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LIFE QUALITY INDEX AS INSTRUMENT FOR SOCIAL LIFE CYCLE ASSESSMENT IN ENGINEERING STRUCTURES

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Abstract. While environmental life cycle assessment is an established method for predicting environmental impacts over the lifetime of a structure or building, and is supported by ISO-norms, it overlooks social impacts such as structural safety. The more comprehensive life cycle sustainability assessment, which also includes economic and societal sustainability, is not as mature. There is especially a lack of quantitative indicators for the societal impacts of a structure, which form part of social life cycle assessment.

This paper investigates the use of an existing societal indicator, the Life Quality Index, which has not been used in social life cycle assessment before. It has, however, been used previously in structural engineering applications to establish societally acceptable and economically optimal failure probabilities of structures. In this paper, this use is compared to the most recent guidelines on social life cycle assessment by the United Nations Environmental Programme.

This paper proposes that the current use of the life quality index can be part of the social impact assessment phase of social life cycle assessment. It then forms part of a social mechanism within an impact pathway approach, one of the two approaches towards social impact assessment proposed by the guidelines. This is demonstrated using an example based on the design of a simple structure, following the four phases of a life cycle assessment. The demonstrated approach is able to combine societal and economic considerations, making it a promising candidate for future applications in life cycle sustainability assessment of structures.

1 Introduction

Life cycle assessment methods in the built environment have until now generally been focused on the environmental and economic impacts of buildings and structures [14]. Especially large structures, such as bridges and viaducts, incur significant financial costs and cause negative environmental effects, such as greenhouse gas and nitrogen emissions. However, buildings and structures have societal impacts as well; in the functions they provide, but also in how safe they are. The importance of structural safety is undeniable, but it comes with its own costs. Building a more robust structure, with larger elements being able to withstand heavier loads, requires more investment and causes more harmful emissions.

This dilemma represents a trade-off between the three ‘pillars’ of sustainability: environmental, economic and social. Ideally, all three should be taken into account when making decisions about structures. The life cycle sustainability assessment (LCSA) aims to achieve this: it gives a comprehensive view of the sustainability of a system or product, such as a structure [31].

LCSA is commonly presented as a combination of three methods, one for each pillar:

$$\text{LCSA} = \text{E-LCA} + \text{LCC} + \text{S-LCA} \tag{1}$$

First and most commonly known, the environmental life cycle assessment (E-LCA) can be considered well-established and is supported by ISO-norms 14040 and 14044 [11, 12]. Second, Life Cycle Costing (LCC) is also well-established [28], if not as formalised as E-LCA. The third method, social life cycle assessment (S-LCA), still needs development however [14, 16, 1].

One of the main challenges in this is developing indicators and characterization 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.

A second problem with S-LCA and life cycle assessment - including E-LCA - in general is that it is generally used for comparing several given alternatives, but not for determining an optimal decision directly.

This study addresses both of these issues by proposing the use of an existing method, applied in structural engineering, but not yet in S-LCA: the life quality index or LQI [22]. The LQI is a compound indicator that assesses ‘life quality’ as a utility function, consisting of the resources and time available for consumption. As such, the main component of the LQI are the GDP, life expectancy, and the ratio between work and leisure time. One of the applications of the LQI in current literature is to determine maximum allowable failure probabilities for buildings and structures [6, 10]. In this study, this use of the LQI is compared to current guidelines on S-LCA [30], and its use within these norms is demonstrated.

The next three sections describe the current development of S-LCA in the built environment, the background of the LQI, and its current applications in structural engineering respectively. Afterwards, the use of the LQI within S-LCA is proposed using the current guidelines, then demonstrated through an example of optimising the design of a structure and determining whether its failure probability is acceptably low, following the phases of life cycle assessment. Finally, conclusions and an outlook on future research are provided.

2 S-LCA in the built environment

The most recent S-LCA guidelines by the United Nations Environmental programme and other organizations [30] show that some progress has been made in the development of S-LCA. These UNEP guidelines can be considered the currently leading documents for the development of S-LCA. They propose that S-LCA should be performed in four phases, mirroring those of the E-LCA norms: (1) goal and scope definition, (2) life cycle inventory, (3) social life cycle impact assessment and (4) interpretation.

The most important areas of development are creating databases to be used in the second phase and assessment methods in the third phase. This holds for S-LCA in general, as well as for the built environment specifically. Two literature studies [1, 14] explored the challenges of applying LCSA in this domain. While the importance of the social pillar is acknowledged across literature according to the authors, implementing its method has proven difficult, due to a lack of data, indicators and standardisation.

The UNEP Guidelines provide a list of six stakeholder groups (workers, local community, value chain actors, consumers, society and children) which should be 'covered' by S-LCA. This list is quite general, however, while S-LCA out of the three life-cycle methods can be expected to be the most context-specific. The norm EN-15643 [20], on assessing (social) sustainability for construction works, suggests a number of aspects which should be covered in social assessments of buildings, listed in Table 1.

This list is more applicable to the built environment, and could be considered as 'impact categories', similar to those in E-LCA. Quantifying these aspects using indicators, like in E-LCA, is still considered a major challenge however [1]. For the 'safety' aspect, it seems intuitive that structural failures, causing large costs, unavailability of a structure and possibly fatalities, should be an important consideration in S-LCA. 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 [20]

accessibility	adaptability to user needs	health, comfort, quality of indoor environment
safety	loads on the neighbourhood	sourcing of materials and services
resilience	employment/job creation	stakeholder involvement
security	protection of cultural heritage	

3 The Life Quality Index

The life quality index or LQI is a compound indicator, similar to the human development index [17], introduced by Pandey and Nathwani in the 1990's [23]. It is most often formulated as follows:

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

Where L is te value of the LQI, set by its main components G the GDP per capita per year and E the life expectancy. These represent the resources and time available for consumption per person, respectively, together forming the 'life quality per person'. Multiple definitions for q exist, but generally it represents a difference in valuation of these two aspects. The most common and straightforward definition, used in the current study, is:

$$q = \frac{w}{1-w} \tag{3}$$

With w the fraction of lifetime spent working. This definition is based on the assumption that individuals can choose w such that it maximises their lifetime utility. For a full derivation of the LQI including this definition of q, readers are referred to [18] and [21].

The LQI is an ordinal indicator. Its absolute value has no real meaning, but a larger value does represent a better life quality per person. Because of this, it is usually applied in literature by considering small relative changes, formulated as:

$$\frac{dL}{L} = q\frac{dG}{G} + \frac{dE}{E} \tag{4}$$

Where a positive value of $\frac{dL}{L}$ satisfies the *net benefit criterion*. This can be interpreted as a societal willingness to pay (SWTP): A relative improvement of life expectation $\frac{dE}{E}$ can be 'bought' by 'spending' a small part of GDP $\frac{dG}{G}$ (which would then be negative), weighted by the constant q, and vice versa. This means any investment for which $\frac{dL}{L} > 0$ holds is considered desirable from a societal point of view, as the increase in life expectancy is worth the investment. For example, if $q = 0.2$, and increase in life expectancy of 1% can offset a decrease of 5% of GDP [27]. This criterion can be rewritten as [7]:

$$-dG \leq \frac{G}{q}\frac{dE}{E} \approx -\frac{G}{q}C_x d\mu \tag{5}$$

Where $-dG$ is to 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 mortality per capita, $-d\mu$ (the rate of death per person). The value of $d\mu$ can be interpreted as the change in risk to life safety, and the value of $\frac{G}{q}C_x$ [6] as the SWTP for one additional life saved. So, the net benefit criterion is satisfied for any investment into life safety for which the costs dG are outweighed by the SWTP multiplied by the number of lives saved, meaning the investment is worthwhile from a societal point of view.

The demographic constant C_x is calculated using life tables: demographic statistics showing the probability of death per age group, which are available for many countries [9]. The value of C_x then depends on how the change in mortality due to the investment is distributed over different age groups, and whether discounting and age-averaging over the life table is applied. The two most common 'mortality reduction schemes' apply either an absolute (C_Δ) or proportional (C_π) change to the mortality at different age groups. In other words, one scheme reduces the mortality with the same value for every age group, and the other with the same percentage. For more details, the reader is referred to [27] and [5], where these different schemes are compared. In general, C_Δ is smaller than C_π, though the difference reduces when discounting and especially age-averaging is applied. It is also suggested that the time preference component of the discount rate should be as small as possible.

The marginal change in mortality, $d\mu$, is more difficult to calculate. However, it can be converted to the marginal change in deaths dm by multiplying both sides of Equation 5 with the population size N_p. This converts the $-dG$ to the total costs of the investment in life safety, dC (note also the sign change), which is also more tangible. This leads to:

$$dC = -dGN_p \leq -\frac{G}{q}C_x d\mu N_p = -\frac{G}{q}C_x dm \tag{6}$$

The marginal change in deaths can then be calculated by multiplying the changes in the probability of a hazard occurring (such as a structural collapse) and the expected number of deaths if said hazard occurs. The net-benefit criterion is thus mostly applied in contexts with low-probability, high-impact events where fatalities may occur. Examples are structural safety, flood protection and industrial safety, with the first being the most represented in literature. The next section will present the current application of the LQI in structural safety.

4 The LQI in structural safety

This section presents the application of the LQI in ISO-norm 2394 on structural reliability [10], based on [6] and [7]. This is representative of the most common applications of the LQI in current literature, where it is used to establish a constraint in a continuous monetary optimisation problem. Based on societally desirable investments into safety, this constraint sets an upper bound to the failure probability of an engineering structure.

A generic structure is considered, of which the total *lifetime* cost C_{total} is to be minimised. This cost is formulated as a function of the single decision parameter x, based on the renewal process introduced by Rackwitz [24, 25]:

$$C_{total}(x) = C_0 + C_1 x + (C_0 + C_1 x)\frac{\omega}{\gamma} + (C_0 + C_1 x + H)\frac{P_f(x)}{\gamma} \tag{7}$$

Where C_0 are the constant construction costs, independent of x, while $C_1 x$ are the additional construction costs assumed to be linearly dependent on x. The term with ω represents the process of the structure becoming obsolete and being replaced. For example, if the expected time until obsolescence is 50 years, the obsolescence rate ω is equal to 0.02. The *yearly* failure probability of the structure is $P_f(x)$, which should decrease as x increases, with diminishing returns; its rate of decrease becomes smaller with increasing x (see Figure 1, middle subplot).

Failure requires the structure to be replaced as well, with additional damage costs H, which could include human damage costs or additional material damage. Both obsolescence and failure can occur over the lifetime of the structure, and the associated costs are discounted to their net present value, or NPV. For a constant (expected) yearly cost, constant discount rate γ and a sufficiently long lifetime, the NPV can be approximated by dividing the yearly costs by the discount rate [26] (as the structure is replaced after failure or obsolescence in the renewal model, the lifetime is effectively infinite). For a discussion on discounting in civil structures, the reader is referred to [15].

If the structure fails, a number of mortalities N_f is expected. Over the lifetime of the structure, the marginal change in deaths dm can then be formulated using the derivative of P_f to x:

$$dm(x) = \frac{dP_f(x)}{dx}\frac{N_f}{\gamma} \tag{8}$$

This means that the structure poses an inherent risk to life safety, which must be reduced to acceptable levels. What is 'acceptable' here is determined using the LQI. All investment for which the decrease in mortality outweighs the costs, meaning the net benefit criterion holds, is considered required from a societal point of view. This forms a constraint imposing a lower bound on the investment into reducing the failure probability, formulated by reversing the inequality sign in equation 6.

If the failure probability is reduced, then so are the expected damage costs, the final term in equation 7. This monetary benefit of decreasing the failure probability is positive for the decision-maker (assuming they carry these costs), but this cannot be 'traded' for human safety [7]. For the constraint, the marginal safety investment costs dC are therefore set equal to construction and obsolescence costs, and the damage cost is ignored:

$$C_{safety} = C_0 + C_1 x + (C_0 + C_1 x)\frac{\omega}{\gamma} \tag{9}$$

For the marginal safety investment cost, again the derivative with respect to x can be used. The constraint can now be written as:

$$\frac{dC_{safety}(x)}{dx} = C_1(1 + \frac{\omega}{\gamma}) \geq -\frac{G}{q} C_x \frac{dP_f(x))}{dx} \frac{N_f}{\gamma} \tag{10}$$

Note that the inequality sign is reversed compared to equation 6. This is rearranged to:

$$-\frac{dP_f(x)}{dx} \leq \frac{C_1(\gamma + \omega)}{\frac{g}{q} C_x N_f} = K_1 \tag{11}$$

Which is the final constraint for the problem: the negative slope of the failure probability as a function of x needs to smaller than the constant K_1. The value of K_1 depends on structure use, location and cost model (units given in brackets, where € can be another currency as well):

- x: Decision variable [varying]
- C_1: Linear term of investment cost function [€/x]
- γ: discount rate [$-$]
- ω: obsolescence rate [$-$]
- $\frac{g}{q} C_x$: SWTP for saving one statistical life [€/person]
- N_f: number of fatalities given failure [person]

The unit on both sides of this equation is [1/x], the reciprocal of the unit of the decision variable x. Typical values of K_1 found in [10] range between 10^{-5} and 10^{-2}, with smaller values indicating smaller relative lifesaving costs compared to the SWTP and N_f, thus requiring more investment and a smaller failure probability. Note however, that these values depend strongly on what the decision parameter x represents. In [6], this is the ratio between the mean resistance μ_R and mean load μ_S on the structure, which is rather abstract. If x represents a more straightforward quantity (e.g. a dimension of a beam), different values of C_1 and thus K_1 will appear, and the function $P_f(x)$ will change as well, though the resulting $P_{f,acc}$ should be similar (see the example in section 6 for more details).

Figure 1 shows an overview of the optimisation problem with the LQI-based constraint. In the top subplot, the monetary optimum results in a failure probability larger than $P_{f,acc}$, the value for which the constraint exactly holds. This means more investment is required to achieve an acceptable level of safety. The opposite could also occur: if the monetary optimum results in a P_f below $P_{f,acc}$, the constraint is inactive. There is no objection to a smaller failure probability if it reduces the lifetime costs, so the optimal decision is then also acceptable.

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 [7, 29, 33].

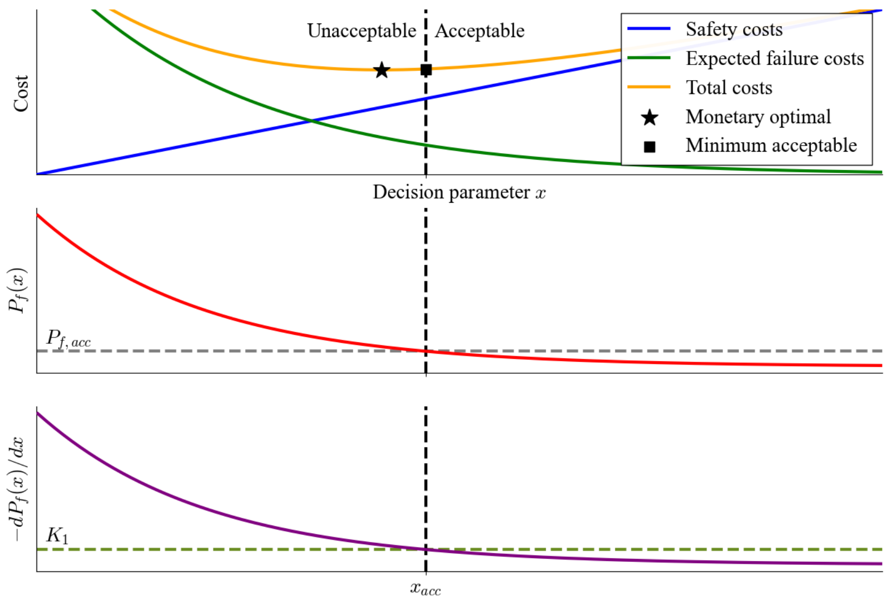

Figure 1: The optimisation from [6]. The lower plot represents Equation 20, which gives x_{acc}, corresponding to $P_{f,acc}$ in the middle plot. The top plot shows the cost functions.

5 S-LCA using the LQI

The LQI appears to be a promising candidate for solving two previously introduced challenges in (social) life cycle assessment in the built environment: developing of social impact indicators, and finding an optimal design or decision instead of comparing separate options. The net benefit criterion allows a relevant social concern - structural safety - to be quantified and combined with an economic optimisation. 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 different approaches towards the third phase of S-LCA, the impact assessment. The first approach is based on reference scales, where the social performance is 'scored' on an ordinal scale. The exact form of the scale is flexible, the guidelines give examples of five-point scales indicating levels of compliance to a certain norm, 'traffic lights' indicating a level of risk, and two-point identifiers (yes/no, true/false, present/absent).

The second approach is based on impact pathways (IP) formed by social mechanisms, based on the corresponding phase in E-LCA. If S-LCA and E-LCA are performed in parallel as part of LCSA, it stands to reason that the IP-approach is more straightforward. A social mechanism consists of social impact categories, impact category indicators coming from the inventory data gathered in the previous phase, and characterization models linking the two. Section 2 showed that, while social impact categories can be roughly defined for the built environment using EN 15643, quantifiable indicators forming the social mechanisms are not well-established yet.

A major cause for this is likely that the S-LCA characterization models cannot be constructed based on natural processes as in E-LCA. For example, an environmental characterization model for global warming potential aggregates emissions of several different greenhouse gases (indicators) into their

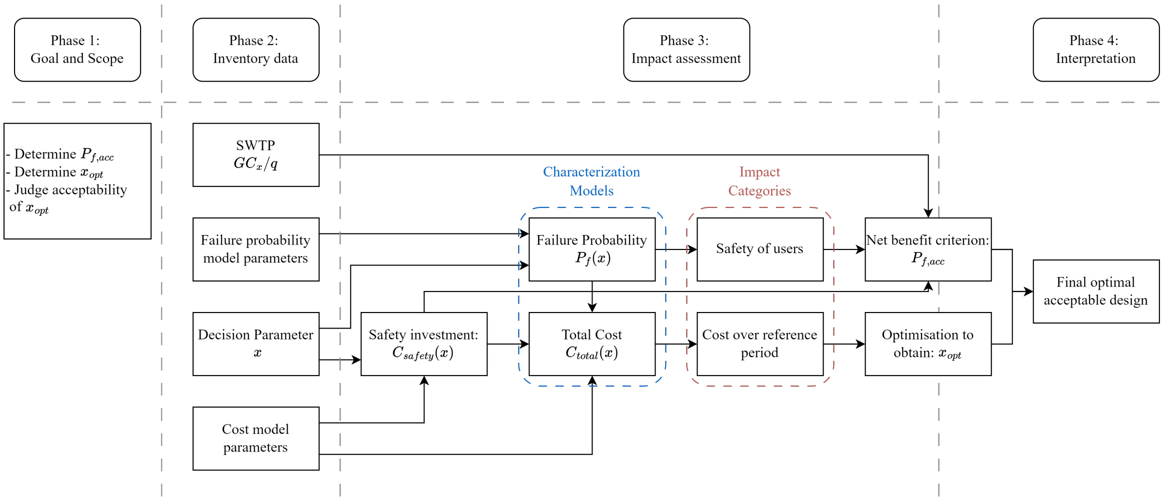

Figure 2: Flowchart schematic of the proposed application of the LQI in S-LCA. The blocks represent information gathered in a corresponding phase, and the arrows indicate how this is used in subsequent phases.

combined global warming effect (impacts), expressed in kilograms CO_2-equivalent. One kilogram of methane has the same effect on global warming as 25 kilograms of CO_2 [3], so the model converts it to 25 kg CO_2-equivalent. Such mechanistic models are difficult to construct in the social domain.

This is where the LQI finds its place in S-LCA. Figure 2 shows proposed application in a flowchart. In the first phase, goal and scope definition, the aim of using the LQI should be stated. This is establishing an acceptable failure probability $P_{f,acc}$. In parallel, a cost optimisation could be performed, which would fall under the economic pillar in and LCSA (the LCC), and would result in a cost-optimal decision x_{opt}. The purpose of doing both of these is then of course to judge whether the cost-optimal decision results in an acceptably low failure probability.

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, too.

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 is then effectively the characterization model. The safety investment costs and total costs are also determined here, and the lifetime cost is considered as a separate, economic impact category with $C_{total}(x)$ as characterization model.

Determining the economically optimal x_{opt} and minimum acceptable x_{acc} and $P_{f,acc}$ based on these functions could fall in either the third or fourth phase (interpretation). In either case, the main interpretation is whether the economic optimum results in a societally acceptable failure probability. If so, x_{opt} can be directly chosen as a final decision. If not, the cheapest option that does lead to an acceptable P_f should be chosen, which will generally be x_{acc}.

6 Numerical Demonstration

This section presents a social life cycle assessment of a simple structure as a case study, which demonstrates the proposed application of the LQI following the UNEP Guidelines. The example case is based on [6], though with a more specific structure. The four phases of life assessment are followed, resulting in an optimal and acceptable structural design.

6.1 Goal and scope

This example concerns the design of a steel beam of length L in an office building, carrying a vertical distributed load f. This is a fictitious problem, but its parameters are based on real data as much as possible. The goal is to design a cost-optimal beam with a sufficiently small failure probability P_f such that it complies with the LQI-based criterion. Aside from the cost and this criterion, no other aspects are considered.

By following the UNEP guidelines, the contribution of the LQI to the development of S-LCA is established. Furthermore, its role in finding an optimal structural design is demonstrated, thereby addressing both problems named in the introduction.

6.2 Inventory

A single failure mode is considered. The yearly failure probability P_f can be formulated as the probability of the yearly maximum dsolicitation S of the beam being larger than its resistance R:

$$P_f = P[R - S < 0] \tag{12}$$

Where both R and S (the yearly maximum) are stochastic variables with assumed lognormal distributions. The single failure mode is the stress in the steel reaching its yield strength σ_y through bending. This means R is the beam's bending moment resistance, while S is the maximum bending moment. The design of the beam is represented by the decision variable x, which sets the mean of its bending moment resistance $\mu_R(x)$ through:

$$\mu_R(x) = x\sigma_y \tag{13}$$

Here, x is the section modulus of the beam, commonly written as W, and σ_y is the yield strength of the material. The section modulus is also used as a decision variable in similar optimisation studies [8]. The coefficient of variation of the resistance is V_R $(= \sigma_R/\mu_R)$ and the distribution of S is defined similarly by μ_S and V_S. The values of all the variables can found in Table 2.

This simple formulation allows the failure probability to be expressed analytically as a function of x [24]:

$$P_f(x) = \Phi\left(-\frac{\ln\left(\frac{\mu_R(x)}{\mu_S}\sqrt{\frac{1+V_R^2}{1+V_S^2}}\right)}{\sqrt{\ln\left((1+V_R^2)(1+V_S^2)\right)}}\right) \tag{14}$$

Where $\Phi(.)$ is the standard normal cumulative distribution function. As mentioned, in [6] the decision parameter x represents the ratio between μ_R and μ_S. The section modulus is chosen here as it has a more physical interpretation (having a unit of [mm^3] instead of being unitless), while still allowing a similar formulation of $P_f(x)$.

The beam is assumed to be simply supported, so the mean bending moment at midspan μ_S is:

$$\mu_S = \frac{1}{8} f L^2 \tag{15}$$

While the section modulus influences the safety of the beam, its construction costs are determined by its volume, equal to its area A multiplied by its length L. It is assumed that the beam has a HEA-type profile [4]. For these, it can be observed that the area is approximately proportional to the square root of the section modulus. Figure 3 shows a fitted curve between the two.

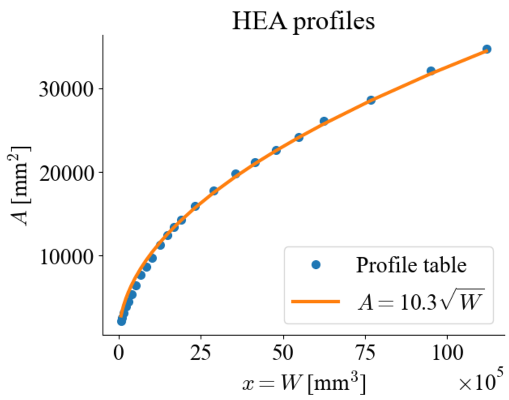

Figure 3: Relation between section modulus W and area A of HEA-profiles. Data from [4].

This simple conversion allows the same decision parameter x to be used in the cost and failure probability function. So, if A is given as:

$$A(x) = 10.3\sqrt{x} \tag{16}$$

The construction cost of the beam $C_{beam}(x)$ is given as:

$$C_{beam}(x) = C_{0,beam} + c_{steel}\rho_{steel}A(x)L \tag{17}$$

With c_{steel} the costs of structural steel per mass, ρ_{steel} its density, and $C_{0,beam}$ the fixed costs independent from x.

The lifetime costs $C_{total}(x)$ are given similarly to equation 7, though now with the less abstract beam costs:

$$C_{total}(x) = C_{beam}(x) + C_{beam}(x)\frac{\omega}{\gamma} + (C_{beam}(x) + H)\frac{P_f(x)}{\gamma} \tag{18}$$

With ω, γ still the obsolescence and discount rates, respectively, and H the additional costs in case of failure. Equation 18 is now the objective function to be minimised.

The constraint to the optimisation which sets $P_{f,acc}$ is similar to equation 11. The safety investment costs $C_{safety}(x)$, still the first two terms of $C_{total}(x)$, are now non-linear in x. Its derivative is inserted into equation 10:

$$\frac{dC_{safety}(x)}{dx} \geq -\frac{G}{q}C_x\frac{dP_f(x))}{dx}\frac{N_f}{\gamma} \tag{19}$$

Which is rearranged to:

$$-\frac{dP_f(x)}{dx} \leq \frac{\gamma\frac{dC_{safety}(x)}{dx}}{\frac{g}{q}C_xN_f} = K(x) \tag{20}$$

So, the constraint on the marginal reduction in $P_f(x)$ is now itself dependent on x, instead of being a constant as in [6]. This is another consequence of the different decision parameter x.

The cost function and LQI-based constraint are now both defined. The values of all parameters can be found in table 2, along with units and sources of the data. The estimated values N_f, V_R and V_S are based on the similar example found in [6]. The load f is roughly based on codes [13], though could be considered rather large for an office building (depending on the floor width carried by one beam). The societal constant C_x is based on the proportional mortality reduction scheme, using demographic data of the Netherlands in 2023. The SWTP with these values is €6.6 million.

Table 2: Parameters for the example application of the LQI criterion

Parameter	Description	Value	Unit	Source
σ_y	Yield strength steel	235	N/mm^2	Standard value
f	Load on beam	5	N/mm	Estimate
L	Beam length	5000	mm	Estimate
$C_{0,beam}$	Cost independent of x	100	€	Estimate
c_{steel}	Steel material cost	0.75	€ /kg	[2]
ρ_{steel}	Steel density	7850 $\times 10^{-9}$	kg/mm^3	Standard value
H	Additional damage cost	100	€	Estimate
ω	Obsolescence rate	0.02	-	[6]
γ	Discount rate	0.03	-	[6]
G	GDP per capita (NL)	60,000	€	[32]
q	Work-leisure time ration	0.1	-	[27]
C_x	Societal constant	11	1/persons	[27, 9]
N_f	Expected number of deaths for failure	0.01	persons	Estimate
V_R	Coefficient of variation for moment resistance	0.1	-	Estimate
V_S	Coefficient of variation for bending moment	0.6	-	Estimate

6.3 Impact Assessment

Now, the impact of different values of x is calculated. Figure 4 shows how the costs, failure probability and the two sides of the constraint in equation 20 vary over x. The star indicates x_{opt}, the design leading to the smallest lifetime cost. If only life cycle costing (LCC) had been performed, this would be the final design to be chosen. However, in this social life cycle assessment (S-LCA), the societal acceptance of the design forms a constraint on the optimisation. The dashed lines indicate x_{acc}, the smallest section modulus leading to an acceptable failure probability through the LQI-based criterion. The corresponding maximum failure probability $P_{f,acc}$ is also indicated in the middle subplot. Numerical values belonging to both x_{opt} and x_{acc} are given in Table 3.

Table 3: Numerical values corresponding to the cost-optimal and minimum acceptable design of the beam.

	Economic Optimum x_{opt}	Societal acceptance x_{acc}
x [mm^3]	3.82×10^5	8.22×10^5
C_{total} [€]	508.21	625.27
P_f [/year]	2.2×10^{-3}	1.3×10^{-5}

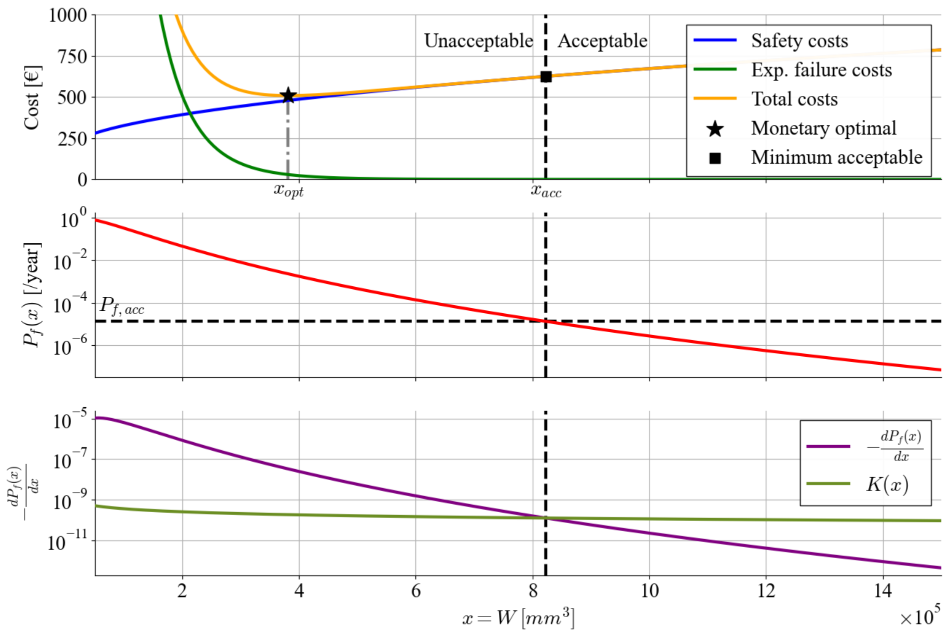

Figure 4: Results of the economic optimisation and of applying the LQI criterion

6.4 Interpretation

It is clear that x_{opt} leads to a failure probability larger than $P_{f,acc}$, so this cannot be chosen as the final design. Instead, x_{acc} should be chosen, as it is the cheapest value that meets the societal acceptance criterion. This demonstrates how two of the three pillars of sustainability can interact: the economic optimisation is 'corrected' by the social impacts from S-LCA, quantified through a characterization model and the life quality index.

The value of $P_{f,acc}$ corresponds to a reliability index $\beta = -\Phi(P_f)$ of 4.2. Fischer et al. obtain similar values for structures with small relative life-saving costs (small value of K_1). It is reasonable to state that this fictitious structure also belongs to this category, as the material cost of additional steel is small compared to the SWTP multiplied with N_f.

Most of the parameter values are based on real data, as can be seen in table 2. Of the handful of estimates, the cost values C_0 and H only influence x_{opt}, and not the LQI criterion. The expected failure costs are much smaller than the safety costs, as can be seen in figure 4, meaning the additional damage costs H do not influence the results significantly. In some literature, howveer, compensation costs for fatalities are included in H [8, 19], leading to more significant effects on C_{total}. The values of N_f and C_x can also vary across different cases. The demographic constant C_x dependent on the mortality scheme, and possible discounting and age-averaging. Here, a proportional scheme ('π') was used, with no discounting or age-averaging applied. The number of deaths in case of failure N_f is very dependent on the design and use of the structure, and is difficult to estimate exactly for a fictitious case. A sensitivity analysis with regards to these parameters could be of added value in future research.

7 Conclusion and future outlook

This study proposed the use of the life quality index as part of social life-cycle assessment in the built environment. It presented the current state-of-the art guidelines in this domain and explained how the application of the LQI could contribute to its development, with regards to current guidelines on S-LCA. An example showed how the current application of the LQI can take shape in impact pathway-based S-LCA of a simple structure. The LQI was used to quantify whether the structure is acceptably safe, through a social mechanism relating its design to the impact of possible failures on its users. This shows that the LQI is a promising candidate for future development of S-LCA, and specifically quantifiable social impact assessment.

The LQI inherently links the social and economic pillars of sustainability. The remaining environmental pillar is the most mature in terms of method development, through the environmental life cycle assessment. Combining these could form in interesting avenue for future research, as this would 'complete' Equation 1; LCSA = E-LCA + LCC + S-LCA.

The 'costs' of harmful emissions are carried by society as a whole, so it stands to reason that they should play a role in the societal acceptability of a failure probability. If the environmental burden (quantified through E-LCA) of additional material would be incorporated into the safety investment costs in some way, the acceptable failure probability could increase. This corresponds to an increase in K_1 or $K(x)$). Combining environmental and social aspects with economic considerations would allow for a truly comprehensive view of the required safety and sustainability of a structure.

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