectively. Section 3.3 specifically addresses the difference in acceptable failure probabilities between countries with different GDP and life expectancies. Afterwards, the use of the LQI within S-LCA is proposed in Section 4, taking account of current guidelines, followed by the augmented LQI-criterion which combines S-LCA and E-LCA. This is then demonstrated in Section 5 through a typical example based on the design of a building, followed by a sensitivity analysis in Section 6. Finally, a discussion and conclusion are provided in Sections 7 and 8.

2. S-LCA in the built environment

The United Nations Environmental Program has published guidelines and methodological sheets on social life cycle assessment [24,32], referred to as the 'UNEP guidelines' in this paper. The most recent versions can be considered the current state-of-the-art in the development of S-LCA, together with the ISO14075 norm [25], which largely overlaps with these guidelines. The UNEP guidelines reveal that much progress has been made in recent years, but more development is still needed. An important recommendation is that S-LCA should be performed in four phases, mirroring those of the E-LCA norms [13]:

1. Goal and scope definition: determining the purpose, system boundaries and methodological framework of the assessment
2. Life cycle inventory: gathering data on the processes within the established boundaries
3. Life cycle impact analysis: evaluating the social impacts of the system or product being assessed
4. Interpretation: reviewing and discussing the results of the assessment, in accordance with the purpose established in the first phases

According to three literature reviews [1,23,26], all published after the newest version of the UNEP guidelines and focusing on S-LCA within the built environment, the two currently most critical needs in the development of S-LCA are creating databases to be used in the second phase and assessment methods for the third phase. The importance of the social pillar is acknowledged across literature, but implementing its associated method has proven difficult due to a lack of data accessibility, indicators and standardisation [10,11]. As previously mentioned, LCA in general also does not allow for the direct identification of an optimal or acceptable design.

The UNEP Guidelines also contain a list of six stakeholder groups (workers, local community, value chain actors, consumers, society and children) which should ideally be taken account of in S-LCA. This list is quite general, however, while the impacts measured in S-LCA will generally be more context-specific compared to those in the other two life-cycle methods.

Another norm relevant to S-LCA in the built environment is EN-15643 [33], on assessment of (social) sustainability for construction works. This norm contains several aspects which should be covered in social assessments of buildings, listed in Table 1. These are more applicable to the built environment, and they could be considered as 'impact categories', similar to those defined in E-LCA norms [13]. Quantifying these impacts in a similar manner to E-LCA can still be considered a major challenge, however [23] (see also Section 4). For the 'safety' aspect, it is intuitive that structural failures, causing large costs, non-functioning of a structure and possibly fatalities, should be an important consideration in S-LCA. Furthermore, as societal acceptance is crucial for safety, a simple comparison between different alternatives is insufficient. To further develop S-LCA in the built environment, a method is therefore desirable that establishes a societal criterion for the acceptable safety of a building or structure. Thus, the following section presents a quantitative instrument that has been used in structural safety research and decision-making, but not yet within S-LCA: the life quality index.

Table 1
Social aspects of construction works suggested by EN 15643 [33].

Accessibility	Adaptability to user needs
Safety	Loads on the neighbourhood
Resilience	Health, comfort, quality of indoor environment
Security	Protection of cultural heritage
Employment/job creation	Sourcing of materials and services
Stakeholder involvement	

3. The life quality index

This section briefly introduces the LQI and its application in structural safety, in order to explain the proposed use and environmental augmentation in Section 4.

3.1. General principles

The life quality index or LQI is a compound indicator, similar to the human development index [34], introduced by Pandey and Nathwani [35]. For a full derivation, readers are referred to their work [36,37]. A brief overview is given here.

The LQI is formulated as:

$$L = G^q E \tag{2}$$

where L is the value of the LQI, set by G, the gross domestic product (GDP, per capita per year) and the life expectancy E, and the ratio between work and leisure time q [37].

The LQI is an ordinal indicator. To quantify the trade-off between time and resources for consumption, relative changes of L are therefore considered instead of its absolute value:

$$\frac{dL}{L} = q\frac{dG}{G} + \frac{dE}{E} \tag{3}$$

where a positive value of $\frac{dL}{L}$ satisfies the *net benefit criterion* (also called the LQI invariance prinicple [28]). This leads to the concept of a societal willingness to pay (SWTP) in a marginal life-saving cost (MLSC) approach: any investment for which $\frac{dL}{L} > 0$ is considered desirable from a societal point of view.

The net benefit criterion can be rewritten as [38]:

$$-dG \leq \frac{G}{q}\frac{dE}{E} \approx -\frac{G}{q}C_x d\mu \tag{4}$$

where $-dG$ is the marginal cost per capita invested to achieve a relative improvement in life expectancy, $\frac{dE}{E}$. This improvement is in turn approximated by multiplying two terms: a demographic constant C_x, and the marginal reduction in yearly mortality per capita, $-d\mu$; the rate of death per person. The value of $d\mu$ represents the change in risk to life safety, and the value of C_x how this change is distributed across different age groups, and can be calculated using life tables [39–41]. The marginal change in mortality is converted to the marginal change in yearly deaths dm by multiplying both sides of Eq. (4) by the population size N_p. This converts the $-dG$ on the other side of the inequality to the total costs of the investment in life safety, dC (note the sign change). This leads to:

$$-dG \cdot N_p = dC \leq -\frac{G}{q}C_x dm = -\frac{G}{q}C_x d\mu \cdot N_p \tag{5}$$

which is the general form of the LQI net benefit criterion, with $\frac{G}{q}C_x$ as the SWTP [38,42]. This is satisfied for any investment into life safety of which the costs dC are outweighed by the SWTP multiplied by the number of lives saved dm.

3.2. The LQI in structural safety

In the structural safety field, the LQI net benefit criterion is used to establish an acceptable upper bound to the failure probability of a structure through a marginal life saving cost (MLSC) approach [6,8,9,30,38,43]. The total lifetime cost C_{total} of a structure is formulated as a function of a single decision parameter x (representing e.g. the dimension of a beam), based on the infinite renewal model introduced by Rackwitz [18,44]:

$$C_{total}(x) = C_{const}(x) + (C_{const}(x))\frac{\omega}{\gamma} + (C_{const}(x) + C_H)\frac{P_f(x)}{\gamma} \tag{6}$$

where $C_{const}(x)$ represents the construction costs of a single realisation of the structure. A linear expression, $C_{const}(x) = C_0 + C_1 x$, is often used in literature [6,30]. The first term in C_{total} represents the initial construction. The following terms, with ω/γ and $P_f(x)/\gamma$, represent the structure becoming obsolete or failing, respectively. If either occurs, the construction costs are incurred costs again, plus additional damage costs C_H in case of failure [18]. Both failure and obsolescence are modelled as stationary Poisson processes [6], occurring over the lifetime of the structure. The associated costs are discounted to their net present value (NPV) by dividing the expected annual costs by the discount rate γ [45,46], such that the total lifetime costs valued at the decision point are considered, as opposed to yearly rates.

The value of ω is set by the expected time until obsolescence (e.g. for 50 years, $\omega = 1/50$). The annual failure probability of the structure, $P_f(x)$, generally decreases with increasing x (see Fig. 1, middle panel) This approach assumes that the failure probability remains constant in time.

The marginal investment into life safety, dC, consists of a part of C_{total}. If the failure probability is reduced, then so are the expected damage costs, the final term in Eq. (6). This monetary benefit of decreasing the failure probability is a positive for the owner or maintainer of the structure, but this cannot be 'traded' for human safety [38,42]. From the ethical principle of distributive justice, an important perspective in judging the acceptability of risks [27], a monetary benefit for the owner should not be commensurate with a change in risk to life safety for the users. This term is therefore not considered for the marginal cost dC in the net benefit criterion. At the same time, the owner cannot be expected to make an infinite investment in structural safety, so an *increase* in the cost they carry *should* be taken into account in the net benefit criterion. So, the safety investment costs are defined as the derivative of the construction and obsolescence costs, the terms that increase with x, and the damage cost is ignored (see also Table 2):

$$C_{safety} = C_{const}(x) + (C_{const}(x))\frac{\omega}{\gamma} \tag{7}$$

and the marginal safety costs dC are defined as the derivative of C_{safety}, which can be inserted in Eq. (5):

$$dC = \frac{d}{dx}C_{safety}(x) = \frac{d}{dx}C_{const}(x) \cdot \left(1 + \frac{\omega}{\gamma}\right) \tag{8}$$

If the structure fails, a number of mortalities N_f is expected (note that N_f and N_p are not the same number). The marginal change in deaths dm (per year) in the net benefit criterion can then be formulated using the derivative of P_f to x:

$$dm(x) = \frac{dP_f(x)}{dx}N_f \tag{9}$$

This can be inserted into Eq. (5), taking the conversion from yearly rates to the NPV into account.

To determine an acceptable level of structural safety, it is mandated that all investments into structural safety are made, which can be considered societally efficient [6]. This means that all investments for which Eq. (5) holds are required, leading to a constraint on the decision parameter x derived by reversing the inequality sign in Eq. (5):

$$\frac{dC_{safety}(x)}{dx} = \frac{d}{dx}C_{const}(x) \cdot \left(1 + \frac{\omega}{\gamma}\right) \geq -\frac{1}{\gamma}\frac{G}{q}C_x\frac{dP_f(x)}{dx}N_f \tag{10}$$

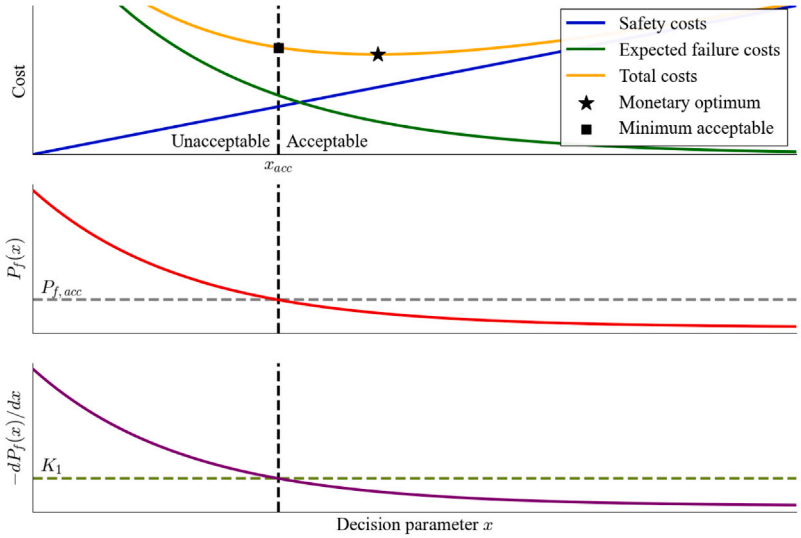


Fig. 1. The cost and failure probability functions from [30] visualised. The lower plot represents Eq. (11), which gives x_{acc}, corresponding to $P_{f,acc}$ in the middle plot. The top plot shows the cost functions.

Table 2
Cost terms included in the marginal safety investment costs $dC = \frac{d}{dx}C_{safety}$ for the conventional LQI net benefit criterion.

Cost terms	Expression	Included in dC
Construction	$C_{const}(x)$	Yes
Obsolescence	$C_{const}(x)\frac{\omega}{\gamma}$	Yes
Failure	$(C_{const}(x)+C_H)\frac{P_f(x)}{\gamma}$	No

Note that the inequality sign is reversed, and that discounting is applied on the right-hand side as well so that both sides represent the NPV over the lifetime of the structure, instead of yearly values. This is rearranged to:

$$-\frac{dP_f(x)}{dx} \leq \frac{\frac{d}{dx}C_{const}(x)\cdot(\gamma+\omega)}{\frac{G}{q}C_x N_f} = K_1(x) \tag{11}$$

This is the final constraint for the problem: the negative slope of the failure probability as a function of x needs to be smaller than the constant K_1, referred to as *relative life saving costs;* the costs of increasing safety relative to the lives saved. This reflects the MLSC approach. The value x for which this inequality holds exactly is denoted as x_{acc}, and the corresponding failure as $P_{f,acc}$

Fig. 1 shows an overview of the problem with cost and failure probability functions and LQI-based constraint (with aribtrary parameters and a linear expression for C_{const}). The value x_{acc} is marked where Eq. (11) exactly holds. The value of x minimising C_{total} (including the failure costs) is indicated by a star marker. Until now, this has been the most common use of the LQI in literature, with some differences in discounting schemes and damage costs functions, but following the same general principle [38,47,48].

3.3. Differences in acceptable failure probability between countries

Recently, Bhattacharya [49] presented a critical appraisal of the LQI-based approach towards establishing acceptable failure probabilities, arguing that it is unfair to developing countries. These have a smaller GDP per capita and shorter life expectancy, leading to a smaller SWTP, larger K_1 and larger $P_{f,acc}$. This means that the LQI-based approach inherently yields larger acceptable failure probabilities for less-affluent societies.

Bhattacharya quantifies this using numerical examples based on generic structures with a linear formulation for C_{const}, computing $P_{f,acc}$ for two different values of the SWTP: one for Switzerland and one for India. The resulting difference in acceptable failure probability between these two countries is one to two orders of magnitude.

A difference in failure probability due to a difference in GDP can be defended by considering the difference between placing a monetary value on a human life in an absolute sense, and considering a societal willingness to pay for saving one life relative to total resources available, as is done with the LQI-based criterion. The value of a human life in the broad sense should be considered universal and should not vary between countries. However, the resources available to invest in different aspects of life will inevitably vary between countries. It is not unreasonable to expect richer countries to invest more in structural safety than poorer ones, and this is what the SWTP quantifies. It should not be viewed as a direct evaluation of a human life, but rather a trade-off reflecting the availability of these resources.

Consider, if a developing country were required to commit the same absolute amount of resources to structural safety as a richer country, the relative burden on its resources would be much larger. This might cause critical housing and infrastructure to not be built, which could hinder the development of these countries. This has no bearing on the value society places on a life, but only on the resources available to protect and improve it. Differences in acceptable failure probability are then an inevitable but justifiable consequence of differences in these resources.

Additionally, besides the LQI-based criterion, an individual risk criterion can be considered as a lower bound for structural reliability, in case the LQI yields a noticeably large acceptable failure probability. See for example [50], where this concept has been applied.

4. Life cycle assessment using the LQI

This section presents the proposed application of the life quality index in (social) life cycle assessment. The first subsection explains how the current application of the LQI fits within the UNEP guidelines on S-LCA. The second subsection then presents an augmentation to this approach, where E-LCA is used to incorporate the environmental pillar into the relative cost of life safety. Finally, the life cycle stages considered by this approach are explained.

4.1. Applying the LQI in S-LCA

The LQI is a promising candidate for solving the challenges in (social) life cycle assessment in the built environment, previously introduced in Section 2: developing social impact indicators, and providing

a method to determine acceptability. The net benefit criterion allows a relevant social value – structural safety – to be quantified and weighed against monetary costs of improved structural safety. This section investigates the existing UNEP guidelines on S-LCA in more detail and explains how the current applications of LQI could fit within the development of impact indicators.

The UNEP guidelines propose two approaches towards the third phase of S-LCA, impact assessment. The first is based on reference scales, where ordinal scales are used to 'score' social performance. The second approach is based on impact pathways formed by social mechanisms. A social mechanism consists of social impact categories, impact category indicators coming from the inventory data gathered in the previous phase, and characterisation models linking the two. This is similar to the environmental characterisation models used in the impact assessment phse of E-LCA. Therefore, if S-LCA is performed as part of LCSA, it stands to reason that following the impact pathway approach is more straightforward.

As mentioned in Section 2, quantifiable indicators forming the social mechanisms are not well-established yet. A major cause for this is that social characterisation models are difficult to construct compared to their environmental counterparts [26]. For example, a common environmental characterisation model, for global warming potential, aggregates emissions of several greenhouse gases (indicators) into their combined global warming effect (impacts), expressed in kilograms CO_2-equivalent (or kg CO_2eq). One kg of methane has the same effect on global warming as 25 kg of CO_2 [51], so the model converts it to 25 kg CO_2-equivalent. Such mechanistic models are difficult to construct for the social domain, as there are generally no underlying physical processes that could be measured.

The LQI can be used in S-LCA to address this problem, as it allows a societal benefit, structural safety, to be quantified against the investments needed to achieve the benefit, thereby forming a quantitative social mechanism. Fig. 2 shows the proposed application in a flowchart. In the first phase, goal and scope definition, the aim of using the LQI should be stated. This goal is establishing an acceptable failure probability $P_{f,acc}$. In the second phase, life cycle inventory, the data underlying the cost and failure probability functions are gathered, as well as the data for the SWTP and the number of expected fatalities in case of failure. This all depends on what the decision parameter x represents, so this should be determined at this point as well.

In the third phase, impact assessment, the social mechanism then describes the risk of mortalities due to structural failure. The impact category is the safety of the occupiers and users of a structure, measured through the failure probability P_f as a function of x (the indicator). This function then forms the characterisation model. The safety investment cost is considered as a separate, economic impact category with $C_{safety}(x)$ as a characterisation model. Determining the minimum acceptable x_{acc} and $P_{f,acc}$ based on these functions forms the fourth phase, interpretation.

4.2. Adding E-LCA to the LQI

The LQI-based criterion weighs an improvement in life safety against the costs needed to achieve it. This combines economic and social aspects, thereby covering two of the three pillars of sustainability. Naturally, it is desirable to incorporate the environmental pillar as well. In fact, environmental impacts such as climate change have large societal effects as well, so one could argue that environmental considerations should be part of S-LCA anyhow (if it is not already part of a comprehensive LCSA). Furthermore, there is an increasing interest in taking carbon emissions into account in structural design in general [52,53].

A common method to commensurate environmental effects with economic considerations is through shadow costing. These are monetary values assigned to undesirable outputs, which are not taken into account in market prices, such as greenhouse gas emissions [54]. The shadow costs then represent the negative impacts of the emissions, such as the burden placed by climate change on future generations, caused by the consumption of resources in the present day. This method of environmental commensuration is reflected on in Section 7.

Table 3
Cost and emission terms included in the augmented marginal safety investment costs: $dC_{aug} = \frac{d}{dx}C_{safety,aug}$ for the augmented LQI-based net benefit criterion.

Cost/Emission terms	Expression	Included in dC_{aug}
Construction costs	$C_{const}(x)$	Yes
Obsolescence costs	$C_{const}(x)\frac{\omega}{\gamma}$	Yes
Failure costs	$(C_{const}(x)+C_H)\frac{P_f(x)}{\gamma}$	**No**
Construction emissions	$E_{const}(x)$	Yes
Obsolescence emissions	$E_{const}(x)\frac{\omega}{\gamma}$	Yes
Failure emissions	$(E_{const}(x)+E_H)\frac{P_f(x)}{\gamma}$	**Yes**

This study proposes using a shadow price to augment the costs invested into life safety in the LQI criterion, as follows:

$$C_{safety,aug} = C_{safety} + c_e E_{total} \tag{12}$$

where c_e is the shadow price, and E_{total} the total lifetime emissions. This represents the aforementioned CO_2-equivalent emissions of the structure, effectively the output of an E-LCA impact analysis with global warming potential as the corresponding impact category. The shadow price is given in monetary units per kilogram CO_2-equivalent.

Like the costs, the emissions depend on the decision parameter x, which can for example be linked to the volume or mass of a structural element, of which the production results in emissions. For the lifetime emissions, a model similar to Rackwitz's renewal model is proposed [18,44]:

$$E_{total}(x) = E_{const}(x) + (E_{const}(x))\frac{\omega}{\gamma} + (E_{const}(x)+E_H)\frac{P_f(x)}{\gamma} \tag{13}$$

where $E_{const}(x)$ represents the emissions embodied in a single realisation of the structure. Here, too, a linear formulation could be used: $E_{const}(x) = E_0 + E_1 x$. This model also features obsolescence and failure emissions, as the cost model does. Similarly, a choice of structural material and sourcing (e.g. newly constructed or re-used elements [55]) is assumed to be made beforehand. As these are added to the net present value of the cost, the emissions are also discounted. An identical discounting rate γ is used for costs and emissions. Some literature suggests that differential discounting should be applied for environmental impacts [56–58]. This is an interesting aspect to investigate, but considered outside the scope of the current paper.

The failure emissions, including the term E_H, are included in E_{total} and $C_{safety,aug}$, while the failure costs are not included in either C_{safety} or $C_{safety,aug}$. The reasoning for excluding the failure cost term was explained in Section 3.2, but the same argument does not hold for failure emissions. Emissions affect society as a whole, whereas the failure costs are borne only by the decision-maker. A reduction in failure emissions is therefore a societal benefit, not a private one. From the same distributional justice perspective as before, it can thus be argued that a reduction in failure emissions *should* be included in the criterion, while a reduction in failure cost *should not*. An overview of this distinction is given in Table 3.

The expression of K_{aug} is then constructed by replacing C_{safety} with $C_{safety,aug}$ in Eq. (10):

$$\begin{aligned} dC_{aug} = \frac{dC_{safety,aug}(x)}{dx} = \frac{d}{dx}C_{const}(x)\cdot\left(1+\frac{\omega}{\gamma}\right) + \\ c_e\left(\frac{d}{dx}E_{const}(x)\cdot\left(1+\frac{\omega}{\gamma}+\frac{P_f(x)}{\gamma}\right)+\frac{dP_f(x)}{dx}\right. \\ \left.\times\frac{E_{const}(x)+E_H}{\gamma}\right) \geq \\ -\frac{G}{q}C_x\frac{dP_f(x)}{dx}\frac{N_f}{\gamma} \end{aligned} \tag{14}$$

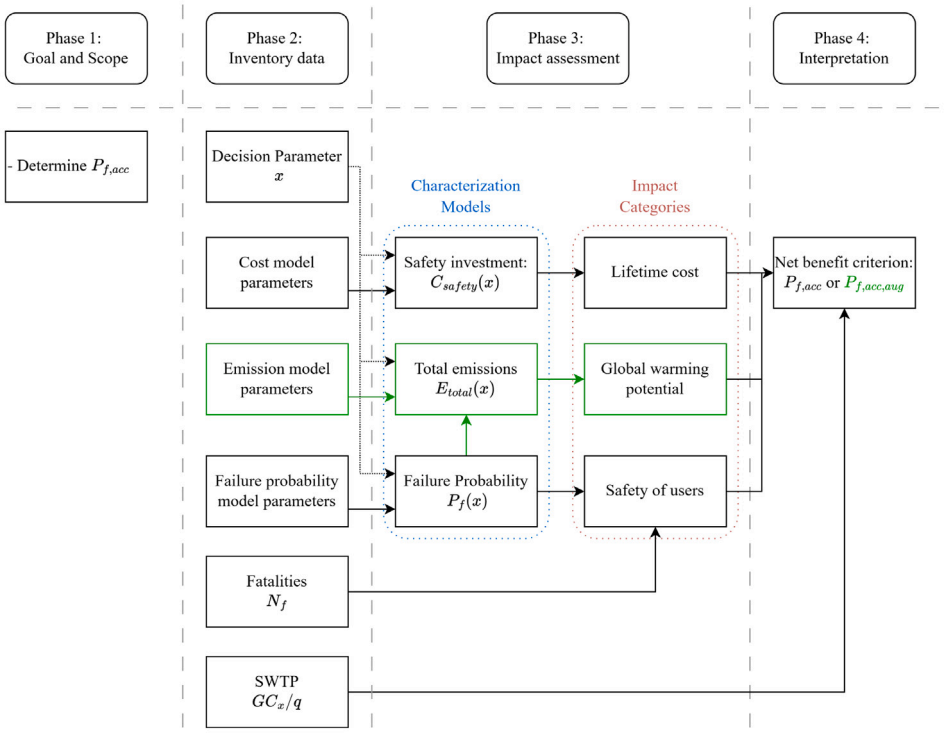


Fig. 2. Flowchart schematic of the proposed application of the LQI in S-LCA. The blocks represent information gathered in a corresponding phase, and the arrows indicate how this is used in subsequent phases. The green boxes and arrows represent the emission-based augmentation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This is rearranged so the derivative of P_f only appears on the left-hand side:

$$-\frac{dP_f(x)}{dx} \leq \frac{\frac{d}{dx}C_{const}(x)\cdot(\gamma+\omega)+\frac{d}{dx}E_{const}(x)\cdot c_e(\gamma+\omega+P_f(x))}{\frac{g}{q}C_x N_f + c_e(E_{const}(x)+E_H)} = K_{aug}(x) \quad (15)$$

The emissions augment $K_{aug}(x)$ with respect $K_1(x)$ in two ways (recall that a smaller value represents a smaller relative life-saving costs, leading to a smaller acceptable failure probability). In the enumerator (above the division line), the emissions from construction, obsolescence and failure add to the aforementioned 'burden', increasing the relative life-saving cost. In the denominator (below the division line), the consequences of failure are augmented, decreasing the relative life-saving costs.

In the next section, both the regular and proposed augmented criteria are applied in a case study based on a simple structure.

4.3. Life cycle stages

Norms on assessment of structures often define a specific set of life cycle stages and substages, as shown in Fig. 3. These stages are most intuitively associated with E-LCA, but are usable for LCC and S-LCA just as well [59].

Which stages are covered depends on which aspects are taken into account in the cost functions C_{total} and C_{safety} (and E_{total}). In theory, these can be adapted to fit many different combinations. However, the formulation applied by Rackwitz and later Fischer and Viljoen [18,30,44] can be stated to only explicitly include stages A1, assuming the decision parameter x represents a physical aspect of the structure influencing material costs, as well as B3 through B5 through the obsolescence and expected damage costs. Many of the costs in stages A1 through A4 could be included more implicitly, depending on the interpretation of the parameter C_0. The rest of stage B (B1, B2, B6, B7) are ignored, as is stage D. That said, potential mortalities due to structural collapse would occur during the use stage, so the LQI-based criterion specifically does consider stage B1.

Alternatively, the infinite renewal model could cover stage C instead of B. However, the obsolescence and renewal costs correspond more intuitively to substages B3, B4 and B5 compared to the C-substages. Therefore, stage C is ignored as well. Considering this, the proposed method falls between the well-known 'cradle-to-gate' (only stage A) and 'cradle-to-grave' (stages A, B and C) descriptions.

More specific cost and emission models could take more life cycle phases into account. If the total lifetime of the structure (after a finite number of renewals) is specified, a distinction could be made between obsolescence and renewal in phase B, and the 'true' end-of-life in phases C and D. Environmental costs, and potential benefits through re-use or recycling, could then be taken into account in a criterion for acceptable failure probability, through a similar formulation as Eq. (15). For simplicity, the more general formulation is followed in the remainder of this work.

5. Case study

This section demonstrates the proposed application of the conventional and augmented LQI-based criterion. The demonstration is structured using the four phases of social and environmental life cycle assessment as described in the previous section. A sensitivity analysis is performed for several important parameters, the values of which vary across literature or are difficult to estimate accurately. These are mainly the material costs c_{steel}, the number of fatalities N_f and shadow price c_e.

5.1. Goal and scope

This assessment concerns a typical structural design problem: a simply supported steel beam underneath a hollow-core concrete slab

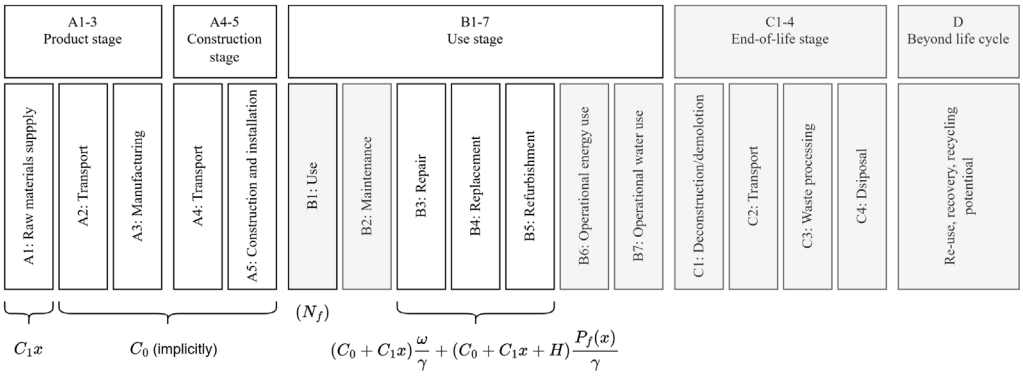


Fig. 3. Life cycle phases, adapted from [59]. The stages covered by the different components of C_{total} are indicated. The proposed E_{total} covers the same stages.

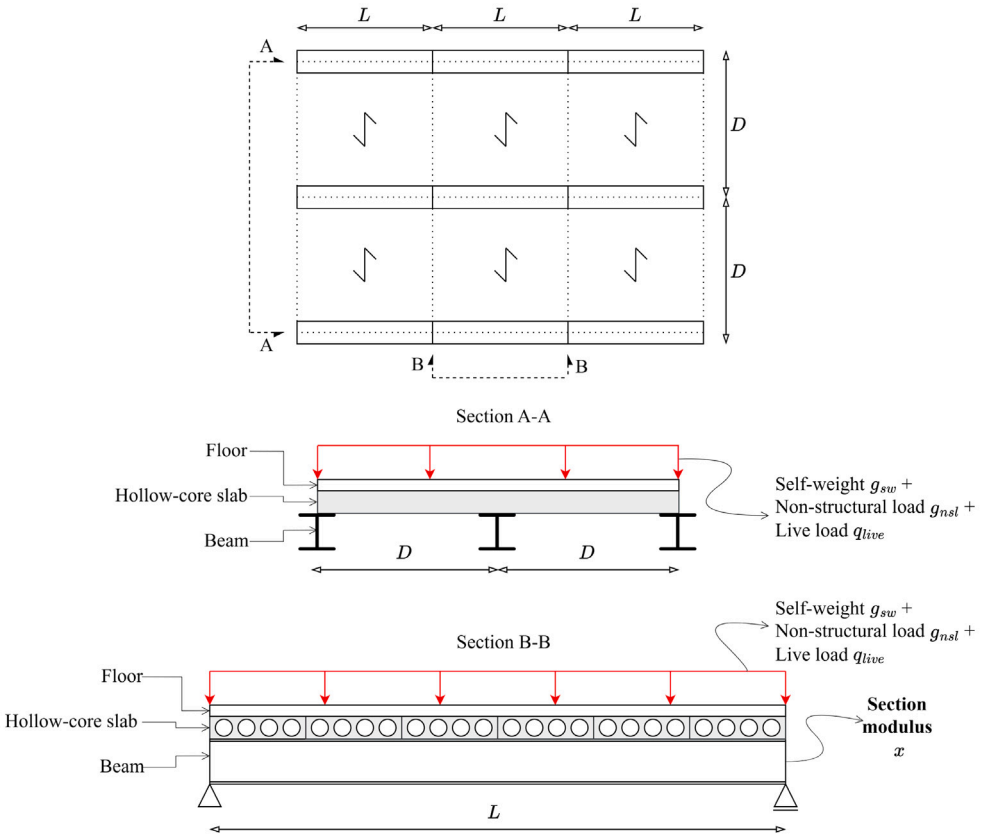


Fig. 4. The typical case study, with the loads, dimensions and decision variable indicated. Not to scale.

floor in an office building, see Fig. 4. The case study is partially adapted from previous work by Hingorani and Köhler [60]. A beam is considered with length $L = 12$ m, spacing $D = 12$ m and characteristic steel strength $f_{y,k} = 235$ N/mm^2. This case study has been chosen as it involves a typical design scenario, and can be used to demonstrate the proposed new approach without adding unnecessary complexity.

5.2. Inventory

5.2.1. Limit state function and probabilistic model

The considered failure mechanism is a plastic hinge forming in the beam due to the bending moment at midspan, represented by the following limit state function:

$$Z = \theta_R f_y x - \theta_E \frac{(g_{sw} + g_{nsl} + \theta_q q_{live}) \cdot D \cdot L^2}{8} \tag{16}$$

The decision variable x represents the plastic section modulus, which sets the plastic moment resistance together with the steel yield strength f_y. Failure occurs when the bending moment (represented by the second term in Eq. (16)) exceeds this resistance. A plastic hinge then forms, causing the beam to collapse. It is assumed that the beam can develop its full plastic moment resistance according to the requirements set out in EN 1993 (section 7.6, pages 52-56 [61]), with respect to cross-section classification, rotational capacity and local buckling. Other failure mechanisms, such as shear failure or lateral torsional buckling, are neglected to keep the scope of the case study limited to a demonstration of the two criteria. Other structures with, for example, brittle failure mechanisms such as reinforced concrete slabs or prestressed beams could also be considered in future studies. The chosen structure and failure mechanism thus form a precondition to this application, but are considered to be appropriate to demonstrate its purpose.

Table 4
Distributions of random variables in the limit state function used in the case study. The distribution of q_{live} represents the combined sustained and intermittent load with 5 year imposed load reference period, used to determine annual reliabilities.
Source: Derived from [52,62].

Variable	Description	Unit	Distribution	Mean	CoV
q_{live}	Variable load	kN/m^2	Gumbel	1.2	0.5
g_{sw}	Self-weight load	kN/m^2	Normal	4.137	0.1
g_{nsl}	Non-structural load	kN/m^2	Normal	2.8	0.1
f_y	Yield strength steel	N/mm^2	Lognormal	282	0.05
θ_R	Resistance model uncertainty	–	Lognormal	1.225	0.075
θ_E	Load effect model uncertainty	–	Lognormal	1.0	0.1
θ_q	Live load model uncertainty	–	Lognormal	1.0	0.1
L	Beam length	m	Deterministic	12	–
D	Beam spacing	m	Deterministic	12	–
x	Plastic section modulus	mm^3	Deterministic	*To be optimised*	–

The beam is subjected to three distributed loads: its own self-weight and that of the floor slab g_{sw}, non-structural permanent loads g_{nsl}, and a variable live load q_{live}. Model uncertainties are taken into account for the resistance (θ_R), load effect (θ_E) and variable load (θ_q).

The distributions of the variables in Eq. (16) are described in Table 4. These were derived from the reliability background document of the Eurocodes [62], the JCSS probabilistic model code [63] and Hingorani and Köhler [52]. Independence between the random variables is assumed.

5.2.2. Safety costs

The construction cost and emissions each consist of a constant term and a term that depends on the beam volume. An approximate linear relation between this volume and the section modulus is proposed in [60], assuming the beam has an HE profile. Accounting for units (x is given in mm^3 and V in m^3), this function is expressed as:

$$V_{beam}(x) \approx 62.5 \cdot 10^{-9} \cdot x \tag{17}$$

The construction cost of the beam is then given by:

$$C_{const}(x) = C_{beam}(x) = C_0 + c_{steel}\rho_{steel}V_{beam}(x) \tag{18}$$

where c_{steel} is the material cost per kg of steel, including fabrication and installation, and ρ_{steel} is the material density. The steel material costs are adapted from steel cost data [64], which also served as a primary source in [60]. Values for all parameters are given in Table 5.

The safety investment cost is given by:

$$C_{safety}(x) = C_{beam}(x) + C_{beam}(x)\frac{\omega}{\gamma} \tag{19}$$

The discount and obsolescence rates are adapted from ISO2394 [8]. Eq. (19) can now be used to formulate the conventional LQI-based criterion:

$$-\frac{dP_f(x)}{dx} \leq \frac{\gamma\frac{dC_{safety}(x)}{dx}}{\frac{G}{q}C_x N_f} = K_1(x) \tag{20}$$

Note that the safety costs are linear in x. Its derivative is a constant, and so is $K_1(x)$. The cost term independent of x, C_0, disappears when taking the derivative of C_{safety}, hence it does not influence the acceptable failure probability and no value is assigned to it. The material cost c_{steel} is an important parameter in $K_1(x)$, so the effect of different values [60,64–66] will be investigated in the sensitivity analysis.

5.2.3. SWTP and fatalities at failure

The structure is assumed to be located in the Western world. Existing literature on the variation of the SWTP across countries [39,40] suggests reasonable consistency within this region. The SWTP value applied in [60] is in line with this, and is therefore adopted here.

The number of fatalities occurring at failure is based on a model by Hingorani et al. [67]. This model is based on a dataset of collapsed buildings with recorded fatalities, collapsed area, and expected occupancy, which was used to fit multiple regression models. The best performing model (in terms of explaining variability in the dataset) considered the collapsing area A_{col} (in m^2) and occupancy Ocu_{col} (in persons/m^2) of said area as log-transformed independent variables, a dummy variable CE indicating the element type, and N_f as the dependent variable. The following expression is used:

$$N_f = 0.26 \cdot A_{col}^{0.19} \cdot Ocu_{col}^{0.7} \cdot 0.38^{CE} \cdot r_{ductile} \tag{21}$$

This expression is derived in [67], except for the last term. For a horizontal element, CE is set to zero. The collapsing area is taken as $A_{col} = L \cdot D$, the floor supported by this beam, while the occupancy is set at $0.032A_{col}$, the mean for similar buildings in the dataset of [67]. The fitted model does not consider the 'early warning' of ductile failure mechanisms [67]. To account for this, a reduction factor $r_{ductile}$ is applied in Eq. (21), for which a value of 0.5 is assumed. This leads to an N_f of 0.97 persons. This parameter will also be considered in the sensitivity analysis, as it is expected to have a large influence on the result, and the ductility assumption adds uncertainty.

5.2.4. Emissions

The construction emissions are based on the same expression for the volume of the beam as the construction cost:

$$E_{const}(x) = E_{beam}(x) = E_0 + e_{steel}\rho_{steel}V_{beam}(x) \tag{22}$$

where e_{steel} is the CO_2 equivalent emissions per kilogram of steel, also referred to as the emission intensity. Its value is adapted from recent data on steel produced in Europe [68].

A constant emission value E_0 is also considered here. It is assumed that the embodied emissions not varying with x are dominated by the transportation of the beam to the construction site (life cycle phase A4). The most common type of transport truck in Europe emits 56 g of CO_2 per ton material transported over 1 km [69]. A distance of 100 km from the production to the transportation site is assumed for both the beam and the concrete floor slabs, along with a transported weight of 60 ton, based on the mean self-weight and floor area (LD).

The emissions occurring at failure, E_H, are approximated based on the collapsed area A_{col} and the objects damaged in the collapse, aside from the beam itself. These are in turn based on the collapsed floor slab $g_{sw,hcs}$, the non-structural permanent loads g_{nsl}, and the non-permanent sustained load q_s. These are each assigned an emission intensity, which is taken from [60].

The lifetime, net-present-value emissions can now be expressed as:

$$E_{tot}(x) = E_{beam}(x) + E_{beam}(x)\frac{\omega}{\gamma} + \left(E_{beam}(x) + E_H\right)\frac{P_f(x)}{\gamma} \tag{23}$$

From this, the augmented LQI-based criterion can be formulated:

$$-\frac{dP_f(x)}{dx} \leq \frac{\frac{d}{dx}C_{beam}(x)\cdot(\gamma+\omega) + \frac{d}{dx}E_{beam}(x)\cdot c_e(\gamma+\omega+P_f(x))}{\frac{G}{q}C_x N_f + c_e(E_{beam}(x)+E_H)} = K_{aug}(x) \tag{24}$$

Table 5
Values of parameters for the case study.

Parameter	Symbol	Value	Unit	Source
Steel material cost	c_{steel}	2.00	€/kg steel	[60,64]
Steel density	ρ_{steel}	7850	kg/m^3 steel	[60]
SWTP	$\frac{G}{q}C_x$	2,775,000	€/person	[60]
Fatalities at collapse	N_f	0.97	person	[67]
Discount rate	γ	0.03	/year	[8]
Obsolescence rate	ω	0.02	/year	[8]
Steel emission intensity	e_{steel}	1.87	kg CO_2eq/kg steel	[68]
Failure emissions	E_H	65,500	kg CO_2eq	[60,76]
Constant emissions	E_0	333	kg CO_2eq	[69]
Emission shadow price	c_e	0.8	€/kg CO_2eq	[75]

Table 6
Numerical values corresponding to the acceptable designs for the regular and augmented LQI-based criterion.

	Original LQI-based criterion	Augmented LQI-based criterion
x [mm^3]	1.071×10^7	1.045×10^7
P_f [/year]	8.7×10^{-6}	1.5×10^{-5}
β	4.30	4.18

Note that E_{beam} is linear in x, but $K_{aug}(x)$ is not due to the inclusion of the failure emissions which depend on $P_f(x)$.

The shadow price represents the 'burden' of CO_2-equivalent emissions in monetary terms. This can represent future economic damages caused by climate change, as well as health impacts, loss of living standards and reduced opportunities for future generations [70]. Varying methodologies are used across literature to estimate the shadow price, resulting in values varying from less than 100 [71] to several thousand [72] dollars per ton CO_2-equivalent (the commonly-used unit for the 'social cost of carbon'). This value also depends on policies adopted to address climate change [73,74].

The considered structure is located in Europe. Hence, an estimate by the European investment bank [75] of 0.8 Euro per kg of CO_2 is used as an initial value for c_e. By taking a more broad perspective on the aforementioned 'burden', larger values could be considered. Therefore, this value should be seen as a 'first guess' and will also be further analysed in the sensitivity analysis.

5.3. Impact assessment

The impact of different values of the decision parameter x can now be calculated. Fig. 5 shows, from top to bottom, how the costs, failure probability, and the two sides of the LQI-constraints in Eqs. (20) and (24) vary over x. The dashed lines indicate x_{acc}, the smallest section modulus leading to an acceptable failure probability through the conventional criterion. The dotted lines indicate $x_{acc,aug}$, for the augmented criterion. The corresponding failure probabilities $P_{f,acc}$ and $P_{f,acc,aug}$ are also indicated in the middle subplot. Numerical values belonging to both are given in Table 6, in addition to the corresponding reliability indices $\beta = \Phi^{-1}(1 - P_f)$ with Φ^{-1} the inverse CDF of the standard normal distribution. The optimisation was performed using the Nelder–Mead algorithm [77], and the reliability analysis for $P_f(x)$ through PyStra [78].

5.4. Interpretation

The LQI-based criterion and its augmented version were applied to establish an acceptable failure probability for a structure, following the phases of S-LCA. The resulting values in Table 6 are in line with ISO2394, Table G.4, where the target reliability index β for a CC2 structure with 'medium' relative safety costs is equal to 4.2. The augmented criterion results in nearly the same value, while the conventional criterion returns a slightly larger β, halfway towards the value for 'small' relative safety costs (4.4). In other words, the augmentation of the LQI-based criterion can be said to move the acceptable reliability by 'one-half cost class'.

The difference between $P_{f,acc}$ and $P_{f,acc,aug}$ is caused by the difference in relative life safety costs $K_1(x)$ and $K_{aug}(x)$. Comparing Eqs. (20) and (24), $K_{aug}(x)$ contains two (positive-valued) additions compared to $K_1(x)$: one above and one below the division line, referred to as the enumerator and denominator, respectively (or top and bottom for simplicity). The former represents the marginal increase in emissions for increasing x, while the latter represents the emissions occurring at failure. It appears that the effect on the enumerator is stronger than on the denominator, causing $K_{aug}(x)$ to be larger than $K_1(x)$, which allowed the criterion to be met for a smaller value of x and hence a larger value of $P_f(x)$. The sensitivity of these results with respect to a number of crucial parameters is investigated in the next section.

6. Sensitivity analysis

This section presents the effect of varying a number of crucial parameters on the acceptable failure probability found through the conventional and augmented LQI-based criterion. In this analysis, the reliability indices β_{acc} and $\beta_{acc,aug}$ are considered, and the difference between these two values is discussed. The investigated are the number of fatalities N_f, the steel cost c_{steel}, and the emission shadow price c_e These were chosen based on their (expected) influence on the results, specifically the difference between β_{acc} and $\beta_{acc,aug}$, and the range over which they are varied is based on values encountered in literature cited in the previous section. First, they are varied separately from each other, to gauge their individual effect on both β_{acc} and $\beta_{acc,aug}$. Next, their interaction effect on the *difference* between β_{acc} and $\beta_{acc,aug}$ is considered.

Other variables that could have been considered are the coefficients of variation in the probabilistic model (Table 4). However, these were kept unchanged in order to keep the model consistent with reliability background document of the Eurocodes [62] and the JCSS probabilistic model code [63].

6.1. Separate parameters

The number of fatalities N_f, the steel cost c_{steel}, and the emission shadow price c_e are first varied separately, with the other two kept at the value used in the previous section. The result of this analysis is given in Fig. 6.

The fatalities N_f have a clear effect on both acceptable reliability indices. The larger the consequence of structural failure in terms of human lives, the more stringent the acceptable reliability requirement intuitively becomes. The difference between β_{acc} and $\beta_{acc.ag}$ is roughly constant over the considered range of N_f, except for small values, where the gap reduces. This can be explained by considering the enumerator and denominator of $K_{aug}(x)$. For smaller N_f, the term $c_e(E_{beam}(x) + E_H)$ below the division line in Eq. (24) becomes larger relative to $\frac{G}{q}C_x N_f$. Compared to the conventional criterion, the relative increase in the denominator then grows, while that of the enumerator stays the same. The smaller N_f becomes, the more these relative increases 'cancel out', decreasing the difference between $K_{aug}(x)$ and K_1 and hence that between β_{acc} and $\beta_{acc,aug}$.

The steel cost has a noticeable effect as well, though it is smaller for the augmented criterion. For a larger c_{steel}, the resources required to increase safety increase, hence the acceptable reliability becomes smaller. Furthermore, the monetary term $\frac{d}{dx}C_{beam}(x) \cdot (\gamma + \omega)$ increases relative to the emission term $\frac{d}{dx}E_{beam}(x) \cdot c_e(\gamma + \omega + P_f(x))$, hence the difference between the two acceptable reliability indices decreases.

The shadow price naturally does not affect the conventional β_{acc}, but does indeed drive the difference between the two results. Both additions in $K_{aug}(x)$ increase with increasing c_e, but the relative increase above the division line remains larger, so the difference β_{acc} and $\beta_{acc,aug}$ increases as well.

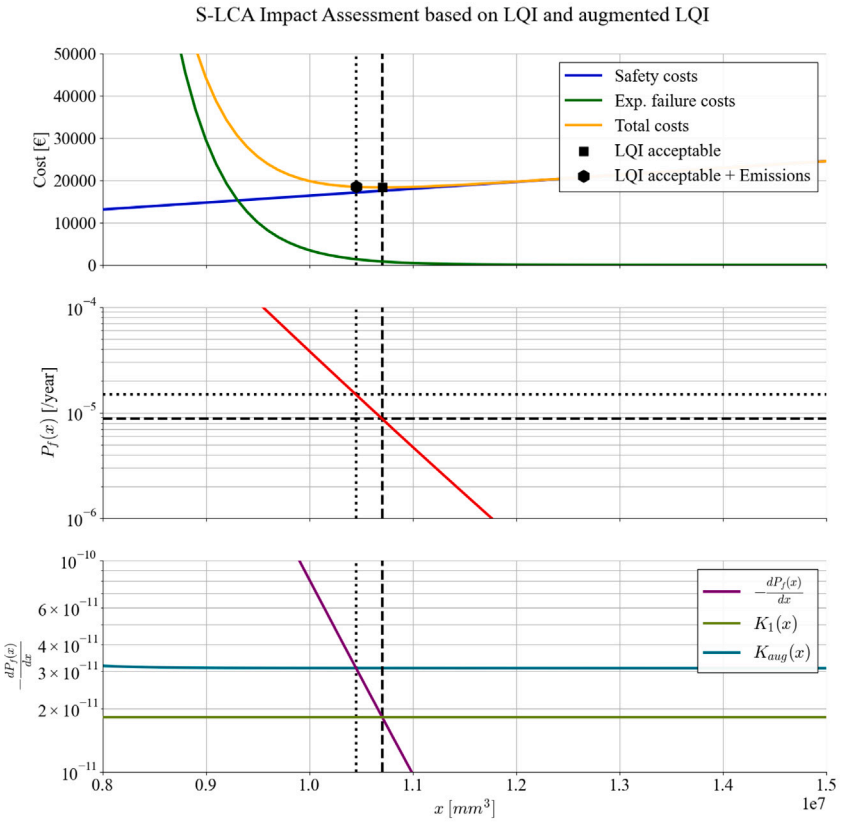


Fig. 5. Results of the case study, applying both the conventional and augmented LQI-based criterion.

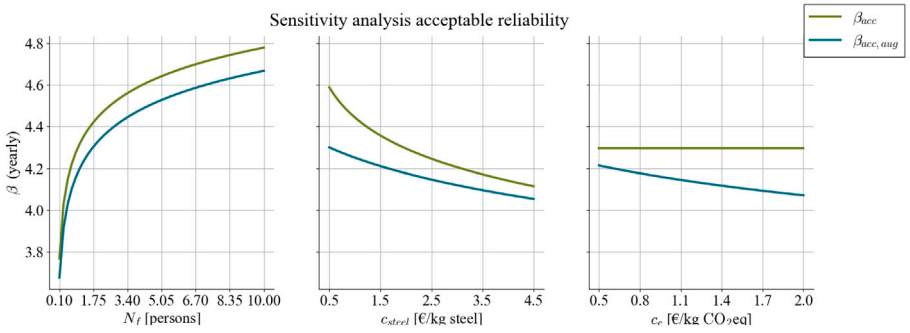


Fig. 6. Results of the one-at-a-time sensitivity analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6.1.1. *Ductility reduction factor*

The value of the reduction factor $r_{ductile}$ applied in Eq. (21), taking account of ductility effects, was assumed at 0.5. A parametric study of this factor is presented here, to analyse the effect of potentially different assumptions. A very small $r_{ductile}$ represents an easy escape, such that human life safety becomes less of a concern when failure occurs, while a value close or equal to 1 can represent a sudden, brittle failure where escape becomes difficult (as assumed in [67]). To investigate this effect, $r_{ductile}$ is varied on a logarithmic scale, and the resulting values of β_{acc} and $\beta_{acc,aug}$ are shown in Fig. 7. As N_f and $r_{ductile}$ are related linearly, the corresponding values of N_f are also indicated above the figure.

Fig. 7 can be seen as an extension of the left panel of Fig. 6, and the aforementioned effect of the denominator of $K_{aug}(x)$. Both β_{acc} and $\beta_{acc,aug}$ decrease as $r_{ductile}$ decreases, but the slope of $\beta_{acc,aug}$ eventually reduces until it remains nearly constant at 3.2 for reduction factors smaller than approximately 10^{-3}. As the environmental consequence of failure is unaffected by $r_{ductile}$, it eventually starts to dominate the acceptance criterion over the human life safety aspects. As such, β_{acc} crosses below $\beta_{acc,aug}$ at $r_{ductile} \approx 0.014$, and eventually reaching values lower than those found in norms [8,9] or literature [18,30]. These hypothetical values of $r_{ductile}$ (and N_f) therefore represent structures where life safety is of negligible concern with respect to environmental damage. To keep the remaining sensitivity analyses relevant to the rest of the current work, the rest of this section will consider the range of N_f used previously.

6.2. *Interaction effects on difference in reliability index*

In this analysis, the three parameters were varied simultaneously. The steel cost c_{steel} and the shadow price c_e were varied along the same continuous range as in the previous analysis, while three discrete values were considered for the number of fatalities, N_f. For each combination of these parameter values, the difference between β_{acc} and $\beta_{acc,aug}$ was

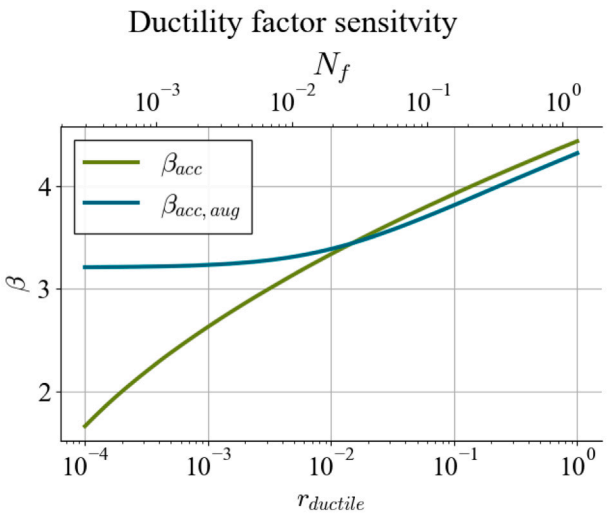


Fig. 7. Results of the ductility reduction factor variation. Note that the vertical gridlines correspond to the bottom axis.

computed and denoted as $\Delta\beta$:

$$\Delta\beta = \beta_{acc} - \beta_{acc,aug} \tag{25}$$

This way, the combined effects of the three parameters can be visualised in two-dimensional plots. Fig. 8 shows this result. The three panels represent three values of N_f of different orders of magnitude, to exemplify the effect on $\Delta\beta$ described above. The plots themselves contain a surface plot of $\Delta\beta_{acc}$, as it varies with c_{steel} and c_e given the corresponding N_f. There is little difference in the variation of $\Delta\beta$ for 1 or 10 fatalities; the surface plots are virtually identical. For larger values of N_f, the term $c_e(E_{beam}(x)+E_H)$ is negligible relative to $\frac{G}{q}C_x N_f$. In other words, the fatality term dominates the consequence of failure over the emissions term. As N_f does not influence the enumerator (top part) of either $K_1(x)$ or $K_{aug}(x)$, a further increase in N_f does not affect the difference between the two.

In the left panel of Fig. 8, the gradient in the surface plot aligns more with the horizontal axis (contour lines are more vertical), compared to the other two panels. This indicates that for small N_f, c_e has less influence on $\Delta\beta$ compared to c_{steel}. This is again caused by the contributions of the emission terms in K_{aug} cancelling each other out. If c_e is also small, the gradient becomes more diagonal as the term $\frac{G}{q}C_x N_f$ dominates the denominator of $K_{aug}(x)$ again.

The other panels clearly show that small c_{steel} and large c_e lead to a large $\Delta\beta$, and vice versa, corresponding to the findings of Fig. 6. The surface plots show diagonal 'bands' of identical colour, extending from the origin. These indicate that $\Delta\beta$ is determined by the ratio c_e/c_{steel}. Intuitively, these two parameters could be compared to weight factors assigned to different objectives (cost and emissions) in a multi-objective optimisation problem. The ratio of such weight factors influences the optimal solution [79], so this result is not unexpected. To illustrate this effect further, Fig. 9 presents $\Delta\beta$ as a function of this ratio. Each data point corresponds to a specific combination of N_f, c_e, and c_{steel} used in Fig. 8, with the colour indicating the value of N_f. For $N_f = 1$ and $N_f = 10$ fatalities, these points form smooth curves, with a small difference between them for larger ratios (which are not necessarily realistic considering the values found in literature). For $N_f = 0.1$, a larger spread is visible. This shows that the ratio c_e/c_{steel} only governs $\Delta\beta$ if N_f is large enough to dominate the denominator of $K_{aug}(x)$, which still corresponds to the findings of Figs. 6 and 8.

In general, considering commonly-encountered values for the parameters, $\Delta\beta$ can range from 0.1 to 0.2. A larger value of the shadow price could lead to $\Delta\beta$ towards 0.3, or even beyond for the largest values encountered in literature [72]. Such values could be applied when the shadow price is based on a broader evaluation of the impact of climate change, including intergenerational ethics in addition to economic damages. The larger the burden of emissions is considered c_e, the more lenient the augmented criterion becomes with respect to the conventional approach.

7. Discussion

The typical case study shows how the LQI can be of added value to the development of S-LCA by addressing two aspects: quantitative impact assessment and determining the societal acceptability of a product or system. First, by linking the design of an engineering structure to the safety of its users as an impact category, using the failure probability as a characterisation model, a quantitative social mechanism can be formed. Furthermore, by determining the acceptable failure probability of the structure through the societal willingness to pay, S-LCA can be used to determine whether a given structure is sufficiently safe or not, instead of only being able to compare alternatives. As presented in this work, this method assumes that the failure probability of the considered structure is constant over time. This will not hold for specific structures vulnerable to structural deterioration.

Given a (country-dependent) value for the SWTP, the acceptable failure probability strongly depends on the cost of increasing safety (c_{steel} in the case study, C_1 in the more abstract formulation found in [30]), and the expected number of fatalities at failure N_f, as indicated by the sensitivity analysis. The values of these parameters differ strongly per structure, so it is important to use accurate values in order to arrive at realistic values for $P_{f,acc}$.

The proposed application of the LQI in S-LCA can be further augmented by including shadow-costed emissions in the relative life-saving costs, thereby also involving E-LCA. As mentioned, the effect on the denominator of these costs is negligible compared to that on the numerator, thereby increasing the relative life-saving costs and allowing for a larger failure probability. The resulting difference between $P_{f,acc}$ and $P_{f,acc,aug}$ is mainly driven by the CO_2eq intensity (e_{steel}) and shadow price ($e_{emissions}$). The augmented criterion yielded a failure probability that is moderately larger than the value derived through the conventional LQI-based criterion. A larger difference will occur if the shadow price of the emissions increases, as is expected to occur over the next decades, though the magnitude depends strongly on worldwide policy and development regarding climate change [73].

Hypothetically, this difference could be artificially inflated by overestimating the environmental impact of the structure under consideration, potentially leading to cost reductions for builders. Structural safety norms, where the proposed approach would be applied, prohibit this adverse scenario by mandating a societal perspective on structural safety. This should consider the three actors mentioned in the introduction, and prevent one of them from maximising their own interests at the expense of others. Inflated environmental impacts, specifically, should be guarded against by requiring proper E-LCA procedures to be followed [59], including modelling, data sources, and transparency. The maturity of E-LCA and wide availability of environmental product declarations as independent data sources may prove advantageous in this regard, as would increased maturity of S-LCA.

In order to further develop S-LCA, more quantitative social mechanisms should be developed [1,10,11,23]. The aspects from Table 1 could guide this. In order to involve social aspects in decision-making problems also involving economic and environmental concerns, the different pillars of sustainability inevitably need to be weighed against each other. This could be achieved through monetarisation or willingness-to-pay approaches, but capturing all social concerns in economic valuations is difficult, and differences in countries can further complicate this. An alternative could be sought in multi-criteria decision analysis [80,81]. However, these too require assigning weight values to different objectives, so some sort of valuation of emissions against costs would still be needed [26].

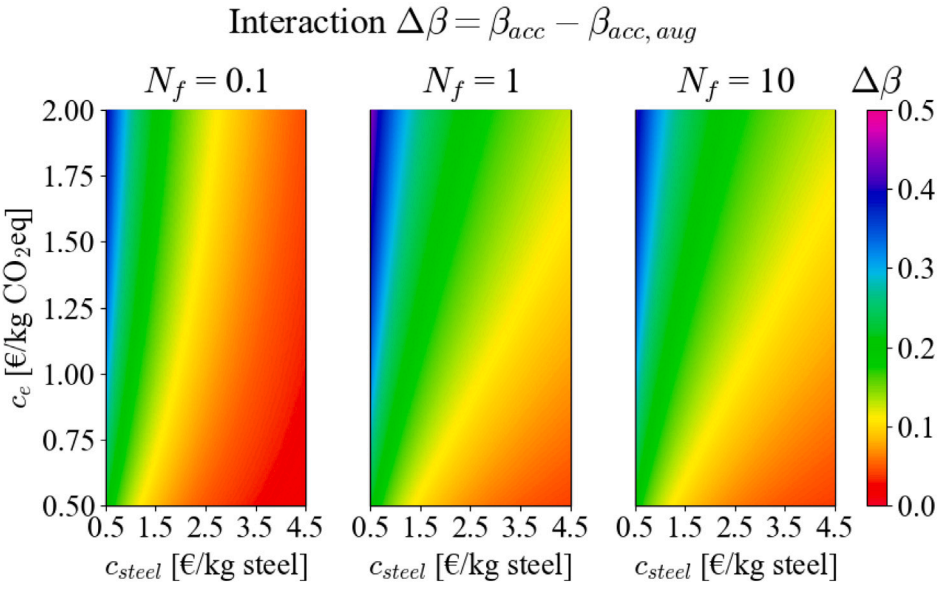


Fig. 8. Results of the interaction sensitivity analysis: surface plots showing $\Delta\beta$ for different combinations of N_f, c_e and c_{steel}. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

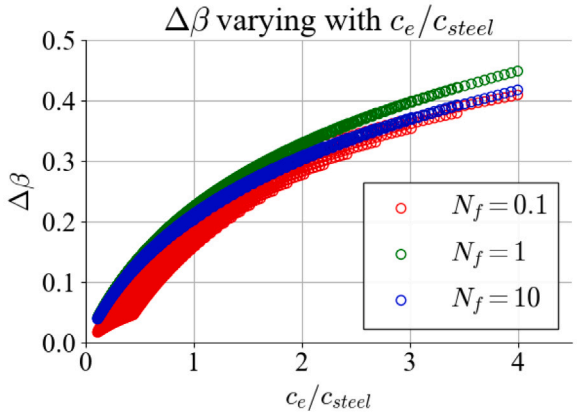


Fig. 9. Difference between the two acceptable reliability values against the ratio between c_e and c_{steel}.

8. Conclusion

This study proposed the use of the life quality index as part of social life-cycle assessment in the built environment and showed how this approach can be augmented to incorporate environmental aspects as well. It presented the current applications of the LQI and the state-of-the-art guidelines on S-LCA, and explained how the former could contribute to the development of the latter.

A typical case study was presented along with a sensitivity analysis, showing how the LQI can be applied in an impact pathway-based S-LCA and E-LCA of a simple structure. The LQI was used to quantify the acceptable failure probability of the structure, through a social mechanism relating its design to the impact of possible failures on its users. This shows that the LQI is a promising tool for quantifiable social impact assessment and can contribute to more comprehensive life cycle sustainability assessments by comparing important social and economic considerations and making a judgement on their societal acceptability with respect to safety.

In addition, the environmental pillar of sustainability was incorporated by augmenting the costs of structural safety in the LQI-based criterion with a shadow cost of CO_2-equivalent emissions. This expands on previous work on the LQI, such as that of Rackwitz [18] and Fischer [6,30] by providing a comprehensive view of the relative life-saving cost and its distribution across the relevant actors. This augmented LQI-based criterion leads to a moderately larger acceptable failure probability, equivalent to moving one half cost class, though the difference depends strongly on the applied shadow price in relation to the material costs. Given values encountered in literature, the difference in acceptable reliability index $\Delta\beta$ can range from 0.1 to 0.3.

The proposed approach is chosen to be in line with current literature [6,18,30] and codes [8] with respect to discounting. From a principal point of view, it could be argued that costs, fatalities and emissions should be discounted in different manners. This could be a subject of future study, as could application on different or more complex structures, for example featuring brittle failure mechanisms.

CRediT authorship contribution statement

Jelle Knibbe: Writing – original draft, Formal analysis, Conceptualization. **Raphaël Steenbergen:** Writing – review & editing, Conceptualization. **Pieter van Gelder:** Writing – review & editing. **Amir Pooyan Afghari:** Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to help refine the abstract, specifically to shorten it to fewer than 250 words. A small number of paragraphs were also revised using the same tool. The author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication. No generative AI tools were used for other parts of the research or writing process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data and code supporting the publication: Augmented Life Quality Index Approach for Social Life Cycle Assessment in Engineering Structures: Societally and Environmentally Acceptable Failure Probabilit (Original data) (4TU.ResearchData)

References

[1] Larsen VG, Tollin N, Sattrup PA, Birkved M, Holmboe T. What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment, LCSA. J Build Eng 2022;50:104203. http://dx.doi.org/10.1016/j.jobe.2022.104203.

[2] RILEM. GLOBE - Global consensus on sustainability in the built environment. 2022, URL https://www.rilem.net/globe.

[3] Huang L, Krigsvoll G, Johansen F, Liu Y, Zhang X. Carbon emission of global construction sector. Renew Sustain Energy Rev 2018;81:1906–16. http://dx.doi.org/10.1016/J.RSER.2017.06.001, URL https://www.sciencedirect.com/science/article/pii/S1364032117309413.

[4] Ellingwood B, Galambos TV. Probability-based criteria for structural design. Struct Saf 1982;1(1):15–26. http://dx.doi.org/10.1016/0167-4730(82)90012-1.

[5] Rackwitz R. Reliability analysis—a review and some perspectives. Struct Saf 2001;23(4):365–95. http://dx.doi.org/10.1016/S0167-4730(02)00009-7.

[6] Fischer K, Viljoen C, Köhler J, Faber MH. Optimal and acceptable reliabilities for structural design. Struct Saf 2019;76:149–61. http://dx.doi.org/10.1016/J.STRUSAFE.2018.09.002.

[7] Fakharian P, Naderpour H, Sharbatdar MK, Ghasemi SH. Advancements in structural target reliability: A comprehensive examination of theories and practical applications (2013–2024). Structures 2024;66:106930. http://dx.doi.org/10.1016/J.ISTRUC.2024.106930, URL https://www.sciencedirect.com/science/article/pii/S2352012424010828.

[8] ISO. ISO 2394 General principles on reliability for structures. Tech. Rep., 2015, URL https://connect.nen.nl/Family/Detail/60973?compId=10038&collectionId=0.

[9] NEN-EN. NEN-EN 1990 Eurocode - Basis of structural and geotechnical design. Tech. Rep., 2025, URL https://connect.nen.nl/Standard/Detail/3721028?compId=10038&collectionId=0.

[10] Webb D, Ayyub BM. Sustainability quantification and valuation. I: Definitions, metrics, and valuations for decision making. ASCE-ASME J Risk Uncertain Eng Syst Part A: Civ Eng 2017;3(3):E4016001. http://dx.doi.org/10.1061/ajrua6.0000893, URL /doi/pdf/10.1061/AJRUA6.0000893?download=true. https://ascelibrary.org/doi/10.1061/AJRUA6.0000893.

[11] Webb D, Ayyub BM. Sustainability quantification and valuation. II: Probabilistic framework and metrics for sustainable construction. ASCE-ASME J Risk Uncertain Eng Syst Part A: Civ Eng 2017;3(3):E4016002. http://dx.doi.org/10.1061/ajrua6.0000894, URL /doi/pdf/10.1061/AJRUA6.0000894?download=true. https://ascelibrary.org/doi/10.1061/AJRUA6.0000894.

[12] Valdivia S, Backes JG, Traverso M, Sonnemann G, Cucurachi S, Guinée JB, Schaubroeck T, Finkbeiner M, Leroy-Parmentier N, Ugaya C, Peña C, Zamagni A, Inaba A, Amaral M, Berger M, Dvarioniene J, Vakhitova T, Benoit-Norris C, Prox M, Foolmaun R, Goedkoop M. Principles for the application of life cycle sustainability assessment. Int J Life Cycle Assess 2021;26(9):1900–5. http://dx.doi.org/10.1007/S11367-021-01958-2/FIGURES/1, URL https://link.springer.com/article/10.1007/s11367-021-01958-2.

[13] ISO. NEN-EN-ISO 14040:2006 en. 2006, URL https://connect.nen.nl/Standard/Detail/109085?compId=10037&collectionId=0.

[14] ISO. NEN-EN-ISO 14044:2006 en. 2006, URL https://connect.nen.nl/Standard/Detail/109086?compId=10037&collectionId=0.

[15] European Commission. Life Cycle Assessment & the EF methods - European Commission. URL https://green-forum.ec.europa.eu/green-business/environmental-footprint-methods/life-cycle-assessment-ef-methods_en.

[16] Rijksoverheid. Milieuprestaties van bouwwerken berekenen | Duurzaam bouwen en verbouwen | Rijksoverheid.nl. 2019, URL https://www.rijksoverheid.nl/onderwerpen/duurzaam-bouwen-en-verbouwen/duurzaam-bouwen/milieuprestaties-van-gebouwen-meten.

[17] Rödger J-M, Kjær LL, Pagoropoulos A. Life cycle costing: An introduction. In: Hauschild MZ, Rosenbaum RK, Olsen SI, editors. Life cycle assessment: theory and practice. Cham: Springer International Publishing; 2018, p. 373–99. http://dx.doi.org/10.1007/978-3-319-56475-3_15.

[18] Rackwitz R. Optimization — the basis of code-making and reliability verification. Struct Saf 2000;22(1):27–60. http://dx.doi.org/10.1016/S0167-4730(99)00037-5.

[19] Frangopol DM, Lin K-Y, Estes AC. Life-cycle cost design of deteriorating structures. J Struct Eng 1997;123(10):1390–401. http://dx.doi.org/10.1061/(ASCE)0733-9445(1997)123:10(1390).

[20] Wen YK, Kang YJ. Minimum building life-cycle cost design criteria. I: Methodology. J Struct Eng 2001;127(3):330–7. http://dx.doi.org/10.1061/(ASCE)0733-9445(2001)127:3(330).

[21] Lin KY, Frangopol DM. Reliability-based optimum design of reinforced concrete girders. Struct Saf 1996;18(2–3):239–58. http://dx.doi.org/10.1016/0167-4730(96)00013-6.

[22] Lehmann A, Zschieschang E, Traverso M, Finkbeiner M, Schebek L. Social aspects for sustainability assessment of technologies - Challenges for social life cycle assessment (SLCA). Int J Life Cycle Assess 2013;18(8):1581–92. http://dx.doi.org/10.1007/S11367-013-0594-0/TABLES/3, URL https://link.springer.com/article/10.1007/s11367-013-0594-0.

[23] Amini Toosi H, Lavagna M, Leonforte F, Del Pero C, Aste N. Implementing life cycle sustainability assessment in building and energy retrofit design—An investigation into challenges and opportunities. In: Environmental footprints and eco-design of products and processes. Springer; 2021, p. 103–36. http://dx.doi.org/10.1007/978-981-16-4562-4_6, URL https://link.springer.com/chapter/10.1007/978-981-16-4562-4_6.

[24] UNEP, Benoît Norris, Traverso C, Neugebauer M, Ekener S, Schaubroeck E, Russo Garrido T, Berger S, Valdivia M, Lehmann S, Finkbeiner A, M. Arcese G. Guidelines for social life cycle assessment of products and organizations 2020. Tech. Rep., United Nations Environment Programme; 2020.

[25] ISO. ISO 14075 - Environmental management - Principles and framework for social life cycle assessment. Tech. Rep., ISO; 2024, URL https://connect.nen.nl/Standard/Detail/3713750?compId=10038&collectionId=0.

[26] Atescan Yuksek Y, Haddad Y, Cox R, Salonitis K. Social life cycle assessment: a systematic review from the engineering perspective. Int J Sustain Eng 2026;19(1). http://dx.doi.org/10.1080/19397038.2025.2605864.

[27] van de Poel I, Royakkers L. Ethics, technology, and engineering. Wiley-Blackwell; 2011.

[28] Pandey MD, Nathwani J, Lind N. The derivation and calibration of the Life-Quality Index (LQI) from economic principles. Struct Saf 2006;28:341–60. http://dx.doi.org/10.1016/j.strusafe.2005.10.001.

[29] Pandey M, Viljoen C, Way A, Fischer K, Sýkora M, Diamantidis D, Steenbergen RDJM, Lind N, Frangopol DM, Yang DY, Retief JV, André J, Nathwani J, Lenner R. Life safety in the Reliability-Based design and assessment of structures. Struct Saf 2024;102453. http://dx.doi.org/10.1016/j.strusafe.2024.102453, URL https://www.sciencedirect.com/science/article/pii/S0167473024000249.

[30] Fischer K, Barnardo-Viljoen C, Faber MH. Deriving target reliabilities from the LQI. In: LQI symposium. Lyngby; 2012, URL https://www.researchgate.net/publication/289533079.

[31] Köhler J, Baravalle M. Risk-based decision making and the calibration of structural design codes – prospects and challenges. Civ Eng Environ Syst 2019;36(1):55–72. http://dx.doi.org/10.1080/10286608.2019.1615477.

[32] UNEP, Traverso M, Valdivia S, Luthin A, Roche L, Arcese G, Neugebauer S, Petti L, D'Eusanio M, Tragnone B, Mankaa R, Hanafi J, Benoît Norris C, Zamagni A. Methodological sheets for subcategories in Social Life Cycle Assessment (S-LCA) 2021. Tech. Rep., United Nations Environment Programme; 2021.

[33] NEN-EN. NEN-EN 15643: Sustainability of construction works - Framework for assessment of buildings and civil engineering works. 2021, URL https://connect.nen.nl/Standard/Detail/3647808?compId=10038&collectionId=0.

[34] Lind N. Social and economic criteria of acceptable risk. Reliab Eng Syst Saf 2002;78(1):21–5. http://dx.doi.org/10.1016/S0951-8320(02)00051-0.

[35] Pandey MD, Nathwani JS. Measurement of socio-economic inequality using the life-quality index. Soc Indic Res 1996;39(2):187–202. http://dx.doi.org/10.1007/BF00286973.

[36] Nathwani J, Lind N, Pandaey M. Affordable safety by choice: The life quality method (Ph.D. thesis), Waterloo: University of Waterloo; 1997.

[37] Pandey MD, Nathwani JS. Life quality index for the estimation of societal willingness-to-pay for safety. Struct Saf 2004;26(2):181–99. http://dx.doi.org/10.1016/j.strusafe.2003.05.001, URL https://www.sciencedirect.com/science/article/pii/S0167473003000407.

[38] Fischer K, Virguez E, Sánchez-Silva M, Faber MH. On the assessment of marginal life saving costs for risk acceptance criteria. Struct Saf 2013;44:37–46. http://dx.doi.org/10.1016/J.STRUSAFE.2013.05.001.

[39] Rackwitz R. The effect of discounting, different mortality reduction schemes and predictive cohort life tables on risk acceptability criteria. Reliab Eng Syst Saf 2006;91(4):469–84. http://dx.doi.org/10.1016/J.RESS.2005.03.015.

[40] Faber MH, Virguez-Rodriguez E. Supporting decisions on global health and life safety investments. In: Applications of statistics and probability in civil engineering -proceedings of the 11th international conference on applications of statistics and probability in civil engineering. Taylor and Francis Inc.; 2011, p. 434–43. http://dx.doi.org/10.1201/B11332-64.

[41] HLD Project. Human life-table database. 2025, URL https://www.lifetable.de/.

[42] Fischer K, Virguez-Rodriguez E, Sánchez-Silva M, Faber MH. Defining guidelines for the application of the marginal life saving costs principle for risk regulation. In: Application of statistics and probability in civil engineering, 2011. 2011, http://dx.doi.org/10.1201/b11332-65, URL https://www.researchgate.net/profile/Edgar-Virguez/publication/280881227_Defining_guidelines_for_the_application_of_the_marginal_life_saving_costs_principle_for_risk_regulation/links/55ca142308aebc967dfbd933/Defining-guidelines-for-the-application-of-the-marginal-life-saving-costs-principle-for-risk-regulation.pdf.
[43] Rackwitz R. Optimal and acceptable technical facilities involving risks. Risk Anal 2004;24(3):675–95. http://dx.doi.org/10.1111/J.0272-4332.2004.00467.X, URL https://onlinelibrary.wiley.com/doi/full/10.1111/j.0272-4332.2004.00467.x.
[44] Rackwitz R, Joanni A. Risk acceptance and maintenance optimization of aging civil engineering infrastructures. Struct Saf 2009;31(3):251–9. http://dx.doi.org/10.1016/J.STRUSAFE.2008.07.001.
[45] Rackwitz R, Lentz A, Faber M. Socio-economically sustainable civil engineering infrastructures by optimization. Struct Saf 2005;27(3):187–229. http://dx.doi.org/10.1016/J.STRUSAFE.2004.10.002.
[46] Lee JY, Ellingwood BR. Ethical discounting for civil infrastructure decisions extending over multiple generations. Struct Saf 2015;57:43–52. http://dx.doi.org/10.1016/J.STRUSAFE.2015.06.001.
[47] Roubos AA, Steenbergen RD, Schweckendiek T, Jonkman SN. Risk-based target reliability indices for quay walls. Struct Saf 2018;75:89–109. http://dx.doi.org/10.1016/J.STRUSAFE.2018.06.005.
[48] Zhang H, Ge W, Zhang Y, Li Z, Li W, Zhu J, Wang W. Risk management decision of reservoir dams based on the improved life quality index. Water Resour Manag 2023;37(3):1223–39. http://dx.doi.org/10.1007/S11269-023-03426-Y/TABLES/5, URL https://link.springer.com/article/10.1007/s11269-023-03426-y.
[49] Bhattacharya B. An appraisal of the LQI as an approach to setting target reliabilities in ISO 2394:2015. Struct Saf 2024;109:102482. http://dx.doi.org/10.1016/J.STRUSAFE.2024.102482.
[50] Steenbergen R, Vrouwenvelder A. Reliability based assessment of buildings under earthquakes due to gas extraction. Heron 2014;59(2). URL https://heronjournal.nl/59-23/4.pdf.
[51] CBS. CO2 equivalents | CBS. 2019, URL https://www.cbs.nl/en-gb/news/2019/37/greenhouse-gas-emissions-down/co2-equivalents.
[52] Hingorani R, Köhler J. Towards optimised decisions for resource and carbon-efficient structural design. Civ Eng Environ Syst 2023;40(1–2):1–31. http://dx.doi.org/10.1080/10286608.2023.2198767.
[53] Xia B, Xiao J, Guan X. Target low-carbon conditional probability for low-carbon structural design. Struct Saf 2025;117:102636. http://dx.doi.org/10.1016/J.STRUSAFE.2025.102636, URL https://www.sciencedirect.com/science/article/pii/S0167473025000645.
[54] Kamali Saraji M, Streimikiene D, Balezentis T. Bridging climate change mitigation policies and shadow price of undesirable outputs: a systematic literature review on applications. Management of Environmental Quality 2024;36(1):208–27. http://dx.doi.org/10.1108/MEQ-11-2023-0399/FULL/PDF.
[55] Steenbergen R. Risk based optimized decisions for reuse of structural elements accounting for resource and carbon-efficiency. In: International forum on engineering decision making. Stoos; 2023.
[56] Weikard HP, Zhu X. Discounting and environmental quality: When should dual rates be used? Econ Model 2005;22(5):868–78. http://dx.doi.org/10.1016/J.ECONMOD.2005.06.004.
[57] Gollier C. Ecological discounting. J Econom Theory 2010;145(2):812–29. http://dx.doi.org/10.1016/J.JET.2009.10.001, URL https://www.sciencedirect.com/science/article/pii/S002205310900115X?via%3Dihub.
[58] Nesticò A, Maselli G, Ghisellini P, Ulgiati S. A dual probabilistic discounting approach to assess economic and environmental impacts. Environ Resour Econ 2023;85(1):239–65. http://dx.doi.org/10.1007/S10640-023-00766-6/TABLES/5, URL https://link.springer.com/article/10.1007/s10640-023-00766-6.
[59] NEN-EN. NEN-EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. 2011, URL https://connect.nen.nl/Standard/Detail/165395?compId=10037&collectionId=0.
[60] Hingorani R, Köhler J. Sustainability potential of risk-informed decisions in structural design. In: 14th international conference on applications of statistics and probability in civil engineering. 2023, URL https://www.tara.tcd.ie/handle/2262/103592. http://hdl.handle.net/2262/103592.
[61] Nederlands Normalisatie-instituut. NEN-EN 1993-1-1 Design of steel structures - Part 1-1: General rules and rules for buildings. Tech. Rep., NEN-EN; 2025.
[62] Vrouwenvelder T, Dimova S, Sousa M, Marková J, Mancini G, Kuhlmann U, Taras A, Jockwer R, Jäger W, Schweckendiek T, Franchin P, Skejić D, Sørensen J, Spehl P, Stacy M, Feldmann M, Croce P, Zhao B, Tanner P, Knippers J, Mollaert M, André J, Steenbergen R, Kohler J, Bakeer T, Maljaars J, Allaix D, Spross J. Reliability background of the Eurocodes. 2024, http://dx.doi.org/10.2760/9482837, (KJ-01-24-076-EN-N (online)).
[63] JCSS. Probabilistic model code Part 1 - Basis of design. Tech. Rep., 2000.
[64] bauforumstahl eV. Baukosten für Bauprojekte - bauforumstahl. 2026, URL https://bauforumstahl.de/stahlbau/baukosten.
[65] Farkas J, Jármai K. Optimum design of steel structures. Springer; 2013, p. 265.
[66] Medarac H, Moya JA, Somers J. Production costs from iron and steel industry in the EU and third countries. Publications Office of the European Union; 2020, http://dx.doi.org/10.2760/705636.
[67] Hingorani R, Tanner P, Prieto M, Lara C. Consequence classes and associated models for predicting loss of life in collapse of building structures. Struct Saf 2020;85:101910. http://dx.doi.org/10.1016/J.STRUSAFE.2019.101910.
[68] TATA Steel. Benefits of steel for responsible lightweighting: Evaluation of a door assembly's lifecycle CO2 footprint and total cost of ownership . Tech. Rep., IJmuiden; 2017, URL https://products.tatasteelnederland.com/sites/producttsn/files/tata-steel-automotive-life-cycle-assessment-casestudy-EN.pdf.
[69] Musa A, Basma H, Mulholland E, Rodríguez F. CO 2 emissions from trucks in the European Union: An analysis of the 2021 reporting period. Tech. Rep., 4 INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION; 2024, URL www.theicct.orgcommunications@theicct.org@theicct.org.
[70] Boyce JK. Carbon pricing: Effectiveness and equity. Ecol Econom 2018;150(3–4):52–61. http://dx.doi.org/10.1016/j.ecolecon.2018.03.030.
[71] Lomborg B. Welfare in the 21st century: Increasing development, reducing inequality, the impact of climate change, and the cost of climate policies. Technol Forecast Soc Change 2020;156:119981. http://dx.doi.org/10.1016/J.TECHFORE.2020.119981.
[72] Wang Z, Song Y, Shen Z. Global sustainability of carbon shadow pricing: The distance between observed and optimal abatement costs. Energy Econ 2022;110(2):106038. http://dx.doi.org/10.1016/j.eneco.2022.106038.
[73] Yang P, Yao YF, Mi Z, Cao YF, Liao H, Yu BY, Liang QM, Coffman DM, Wei YM. Social cost of carbon under shared socioeconomic pathways. Glob Environ Chang 2018;53:225–32. http://dx.doi.org/10.1016/J.GLOENVCHA.2018.10.001, URL https://www.sciencedirect.com/science/article/pii/S0959378018304424.
[74] Intergovernmental Panel on Climate Change (IPCC). Summary for policymakers. In: Climate change 2021 – the physical science basis. Cambridge University Press; 2023, p. 3–32. http://dx.doi.org/10.1017/9781009157896.001.
[75] European Investment Bank. Shadow carbon pricing. 2025, URL https://www.e3g.org/bank-metrics/shadow-carbon-pricing-eib/.
[76] DW SYSTEMBAU GMBH. UMWELT-PRODUKTDEKLARATION nach ISO 14025 und EN 15804+A1: Spannbeton-Fertigteildecken. Tech. Rep., Institut Bauen und Umwelt e.V.; 2020, URL https://nssas.dk/wp-content/uploads/2023/08/EPD-huldaek.pdf.
[77] Martins JRRA, Ning A. Engineering design optimization. Cambridge University Press; 2021, http://dx.doi.org/10.1017/9781108980647.
[78] Caprani C, Hackl J. PySTRA 1.3.0 documentation. 2024, URL https://pystra.github.io/pystra/index.html.
[79] Deb K. Multi-objective optimization using evolutionary algorithms. John Wiley & Sons; 2001.
[80] Figueira J, Greco S, Ehrogott M. Multiple criteria decision analysis: State of the art surveys. vol. 78, New York, NY: Springer New York; 2005, http://dx.doi.org/10.1007/b100605.
[81] Angelo ACM, Marujo LG. Life cycle sustainability assessment and decision-making under uncertainties. In: Life cycle sustainability assessment for decision-making: methodologies and case studies. Elsevier; 2020, p. 253–68. http://dx.doi.org/10.1016/B978-0-12-818355-7.00012-9.