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Reliability Approaches Affecting the Sustainability of Concrete Structures

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Abstract: The most important reliability approaches affecting sustainability in construction consist of the target reliability levels, verification methods, and construction or intervention procedures. The optimum target reliability levels can be specified based on probabilistic optimisation considering sustainability aspects including building costs, expected economic, social, and environmental consequences of construction, and possible failures. It appears that the derived reliability levels are strongly dependent on sustainability aspects and may be lower for the assessment of existing structures than for the design of new structures. The most efficient verification methods are based on advanced probabilistic approaches, including risk assessment methods considering actual properties of the structure and related failure consequences. It has been shown that sustainability in construction may be significantly affected by the design and assessment methods. The case study demonstrates that advanced reliability approaches commonly save 10–20% of the consumption of structural materials and natural resources.

Keywords: reliability; sustainability; target; verification; construction; optimization

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1. Introduction

1.1. Definition of Sustainability

"Sustainability" is an extremely broad concept, covering many objectives, requirements, and operational principles. It is one of the most talked-about but least understood terms. There is no universally agreed definition of what sustainability means. There are many different views on what it is and how it can be achieved [1,2]. Definitions of sustainability in various documents are somewhat general [3,4], slightly dissimilar, and do not provide clear principles for operational rules to satisfy desired objectives [5–7]. According to some, the definition is still under development [8,9].

The ASCE (American Society of Civil Engineers) Critical Infrastructure Guidance Task Committee defines sustainable development generally as the challenge of meeting human needs while conserving and protecting environmental quality and the natural resource base essential for future development [10]. This definition provided the basis for the guidelines on sustainability assessment was presented by Webb and Ayyub [11]. Focusing on construction, they discussed several definitions of sustainability, concluding that:

- Sustainability drivers include ecological, social, political, economic, and engineering aspects;
- No specific definition is adequate for all situations;
- Economic considerations should be considered in decision-making about sustainability.

In a specific sustainability assessment, only drivers affected by a decision need to be considered. The submitted contribution investigates the link between approaches to structural reliability verifications and sustainability of the construction work, focusing on its load-bearing structure. This is why only the drivers directly affected by the consumption of structural materials—ecological and economic aspects—are considered hereafter. It is

assumed that, for instance, material consumption reduced by 10% proportionally improves a sustainability indicator.

Engineering aspects are understood in this study as being related to choices amongst technically and economically feasible materials, structural systems, methods of interventions (for existing structures) and methods of verification, etc. This study is particularly focused on the methods of verification for new and existing structures—comparing the partial factor method (the most common in the current practice) with the probabilistic analysis (widely used in research studies). Note that decision-making regarding a choice of structural material is analysed by Zenisek et al. [12], supporting the use of advanced materials such as high-strength concretes.

1.2. Sustainability in Construction

The construction sector is capable of making a significant contribution to general sustainability objectives, particularly due to the amount of material and energy resources required to produce and maintain the built environment [13]. The Global Consensus on Sustainability in the Built Environment [14] indicates that the construction sector is currently responsible for more than 20% of global annual CO_2 equivalent emissions. Between one-quarter and one-half of these emissions are due to the production of cement, and thus are directly related to concrete structures.

EN 1990 [15] and the 2020 draft of its revision [16] include the following general guidance concerning sustainability in construction: the favourable effects to the society, environment, and economy can be achieved by appropriate verification methods, construction process, building materials, their manufacture, durability, and recyclability. Three main aspects of sustainability that can be controlled or affected by design procedures or approaches to reliability assessment are identified:

- Consumption of resources;
- Reuse of resources;
- Use of renewables.

Advanced methods of the design and assessment of structures may be applied to optimise the consumption of structural materials and may contribute to the above-mentioned four principles and the sustainability objectives.

The guidance in EN 1990 is in agreement with the aspirations of a draft fib Model Code (MC) 2020. MC 2020 assumes sustainability drivers similar to those discussed in Section 1.1. Model Code should facilitate designing construction works with low or no carbon impact, such as improving the efficiency of material usage, structural forms, and of re-using existing structures. This is to be achieved by, for example, using advanced methods for reliability verifications and different approaches to structural design and assessment of existing structures. In comparison to structural design, the basis of the assessment of existing structures assumes lower target reliabilities and reduced uncertainties when tests and measurements are taken on the existing structure. For further information on MC 2020, see ref [17].

Many other international codes address the sustainability of construction works. As an example, the set of the ISO 13315 standards provides the basic general rules on environmental management for concrete structures, intending to help with mitigating the environmental impacts resulting from concrete-related activities. The American Concrete Institute ACI in its Building Code (318-14) introduces sustainability as a structural system requirement in addition to strength, serviceability, and durability.

It is broadly recognised that concrete has a leading role in construction; for instance, the calibrations of partial factors in Eurocodes [18] assumed a weight of concrete structures of 45%, while 25% was considered for steel structures and the remaining 30% for structures from other materials and for geotechnical structures. Contemporary developments of concretes with improved durability and mechanical properties suggest that concrete will retain its leading role in the near and mid-term future [17]. It is obvious that enhanced technologies and approaches to designing and/or assessing concrete structures need to

be sought and developed. This is why the following analysis focuses on the sustainability aspects related to concrete structures. However, the general principles apply to other construction materials.

1.3. Need for Advanced Reliability Methods

The Global Consensus [14] emphasises that sustainability in construction needs to be supported by adequate provisions in standards. While the standards, in general, evolve slowly and fail to keep pace with rapidly increasing technological advances (e.g., missing design procedures for high-performance concrete structures), they already allow using a wide range of reliability verification methods, from simplified up to the most advanced.

The commonly used design method, based on the partial factor approach with recommended (fixed) values of partial factors, usually leads to conservative results [19–21]. More advanced reliability approaches were found to provide structural reliabilities closer to the target levels [7,21]. Advanced reliability methods include:

1. Adjusted partial method and design value method where design (or assessment) values are adjusted considering actual probabilistic distributions of basic variables for structure-specific conditions. The resistance and load effect parameters are treated separately, i.e., the so-called sensitivity factors, α, are provided in the standards. The design values are obtained as fractiles corresponding to probability, defined based on the sensitivity factor and a selected target reliability level. The generalised α-values lead, on average, to slightly conservative design values [19–21];
2. The probabilistic assessment also describes all basic variables by appropriate probabilistic models, but the relationship between resistance and load effect is modelled through a limit state function and the α-factors need not be defined. The actual reliability level, commonly expressed through reliability index β, is compared with a defined target reliability level, β_t [7]. Note that uncertainties in basic variables can be alternatively described in reliability analyses by the tools of fuzzy theory (interval-based approaches) [22]. These approaches have been applied particularly in situations with incomplete information. For instance, Holicky [23] demonstrated how fuzziness due to vague or imprecise definitions of performance requirements on structures could be described by the fuzzy sets approach, and proposed the methodology for combining interval-based and probabilistic methods;
3. The risk-based approach takes a basis in the probabilistic assessment, but the target reliability level is not defined, and total risk is estimated for hazard scenarios relevant to the structure. This risk is typically optimised over a set of possible design strategies (cf. engineering sustainability drivers in Section 1.1). The design strategy leading to an optimum risk is then compared with predefined risk acceptance criteria such as those for human safety levels; see ISO 2394 [24]. At present, risk analysis is applied only in exceptional cases.

The Global Consensus [14] recommends design codes be developed or revised, facilitating and rewarding the use of advanced analyses and methods of structural reliability including probabilistic approaches.

1.4. Research Objectives and Methodology

Recognising the leading role of concrete structures and their significant impact on sustainability, the main objective of this contribution is to critically compare two advanced approaches—*approaches (1) and (2)*—and to discuss the implications of their use on sustainability. To the best of the authors' knowledge, no detailed study on this topic has been published as yet.

Towards this aim, the following sub-objectives and steps to address them are adopted:

- MC 2020 emphasises that in developed countries, a key role in sustainability efforts plays extending the service life of existing structures and/or their appropriate re-use; therefore, the differences between new and existing structures are discussed in detail

in Section 2. Sustainability aspects are critically discussed considering the state of the art of knowledge in the field;

- Both advanced approaches under investigation—(1) updated partial factors and (2) probabilistic assessment—are affected by the choice of the target reliability level; therefore, the contribution continues with the reflections on appropriate target levels considering sustainability aspects (Section 3);
- Section 4 presents a generic example of design of reinforced concrete (RC) members. The results of a numerical study make it possible to critically compare *approaches (1) and (2)*;
- The effect of target reliability and the use of advanced reliability method (2) on sustainability indicators is indicated in Section 5 by means of other representative examples, focusing on existing RC members.

A summary, concluding remarks, the limitations of this contribution, and further research are then discussed in Section 6.

2. New and Existing Structures

Designs of new structures and assessments of existing structures have distinct features [7,8]. In fact, the assessment of an existing structure is in many aspects different from the design of new structures. The difference between design and assessment may affect the choice of target reliability level and verification procedures and resulting sustainability in construction.

Two main principles are usually accepted when assessing existing structures [13,16]:

- Currently valid codes for verification of structural reliability should be applied; historic codes valid in the period when the structure was designed should be used only as guidance documents;
- Actual characteristics of structural materials, actions, geometric data, and structural behaviour should be considered; the original design documentation including drawings is not decisive and should be used as guidance documents only.

The first principle should be applied to meet the present requirements of the society and to achieve a similar reliability level as in the case of newly designed structures. The second principle should avoid negligence of any structural condition that may affect actual reliability (favourably or unfavourably) of a given structure. For example, models for the shear resistance of RC structural members have significantly changed over the last decades.

Most of the current codes are developed assuming the concept of limit states in conjunction with the partial factor method or similar formats (international ISO, European CEN, or American ASCE standards). In the partial factor method, which is mostly considered here, basic variables are specified by characteristic or representative values. The design (or assessment) values of the basic variables are determined based on the characteristic (representative) values and appropriate partial factors.

Considering the sustainability aspects, the differences between the design of new structures and the assessment of existing structures and possible implications to reliability assessment are given in Table 1.

Table 1. Differences between the design of new structures and the assessment of existing structures considering sustainability aspects.

Aspect	Design of New Structures	Assessment of Existing Structures	Reliability Implications
Economic	Additional costs are usually low	Additional costs are usually high	Reliability of existing structures may be decreased
Social	Restrictions usually less significant than in existing structures	Restrictions of social aspects more important than in new structures	Mitigation of negative aspects may involve decreasing reliability
Environmental	May have significant unfavourable environmental impacts	Re-use of structure or structural materials usually has positive environmental effects	The reliability level of existing structures could be decreased to facilitate their re-use

Economic aspects play an important role when making distinctions between design and assessment. In design, additional costs of increasing reliability (e.g., by increasing reinforcement area) are mostly minor; however, upgrading the existing structure is commonly expensive. Along with upgrade cost, interruptions of business activities, closures of traffic routes and detours, or the relocation of users typically need to be considered. Consequently, economic arguments often provide the justification for decreasing the target reliability level for existing structures [18,21,25,26].

In particular, for structures with many users such as offices or residential high-rise buildings, or bridges on important routes, social aspects may also be significant. The need of upgrade may cause long-term malfunction of the existing structure with severe impacts to the society. In contrast, choosing an appropriate design strategy and execution procedure may lead to acceptable restrictions to inhabitants living in the neighbourhood of the construction site or to users of the route. A special social aspect is preservation of the heritage value associated with the structure. Both the negative impact on affected persons and the need to preserve the heritage value again provide arguments to decrease reliability requirements on existing structure in order to mitigate the negative aspects of possibly unnecessary upgrades.

The sustainability aspects mainly relate to reducing waste production and the recycling of structural materials. While recognising the importance of selecting an appropriate design strategy, e.g., to limit the carbon footprint of the structure, the benefits of re-using the existing structure, e.g., by adaptions to fit a new purpose, are obvious. Wherever possible, attempts are made to keep the existing structure in service, preferably with structural interventions limited to a minimum and using original recycled materials.

The effects of the construction process and the subsequent life of the structure, during which it may have undergone alteration, deterioration, misuse, and other changes to its as-built (as-designed) state, must be taken into account in the assessment of existing structures. However, even though the existing building may be investigated several times, some uncertainty in the behaviour of the basic variables and the whole structure always remains. Therefore, similarly as in the design of new structures, actual variation of the basic variables describing actions, material properties, geometric data, and model uncertainties related to assumed structural analyses are to be considered in the verification procedure. Contributions of design and assessment to the main aspects of sustainability in construction considered in this study are indicated in Table 2.

Table 2. Effects of design and assessment on the main aspects of sustainability as considered in this study.

	Main Elements of Design and Assessment				
	Target Reliability	**Reliability Verification**	**Materials**	**Construction**	**Sustainability Effects**
Design of new structures	Accepted standard levels	General common methods (partial factor method with recommended values)	Locally accessible resources	Common procedure	Partly adverse
Assessment of existing structures	Adjusted, optimised levels	Selected advanced methods (adjusted partial factors, probabilistic or risk-based assessment)	Choice of effective resources (re-use of the structure, re-use of built-in materials)	Advanced procedure (use of high-performance materials for strengthening)	Mostly positive

Considering the economic, social, and sustainability aspects in Table 1, the implications on design and assessment procedures are as follows:

- The target levels may be decreased for existing structures, as already indicated in Table 1. There may be cost benefits to optimise the target level for a particular existing structure, because additional cost of analysis can be outweighed by reduced economic and social demands and gains in sustainability indicators;
- Common design procedures such as the partial factor method are applied. Recommended values of partial factors are based on conservative assumptions regarding statistical characteristics of basic variables and the influence of the variables on structural reliability. The cost of increasing reliability in design is small; therefore, it is acceptable to use design procedures that provide reasonably conservative solutions in most cases of practical relevance;
- In contrast, conservative procedures in the assessment may result in demanding upgrades. Furthermore, detailed information about the actual conditions of the built structure can be acquired through tests and measurements, and uncertainties inherently present at the design phase can be significantly reduced. This motivates experts to apply more advanced procedures and avoid unnecessary upgrades and utilise structure-specific information.

Note that the total expected effects of design and assessment to sustainability indicated in the last column of Table 2 are very vague. However, they may be better specified using reliability methods for analysing the effects of main elements of design and assessment affecting sustainability in construction.

3. Target Reliability

The target reliability levels related to sustainability in the construction of new and existing structures should be specified taking into account:

- The possible consequences of failure in terms of social, economic, and environmental losses;
- The possible causes of attaining a limit state;
- Public aversion to failure;
- The expense and procedures which are necessary to reduce the risk of failure.

Possible consequences of structural failure are split in prEN 1990 [16] into five subsequent classes, denoted CC0 to CC4. Definitions of these classes are provided considering all the above-mentioned types of failure consequences, also including the sustainability aspects. Classes CC0 and CC4 are beyond the scope of prEN 1990, therefore they are not included in this study. Note that similarly to prEN 1990, the international standard ISO 2394 [24] assumes five consequence classes, denoted CC1 to CC5.

Reliability indices β_{50} and approximate failure probability P_f related to a 50-year reference period and consequence classes CC1, CC2, and CC3 in EN 1990 and prEN 1990 are indicated in Table 3 for ultimate limit states (ULS).

Table 3. Reliability levels for consequence classes CC1, CC2, and CC3.

Tentative Reliability Indexes β_{50} and Approximate Probabilities P_f Related to 50 Years and Ultimate Limit States (ULS) in EN 1990 [11].		
CC1	CC2	CC3
$P_f = 10^{-3}$ $\beta_{50} = 3.3$	$P_f = 10^{-4}$ $\beta_{50} = 3.8$	$P_f = 10^{-5}$ $\beta_{50} = 4.3$

The commonly accepted CC2 reliability level of 3.8 may be adjusted in the case of larger or smaller failure consequences (relatively to the middle class, CC2). For instance, the change from 3.8 to 4.3 corresponds to an increase in failure consequences by an order of magnitude as revealed by economic optimisation studies [25,27] and by human safety criteria [28,29].

A special type of reliability differentiation is to make a distinction between designing a new structure and assessing an existing structure. Strengthening the existing structure, in general, requires substantially more effort than strengthening during a design phase (Table 1). This justifies lower target reliability levels for existing structures adopted in some standards (e.g., Canadian bridge code CAN/CSA-S6-06, Dutch NEN 8700, or AASHTO Manual for Bridge Evaluation). However, a broad consensus on whether or not lower target levels should be applied for existing structures has not yet been reached.

4. Advanced Reliability Methods

The partial factor method with fixed values of partial factors leads usually to conservative results. This deficiency can be overcome by using more advanced reliability approaches—*(1) adjusted partial factor method*, *(2) probabilistic assessment*, and *(3) risk-based approach*. They make it possible to achieve uniform reliability levels for structures from different materials, with different structural members (columns, beams, slabs) and exposed to different load effects (ratio of permanent and variable actions, different variable actions) [19–21].

In this section, *approaches (1)* and *(2)* are critically compared and the implications of their use on sustainability are discussed. In *approach (1)*, partial factors are updated considering structure-specific conditions regarding, for example, information about structural materials, quality of execution, detailed measurements or tests, information about load effects, etc. The use of the adjusted partial factor method (*approach 1*) is illustrated by a fundamental example where the partial factor $\gamma(\beta,V)$ for a permanent load is expressed as:

$$\gamma(\beta,V) = 1 + \alpha_E \, \beta_{\text{tar}} V \tag{1}$$

The coefficient $\alpha_E \approx 0.7$ is the first order reliability method (FORM) sensitivity factor for load effects [7,13,15,16,24], the target reliability is assumed as $\beta_{\text{tar}} = \beta_{50}$ (Table 3), and V denotes the coefficient of variability of the permanent load. Variation of partial factor $\gamma(\beta,V)$ with adjusted reliability index $\beta = \alpha_E \, \beta_{\text{tar}}$ and the coefficient of variation V is indicated in Figure 1.

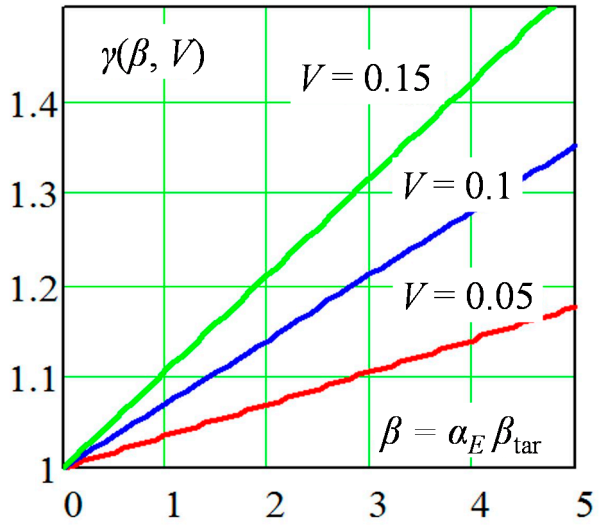


Figure 1. Variation of partial factor $\gamma(\beta,V)$ of permanent load with reliability index β and coefficient of variation V of the load.

Figure 1 indicates that partial factor $\gamma(\beta,V)$ may vary in a broad interval from 1.1 to 1.4, depending on the required target reliability level β_{tar}, assumed sensitivity factor α_E, and coefficient of variation V of the permanent load. Note that $V < 0.05$ is commonly considered for the self-weight of concrete structures, $V = 0.1$ for other permanent actions, and $V = 0.15$ applies in the cases of high variability of the permanent load [29,30].

It appears that $\gamma = 1.35$ recommended in Eurocodes [11,12] is often conservative. Obviously, the partial factor $\gamma(\beta,V)$ may cause a considerable variation of related consumption of structural material and environmental resources. The partial factor $\gamma(\beta,V)$ can be well-adjusted considering structure-specific conditions; therefore, positive effects on sustainability can be readily achieved by using *approach (1)*.

Further reductions in material consumption may be obtained using the probabilistic reliability approach such as the first order reliability method FORM [7]—*approach (2)*. The following analysis is based on the fundamental limit state (performance) function:

$$g = R - E = 0 \quad (2)$$

where R denotes resistance and E denotes the load effect. Two-parameter lognormal distributions are assumed for both basic variables, the resistance R (the mean equal to 100, the varying coefficient of variability V_R) and the load effect E (the mean 50, the varying coefficient of variability V_E). The symbol $R_{d,1}$ denotes the design value of the resistance R obtained using the updated partial factor method—*approach (1)*—and $R_{d,2}$ denotes the design value obtained by the probabilistic method FORM—*approach (2)*. Variations of the ratio $\mu_R = R_{d,1}/R_{d,2}$ with coefficients of variability V_R and V_E are shown in Figure 2.

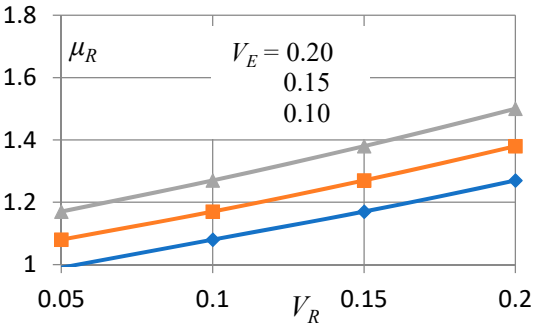


Figure 2. Variation of the partial factor $\mu_R = R_{d,1}/R_{d,2}$ with coefficients of variation V_E of load effect and V_R of resistance.

It follows from Figure 2 that the application of *approach (2)* reduces the consumption of structural materials by 10–20% (as indicated by μ_R-values exceeding the unity) in most cases of practical relevance. Obviously, the use of advanced reliability methods may favourably contribute to sustainability in construction.

Further to Figure 2, note that a V_R-value around 0.1 is representative for bending resistances of RC sections where steel reinforcement yielding is decisive. Greater coefficients of variation, $V_R \approx 0.15$–0.2, are typical for the crushing of concrete in short columns. For shear and slender columns, V_R-values may exceed 0.2 due to larger model uncertainties. A V_E-value around 0.1 is representative for structural members exposed to dominating permanent actions, while higher values are relevant for members exposed to variable actions.

However, when investigating the sustainability of real structures, more sophisticated limit state (performance) functions should be considered. In such a case, the variables R and E become functions of several basic variables (geometrical data, individual actions, and material properties). The analysis then becomes more complicated and software products may be needed.

5. Effect of Target Reliability and Use of Advanced Reliability Method on Sustainability Indicators

Various sustainability indicators have been proposed. For instance, Müller et al. proposed a simplified building material sustainability potential (BMSP) [31,32], while Webb and Ayyub [33] considered a wide range of factors to quantify the overall sustainability impact of various design strategies. All indicators should in principle take into account the construction, operation, and decommissioning phases of a structural lifetime [34].

Detailed investigation of the relationship between sustainability (e.g., BMSP) and structural reliability indicators (β) is beyond the scope of this contribution. The two following simplified examples should provide primary insights into the effect of target reliability and the use of an advanced reliability method on selected sustainability indicators.

5.1. Example 1—Remaining Service Life of an Existing Bridge

In the first example, an RC slab—a key member of an existing road bridge—is considered. The bridge has been in service for 30 years and its reliability is questioned by a highway authority. Reliability assessment should verify whether or not the bridge can remain in service for the next 25 years; considering a target reliability index of 3.1. The reliability assessment of the slab was analysed [35]—the main outcomes of this analysis are applied in the following sustainability assessment. The focus is on ULS. The sustainability impact is assessed through BMSP [31,32]:

$$\text{BMSP} = (\text{Performance } P \times \text{Service life } SL)/(\text{Environmental Impact } EI)$$

It is assumed that the bridge fully provides its function if a ULS criterion is fulfilled (P = 100%). When the ULS condition is violated, the bridge should be closed (P = 0%). Service life is measured in years; a reference level is 25 years (SL = 100%). As an example, if a service life is found to be 50 years, then SL = 200%. Environmental impact is assumed to be unchanged for an existing bridge (EI_{ex}), while it becomes very high when a new bridge needs to be built ($EI_{\text{new}} >> EI_{\text{ex}}$).

A reference $BMSP$-value for an existing bridge with a service life of 25 years is:

$$BMSP_{\text{ref}} = (100\% \times 100\%)/EI_{\text{ex}} \quad (3)$$

When a new bridge needs to be built, the value of the indicator becomes very small, $BMSP \approx 0 \times BMSP_{\text{ref}}$. It follows from this definition that the larger the BMSP, the more favourably sustainability impacts the situation.

The verification considering the partial factors recommended in Eurocodes [35] revealed that actual resistance is 10% lower than that that required to comply with design

requirements (common situation of existing bridges designed according to past standards). This leads to $BMSP = 0$ ($SL = 0\%$, high EI_{new}).

The probabilistic analysis was then conducted [35], considering uncertainties in material and geometrical properties and permanent load effects reduced by tests and measurements. Variations of the reliability index with a reference period (time since assessment) is shown in Figure 3.

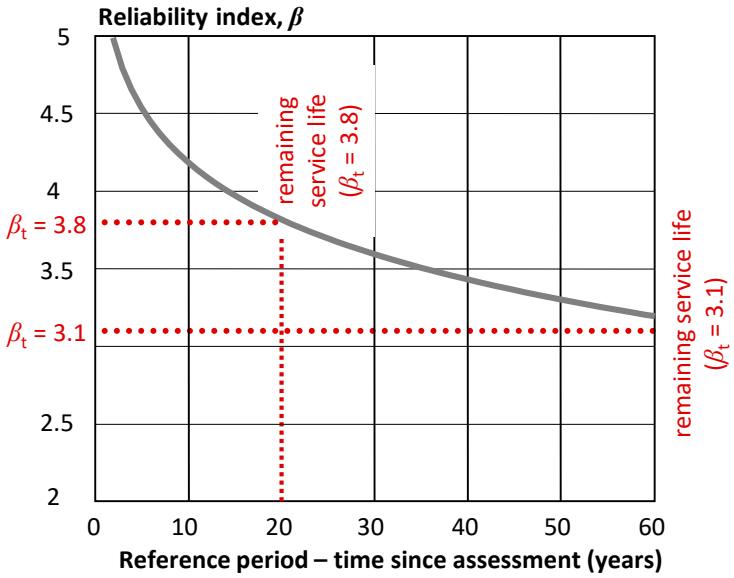


Figure 3. Variation of reliability index with reference period (adapted from [35]).

Figure 3 demonstrates the benefit of using the probabilistic approach. Considering $\beta_t = 3.8$ (Table 3), the remaining service life is estimated as 20 years ($SL = 20/25 = 80\%$). The sustainability indicator increases from zero to $BMSP = 0.8\ BMSP_{ref}$. When a lower target reliability is adopted for the existing bridge [35], the remaining service life exceeds 60 years, and $BMSP$ further increases to about $2.4\ BMSP_{ref}$.

Following this approach, Figure 4 displays the variation of $BMSP$ (relatively to $BMSP_{ref}$) with the target reliability index β_t. It appears that the sustainability indicator is significantly dependent on the accepted target reliability.

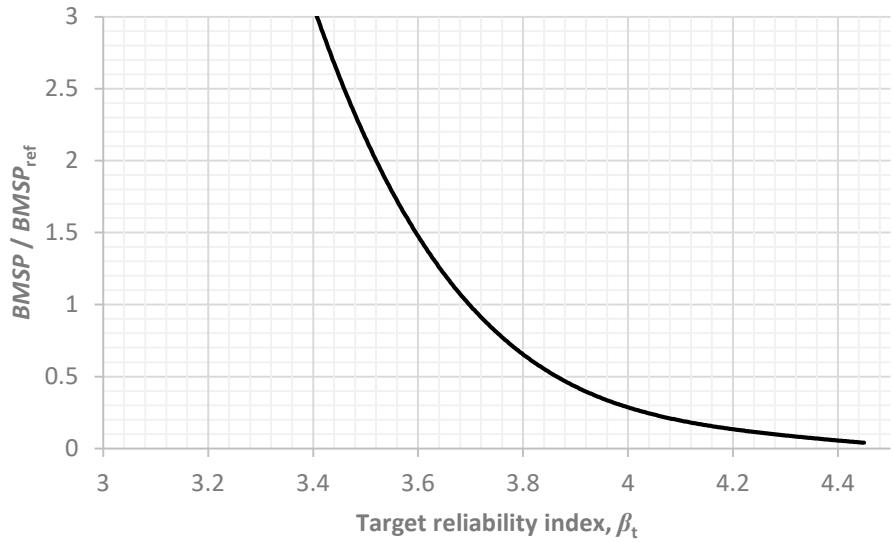


Figure 4. Variation of $BMSP/BMSP_{ref}$ with β_t.

It is emphasised that these results should be considered as indicative only. All sustainability implications should be evaluated through a risk-based approach. For instance, low-reliability levels may be associated with unacceptable human safety risks and/or high failure consequences (due to high failure probability). In contrast, high target levels will likely result in excessive initial structural cost which may jeopardize the feasibility of a new project, thereby hindering societal development.

5.2. Example 2—Approach to Design of a New Structure

Figure 2 in Section 4 shows that the application of the probabilistic approach (*approach 2*) on average reduces the consumption of structural materials by 15% in comparison to the partial factor method (*approach 1*). The second example qualitatively investigates which of the two approaches is more appropriate, considering the multicriterial approach to the sustainability assessment of various proposed design strategies [33]. Table 4 presents the comparison of sustainability indicators (a detailed quantitative comparison requires a separate study). Only sustainability indicators affected by the choice between *approaches 1* and *2* are considered; the focus is only on structural materials. Note that the indications in Table 4 are based on the authors' judgement, made after carefully scrutinising the complex approach to a proposed sustainability assessment [33].

Table 4. Qualitative comparison of sustainability indicators—a choice between *approach 1* and *2*.

Phase	Sustainability Indicator	Expected Change when Using *Approach 2* (Relatively to *Approach 1*)
Construction	Environmental *	Favourable—proportional to reduced consumption of materials
	Economic—structural cost	Favourable—proportional to reduced consumption of materials
Operation	Environmental * and economic—impacts of maintenance	Possibly unfavourable—overdesign may lead to reduced maintenance efforts as higher levels of corrosion may be accepted
Decommissioning	Environmental *	Favourable—proportional to reduced consumption of materials
	Economic	Slightly favourable (no major effect on decommissioning costs is expected)

* CO_2 emissions, raw material consumption, waste, emissions due to increased traffic and traffic disruptions.

It follows from Table 4 that the expected effects of using *approach 2* are mostly favourable. These benefits should outweigh increased design costs for *approach 2* that are mostly marginal. It is noted that the relative importance of the sustainability indicators in Table 4 may significantly differ for various structural types of structures. The expected changes of these indicators may apply for bridges, where costs and impacts related to structural materials play a key role. In contrast, the relative importance of structural materials decreases for low-rise residential or office buildings where the costs and impacts of secondary members and equipment may be dominating.

6. Conclusions

The presented contribution indicates that appropriate selection of a reliability approach to the verification of structures may significantly affect sustainability in construction. The reliability approaches consist of:

- Selection of target reliability—the optimum target reliability should be specified using probabilistic optimisation, taking into account sustainability aspects and considering the differences between structures under design and existing structures;
- Selection of a verification method—the advanced reliability approaches include the adjusted partial factor method and design value method, probabilistic analysis, and risk analysis.

The contribution shows that probabilistic reliability and risk-based methods are the most efficient approaches to analyse sustainability. The use of advanced reliability approaches in design reduces the consumption of structural materials and natural resources on average by 10–20%. These methods make it possible to avoid generally conservative choices regarding uncertainties in basic variables and their influence on reliability (the latter expressed through a sensitivity factor).

A numerical example of an existing bridge further demonstrated how sustainability indicators can be directly related to the level of reliability verification method as well as to the selected target reliability level.

Sustainability is a vast and complex task and intensive further research is needed. Regardless of a selected indicator, sustainability assessments are typically associated with challenging data requirements. Such data are often either lacking or scattered, and additional data are needed to make realistic sustainability assessments [33]. Further investigations of sustainability in construction should focus on real buildings, analysing the costs of their maintenance, service life, and demolition.

Reliability approaches relevant to sustainable assessment should be further investigated. It is recommended to apply probabilistic methods for a more general limit state function when resistance and load effects are described by specific multidimensional functions dependent on particular variables characterising the sustainability aspects. Other topics to be investigated include the effects of required maintenance, proposed service life, and the effect of the demolition of a structure on the overall sustainability. Adequate research on these topics may require the application of advanced reliability methods.

To facilitate practical sustainability assessments, sustainability indicators should be clearly defined, and their values should be optimised considering economic, societal, and environmental impacts of concrete structures. Such optimisations should cover not only the ultimate limit states but also the serviceability and condition (initiation or durability) limit states that often dominate structural design. Furthermore, obsolescence due to non-structural reasons (such as changing requirements on structural function, often important for bridges or industrial structures) may lead to the need for replacement of the structure [36] and should be taken into account.

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