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Towards a Conceptual Framework for Built Infrastructure Design in an Uncertain Climate: Challenges and Research Needs

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Abstract: The potential risks of climate change on the built environment involve large uncertainties. This poses an intricate problem to designers and challenges a long-standing tradition of built infrastructure design. More specifically, designers are faced with this challenging question: how to rationally account for climate change risks when designing a new asset? A framework that holistically addresses this difficult question is missing from the current literature. This study contributes to this gap by (1) proposing a conceptual framework for rationally considering the effects of climate change in the design of these assets and (2) identifying the challenges that need to be overcome to facilitate the transition, and further development, of the proposed framework into practice. First, a detailed overview of important infrastructure performance requirements that are relevant to the proposed framework is presented. The different stages of the proposed conceptual framework are then outlined. The proposed framework progresses in the following order: ranking the importance of the asset, identifying the potential climate change risks, analyzing these risks, selecting a design strategy, and finally evaluating the final design. Lastly, several challenges that impede the application of the proposed framework in practical settings are identified. The proposed conceptual framework and the identified challenges comprise a necessary steppingstone towards addressing this pressing issue and developing a more practically applicable framework for considering the risks of climate change in the design of built infrastructure assets.

Keywords: climate change; adaptation; infrastructure; design; risk; resilience; robustness; sustainability

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1. Introduction

Significant evidence shows that, compared to the preindustrial era, the climate is changing at unprecedented rates. Projections of climate models point to further substantial changes in the future, possibly with even faster rates. Examples of such changes include an increasing temperature trend, altered precipitation patterns, sea level rise (SLR), and changes in the intensity and/or frequency of extreme weather events [1]. These changes to the environment pose intricate challenges to a long-standing tradition of built infrastructure design, operation, and management practices. In addition to introducing additional risks or increasing existing ones (see, e.g., [2–4]) climate change renders some fundamental design concepts and assumptions invalid to a large extent, e.g., reliance on historical data, extreme value assumptions, and climate stationarity.

Despite the evidence of a changing climate, climate projections and the assessment of their potential risks are characterized by large uncertainties. Courtney et al. [5] and

Walker et al. [6] distinguish between four general levels of uncertainty delimited by the following two extremes: determinism and total ignorance. While the first level (level 1) envisages a future in which a precise enough single forecast can be made (referred to as a clear enough future in [5]), the second level of uncertainty (level 2) describes a future where a few discrete, mutually exclusive, and collectively exhaustive scenarios with assignable probabilities define all the possible alternate futures. The last two levels of uncertainty are commonly referred to as deep uncertainties; see, e.g., [6]. Level 3 describes a future in which a range of possible scenarios can manifest, instead of a limited number of discrete scenarios as in level 2. Unlike level 2 uncertainty, assigning plausible probabilities to these future scenarios is not possible under the current state of knowledge. Lastly, level 4 characterizes a future of true ambiguity where there is no basis for forecasting the future. Looking at the uncertainties involved in climate change projections, it becomes evident that problems involving climate change and its risks are characterized by deep uncertainties; see, e.g., [7,8]. The future climate may be described by multiple scenarios for which no objective probabilities can be reliably assigned under current knowledge, and this may suggest level 3 uncertainty. On the other hand, other uncertainty sources (e.g., modelling uncertainties and internal climate variability) further complicate problems involving climate change projections [9–15].

This uncertainty in the future climate poses a serious challenge to built infrastructure designers. Built infrastructure components (e.g., bridges, seawalls, and tunnels) are often designed for long service lives (which may surpass 100 years) and, in many cases, are being operated even beyond these design service lives. In the current design standards and regulations, the weather variations have only been considered through observed historical data. Lacking guidance on how to appropriately deal with this changing design basis, designers may react in several ways. Assuming that climate change is too uncertain to base any decisions on, a “do-nothing” approach where climate change is disregarded in the design may be adopted. On the other extreme, an alternative approach where the built infrastructure asset is designed for a specific climate change scenario which is perceived as being on the safe side (e.g., RCP8.5) may be adopted, possibly resulting in overly conservative design proposals. Generalizing either of these two approaches, however, oversimplifies the issue and regards it as a level 1 uncertainty problem instead of considering the deep uncertainties involved in the design process [16]. It is therefore the authors’ hypothesis that generalizing either of the two approaches is inappropriate for designing built infrastructure assets under considerations of an uncertain climate. Adopting the first approach for all cases of built infrastructure design will likely cause many built infrastructure assets to have unreliable future performances in light of climate change. On the other hand, the second approach (often referred to as armoring or hardening), although commonly cited as an appropriate adaptation to climate change [16], can unnecessarily lead to over-invested infrastructure. Since the building and construction industry is one of the main contributors to greenhouse gas (GHG) emissions, with a contribution of 39% to global carbon dioxide emissions [17], it becomes apparent that generalizing this second approach is not appropriate for a sustainable future. Thus, adopting this approach for all built infrastructure assets is likely to exacerbate climate change in a self-fulfilling prophecy, i.e., a future of high GHG emissions is realized due to unwarrantedly designing all assets to accommodate an unrealistically high GHG emissions scenario.

Up to now, only a few studies have attempted to address the problem of designing built infrastructure in the context of climate change; see, e.g., [18,19]. In [18], two possible approaches for handling the problem are given: (1) reforming design codes to encompass the whole range of possible future scenarios (e.g., changing the partial safety factors, see [20,21]) and (2) taking a more sophisticated approach for considering climate change risks and progressing towards probabilistic or risk-based design codes. The first approach may lead to resource overconsumption and infrastructure overcapitalization and potentially hinder the flow of capital into built infrastructure [18]. The second approach, although arguably more reasonable, lacks clear guidance for practical implementation [18]. Connor et al. [19] suggests four possible design strategies: (1) build to repair, (2) planned adaptation, (3) progressive modification, and (4) build for a predicted "pessimistic" scenario. The same study provides some practical examples for these strategies but lacked guidance concerning design choices (e.g., in which cases are each design option favorable?). A necessary first step towards considering climate change in built infrastructure design, which is missing from the current literature, is to develop a conceptual framework that captures the different possible design choices and gives guidance on how the problem can be approached in a rational manner. Additionally, the challenges hindering the application of this conceptual framework in practice need to be identified. The current article addresses these two gaps.

In this paper, a conceptual framework for rationally considering the effects of climate change in the design of built infrastructure assets, with a specific focus on bridges, is proposed. Although the proposed framework is not a ready-to-use framework that can be directly applied in practical settings, it is an important steppingstone that facilitates the development of such a framework in the future. The paper starts by presenting a detailed overview of important infrastructure performance requirements that are relevant for the last stage of the framework. This is followed by a section presenting the different elements of the proposed conceptual framework. Thereafter, challenges to the application of the proposed framework in practical settings are identified and viable future research directions are presented. Lastly, the final section highlights some concluding remarks.

2. Overview of Important Performance Requirements

2.1. Risk Acceptance Requirements

Risk acceptance requirements (i.e., safety requirements) are derived based on the two fundamental principles of economic efficiency and equity [22–24]. Economic efficiency is defined by the risk level where the marginal risk-reduction benefits are equal to or higher than the marginal risk-reduction costs and hence aims to ensure that the safety budget of a society is allocated and distributed in such a way that the society members receive the maximum benefits. In this regard, further reducing an already low risk becomes counterproductive after a certain point and is no longer justifiable by the potential risk-reduction benefits. This implies that there should be an upper limit to the amount of resources spent in direct risk-reduction measures (i.e., limited safety budget) and that above this limit resources should be diverted towards present or future consumption. Equity, on the other hand, stipulates that all members of a society should be adequately protected, and that economic efficiency should not justify exposing an individual member to excessively high levels of risk. In this sense, equity implies that there should be an upper limit to the level of risk an individual is exposed to and that above this limit the risk should be reduced, regardless of the economic efficiency. Hence, in establishing risk acceptance criteria, a reasonable trade-off between economic efficiency and equity is pursued.

Noting that a limited budget should be allocated to risk-reduction measures, investments into such measures should reflect the preferences of the society under consideration [25]. Such preferences may be assessed in several ways (e.g., stated/expressed preferences, revealed preferences, and informed preferences; see [25–27]). Despite the fact that these preferences may not be optimal [25], they have been found to significantly affect legislative agendas of regulatory agencies [28] and consequently decisions relating to risk acceptance. Hence, public risk perception plays a central role in risk acceptance. Risk perception is affected by several factors including the degree of voluntariness, the degree of personal control, familiarity, and dread [25,29,30]. For instance, the more perceived control individuals have on the outcomes of an activity and the more voluntary it is, the more willing they are to accept the risks. Diamantidis [31] demonstrates this effect with an example of a rail track that transports hazardous materials. In this example, the engine driver, the passengers, and the people living near the tracks each have different levels of risk that they are willing to accept; the engine driver is willing to accept a higher level of risk than the passengers who are willing to accept a higher level of risk than the people living near the tracks. A more elaborate discussion on risk perception can be found in [32].

Several forms of risk acceptance criteria exist [23–25,31,33] depending on the preferences of the involved parties and the decision maker, the type of risk being considered, and the quality of the available information [33]. Diamantidis [31] distinguishes between implicit and explicit risk acceptance criteria. Implicit criteria may be set by comparing the level of accepted risk with, e.g., that accepted for another industrial sector, imposed by natural hazards, etc. [31,34]. As quantitative risk acceptance criteria were developed in, for example, the nuclear and offshore industrial sectors well in advance of the other industries, the use of implicit risk acceptance criteria was more common in the past. However, these have been replaced over time by explicit criteria. Examples of explicit risk acceptance criteria are those based on (1) human safety (i.e., fatality risk), which is subdivided into individual risk criteria and societal risk criteria [23,31,33], and (2) failure probability (or reliability index) [33,35]. For setting individual risk criteria, two annual fatality risk levels are defined representing (1) the maximum tolerable risk level above which risks cannot be accepted (also referred to as the de manifestis risk level [36]) and (2) the broadly acceptable risk level below which risks are of no practical interest and are viewed as negligible (also referred to as the de minimis risk level [24,36,37]). These two risk levels divide the risk domain into an unacceptable risk region, a negligible risk region, and the so-called ALARP region. Risk acceptance within the third region follows the so-called ALARP (as low as reasonably practicable) principle [23,31,38,39], which states that risks should be reduced to a level that is as low as reasonably practicable (see Figure 1).

Similarly, societal risk criteria also divide the risk domain into the three aforementioned regions. Two commonly used representations of societal risk criteria are the so-called F-N diagram (also known as Farmer diagram [40]) and risk acceptability matrices; where F represents the annual frequency of accidents having more than N fatalities [25,31]. Societal risk criteria include so-called risk aversion factors which reflect the notion that a single multiple-fatalities event weighs heavier than a series of single-fatality events with the same total number of fatalities. However, there is considerable criticism and debate with regard to these factors [38,41–44] and whether or not they actually represent societal preferences in comparing multiple- and single-fatality events [45–47]. It is also worth mentioning that due to the ambiguity in its formulation [48], the ALARP principle (and consequently the ALARP region) can be interpreted in several ways. While in some cases ALARP is interpreted to mean that a safety measure should be applied only if its costs are lower than its benefits, in other cases it is interpreted to mean that a safety measure should be applied if its costs are not in gross disproportion to its benefits (i.e., even in some cases where the costs may be higher than the benefits, the safety measure should still be applied); see, e.g., [23,31,38,39,41,49]. Other terms which are closely related to ALARP and sometimes used interchangeably are as low as reasonably achievable (ALARA), as low as practicable (ALAP), so far as is reasonably practicable (SFAIRP), and best available technology not entailing excessive costs (BATNEEC) [41].

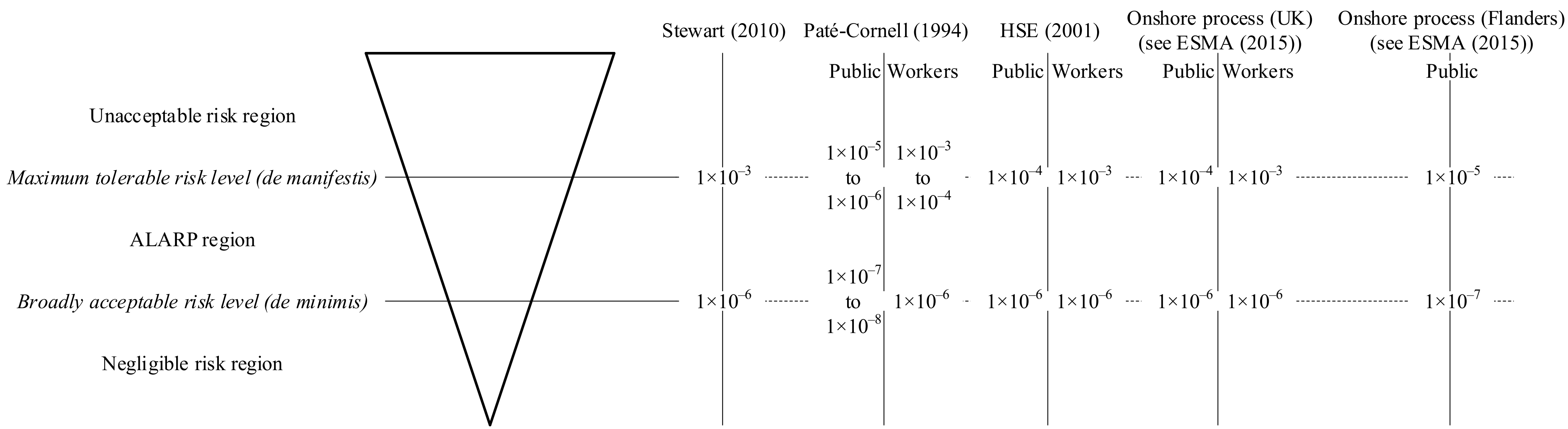

Figure 1. Different individual risk acceptance criteria recommended in the literature; values represent the annual fatality risk.

Most current structural codes of practice use risk acceptance criteria based on failure probability (or reliability index); e.g., [35]. For instance, the Eurocodes for structural design [35] have target annual probabilities of failure ranging from 10^{-5} (reliability index of 4.2) to 10^{-7} (reliability index of 5.2) for the ultimate limit state depending on the consequences of failure, while the probabilistic model code of the Joint Committee on Structural Safety (JCSS) [50] and the standards of the International Organization for Standardization (ISO) [51] have target annual probabilities of failure ranging from 10^{-3} (reliability index of 3.1) to 10^{-6} (reliability index of 4.7) for the same limit state depending on the consequences of failure and the relative cost of the safety measure. Other methods for establishing rational risk acceptance criteria may be based on the so-called life quality index (LQI) concept. The LQI considers socioeconomic parameters such as the gross domestic product (GDP) per capita and life expectancy at birth [52–56]. From this discussion it becomes evident that risk acceptance is an intricate problem on which there is no clear consensus [57]. This is demonstrated by Figure 1, which shows different individual risk acceptance criteria recommended in the literature as examples. To put the numbers in Figure 1 into perspective, it is worth noting that the annual individual risk due to a natural hazard and due to disease (for a 30-year-old individual) are approximately 10^{-6} and 10^{-3}, respectively [58].

2.2. Robustness and Resilience Requirements

2.2.1. Robustness Requirements

Several definitions for robustness can be found in the literature with respect to built infrastructure. However, one of the most common definitions is as follows: "The ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause" [59]. Robustness first emerged as a performance objective following the notorious progressive failure of the Ronan Point Tower in London in 1968. The Ronan Point incident and other progressive failure events which followed (e.g., the Alfred B. Murrah Federal Building in Oklahoma in 1995 and the World Trade Center Twin Towers in New York in 2001 [60]) resulted in widespread attention to this performance characteristic among practitioners and researchers alike and highlighted the need for robustness requirements in design [60,61]. Several measures of robustness can be found in the literature. Lind [62] mentions that robustness measures should be in-line with at least some of the following attributes: expressiveness, objectivity, simplicity, calculability, and generality. However, it has been mentioned that it is not possible to fulfill all of these five attributes simultaneously as they are in partial conflict with one another [63]. Adam et al. [60] categorizes robustness measures into threat-dependent and threat-independent measures. Furthermore, the former is subcategorized into reliability/risk-based and deterministic measures. An example of threat-dependent, reliability/risk-based robustness measures is the robustness index proposed by [64] which is evaluated as the fraction of total system risk resulting from direct consequences (the higher the proportion of direct-consequences risks to the total, i.e., direct and indirect, risk the higher the robustness index). Other threat-dependent, reliability/risk-based measures have been proposed by [62,65,66]. Examples of threat-dependent, deterministic measures have been proposed by [67,68]. Lastly, threat-independent measures were proposed in [63,69,70].

There are four widely recognized groups of design approaches for robustness: tying force prescriptive rules, alternative load path methods, key element design methods, and risk-based methods [60]. The tying force prescriptive rules, which are used in some codes of practice [59] and excluded in others, are generally classified as indirect design approaches in which the resistance to progressive collapse is only considered implicitly. It has been shown that the ductility requirements for this group of approaches may be unachievable in some cases and that the degree of robustness enhancement provided by them is unquantifiable. On the other hand, the alternative load path methods, which are considered as direct-design approaches and are accepted by most codes of practice, involve many simplifications and assumptions, and hence can lead to varying levels of robustness in practice. Although the key element design methods are scenario-specific methods, some codes of practice apply them using a notional static load pressure of 34 kPa, which is estimated based on the Ronan Point incident and hence may not be sufficient to prevent local failure in the case of other extreme events. Lastly, risk-based methods are only implicitly considered in most codes of practice with few exceptions [60]. It is worth noting that the consideration of robustness in design and in codes of practice is still an evolving issue. For example, guidelines for the evolution of the robustness framework in the future generation of Eurocodes have been recently proposed by [71]. Thorough discussions on robustness definitions, considerations in codes of practice, quantification, experimental testing, numerical modelling, etc., can be found in [60,63,69,72–74].

2.2.2. Resilience Requirements

As with robustness, several different definitions for resilience can be found in the literature. The term resilience generally refers to "The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" [75]. Resilience has been recently underscored as a key performance objective that should supplement traditional infrastructure design [76–79]. Linkov et al. [79], for example, argue that resilience should be integrated early-on in the design of infrastructure systems to confront the evolving complexity and uncertainty due to, e.g., climate change. Several measures of resilience exist in the literature. Sun et al. [80] categorize resilience measures into functionality-based and socioeconomic measures. Functionality-based measures are subcategorized into resilience triangle-related (e.g., resilience measure proposed by [76], resilience loss due to an event [81,82], and optimal resilience cost and recovery dependent resilience cost proposed by [83]), resilience index [84], capacity, and other functionality-based resilience measures. Socioeconomic measures, on the other hand, are subcategorized into system-based [85] and capital-based (disaster recovery index and disaster impact index [86,87]). Interestingly, Ayyub [76] argues that many of the existing measures are either inappropriately structured or too complex to be used in practice (i.e., impractical). The same study proposes a practical resilience measure that addresses these issues. A more detailed discussion on the different resilience measures can be found in, e.g., [80,88].

Comparing the definitions of robustness and resilience, it becomes obvious that the two performance objectives are strongly interrelated [76,89,90]. For instance, in [81], which introduced the concept of the resilience triangle, resilience incorporates eleven different aspects including robustness, i.e., the four dimensions of resilience (technical, organizational, social, and economic), the four properties of resilience (robustness, rapidity, redundancy, and resourcefulness), and the three results of resilience (higher reliability, faster recovery, and lower consequences). Within this concept of the resilience triangle, robustness is measured by the residual performance immediately following a performance drop due to a perturbation [76,77]. Faber et al. [89,91] defined resilience failure as the event of a disturbance leading to a capacity loss (social, economic, and/or environmental) of the system beyond its accumulated reserves and mentioned that resilience, as well as robustness, is a characteristic of random nature and hence requirements to resilience are only meaningful if specified probabilistically, e.g., in terms of an acceptable annual probability of resilience failure.

2.3. Sustainability Requirements

Sustainability generally refers to meeting the needs of the present without compromising the ability of future generations to meet their own needs [92]. However, several definitions for sustainability may be found in the literature [93]. For example, in [94] sustainability is defined as "a set of economic, environmental, and social conditions in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely, without degrading the quantity, quality, or the availability of natural, economic, and social resources". This definition demonstrates that there are three sustainability pillars (i.e., aspects): environmental, economic, and social.

Several methods for assessing sustainability exist. One of the most common approaches for assessing sustainability is to assess the life cycle of the infrastructure considering one or more of the aforementioned sustainability pillars, e.g., environmental life cycle assessment (LCA) and life cycle cost analysis (LCCA), which assess the environmental and the economical sides of sustainability, respectively [95]. For instance, Gervásio [96] presents a comprehensive integral life cycle analysis of bridges which considers all three pillars of sustainability. Zavrl et al. [97,98] categorize sustainability assessment methods into (1) methods with environmental focus, (2) methods with economic focus, and (3) methods with social focus. Examples of the first type include environmental impact assessment (EIA), strategic environmental assessment (SEA), LCA, ecological footprints (EF), the ecological rucksack (ER), and the green poster (GP). Examples of the second type include cost-effectiveness analysis (CEA), cost benefit analysis (CBA), multi-criteria decisions aids (MCDA), and environmental accounting (EA). The third type, methods with social focus, includes social impact assessment (SIA) and socio-economic impact assessment (SEIA). In addition, Webb and Ayyub [93,99] propose and demonstrate a framework for the probabilistic quantification of sustainability. It is worth mentioning that several standards which address sustainability in construction exist, e.g., [100–104]. Some practical guidelines for improving the sustainability of infrastructure can be found in the literature [105].

Although sustainability and resilience are related, the nature of this relationship is not yet fully understood [91,106]. Ayyub [107] mentions that the relationship between sustainability and resilience is context-dependent and is governed by the following three precepts: "(1) systems that are resilient might not be sustainable; (2) systems that are not resilient are not sustainable; and (3) systems that are not sustainable might be resilient"; see also [108]. Bocchini et al. [77] suggest that sustainability and resilience are complementary concepts (i.e., considering one of the two concepts does not substitute for considering the other) and proposes a unified framework for their simultaneous consideration. Faber et al. [91] assess sustainability probabilistically and define sustainability failure as the event where one or more of the planetary boundaries are exceeded, i.e., boundaries which represent the capacity of the Earth system to support human activities [109,110]. According to the definitions presented in [91], at the global Earth scale, sustainability failure and resilience failure are equivalent.

3. A Conceptual Framework for Designing Built Infrastructure Assets in a Changing Climate

In this section, the different stages of the proposed conceptual framework are outlined. Although the framework is aimed at built infrastructure assets in general, this section focuses primarily on bridges for the sake of coherence and consistency. As a basis for the framework, alternative preliminary design solutions of a bridge should be made, e.g., using different span arrangements, bridge types, and material types. The proposed framework is then applied to each of the preliminary designs to assist the designer in choosing the most suitable design alternative. The framework distinguishes between three different design strategies: (1) build to repair, (2) planned adaptation, and (3) build for a predicted "pessimistic" scenario. The first strategy entails designing the infrastructure without regard for climate change and thus any damage that may occur in the future is repaired when it occurs. The second strategy consists of designing for a relatively low GHG emissions scenario (e.g., RCP2.6 or RCP4.5) while allowing for the structure to be adapted (i.e., upgraded) in case of a perceived or observed deviation from the initial design scenario. Finally, the third "pessimistic" strategy is based on designing the infrastructure to withstand a relatively high (and more unlikely) GHG emissions scenario (e.g., RCP6.0 or RCP8.5). The progressive modification design strategy presented in [19] is not considered in the proposed framework as it is only slightly different from, and in many cases is expected to be outperformed by, the planned adaptation design strategy [19]. It is worth noting that planned adaptation (also referred to as the observational method [111]) necessitates a continuous monitoring program that observes the behavior of the considered built infrastructure asset through relevant metrics.

Following the preliminary design of the asset, the framework consists of the following five stages: (1) importance ranking, (2) identification of the potential climate change risks, (3) analysis of the potential climate change risks, (4) design strategy selection, and (5) evaluating the final design. These five stages are explained and discussed in the remainder of this section; a detailed overview of all steps within the framework is also provided in Figure 2.

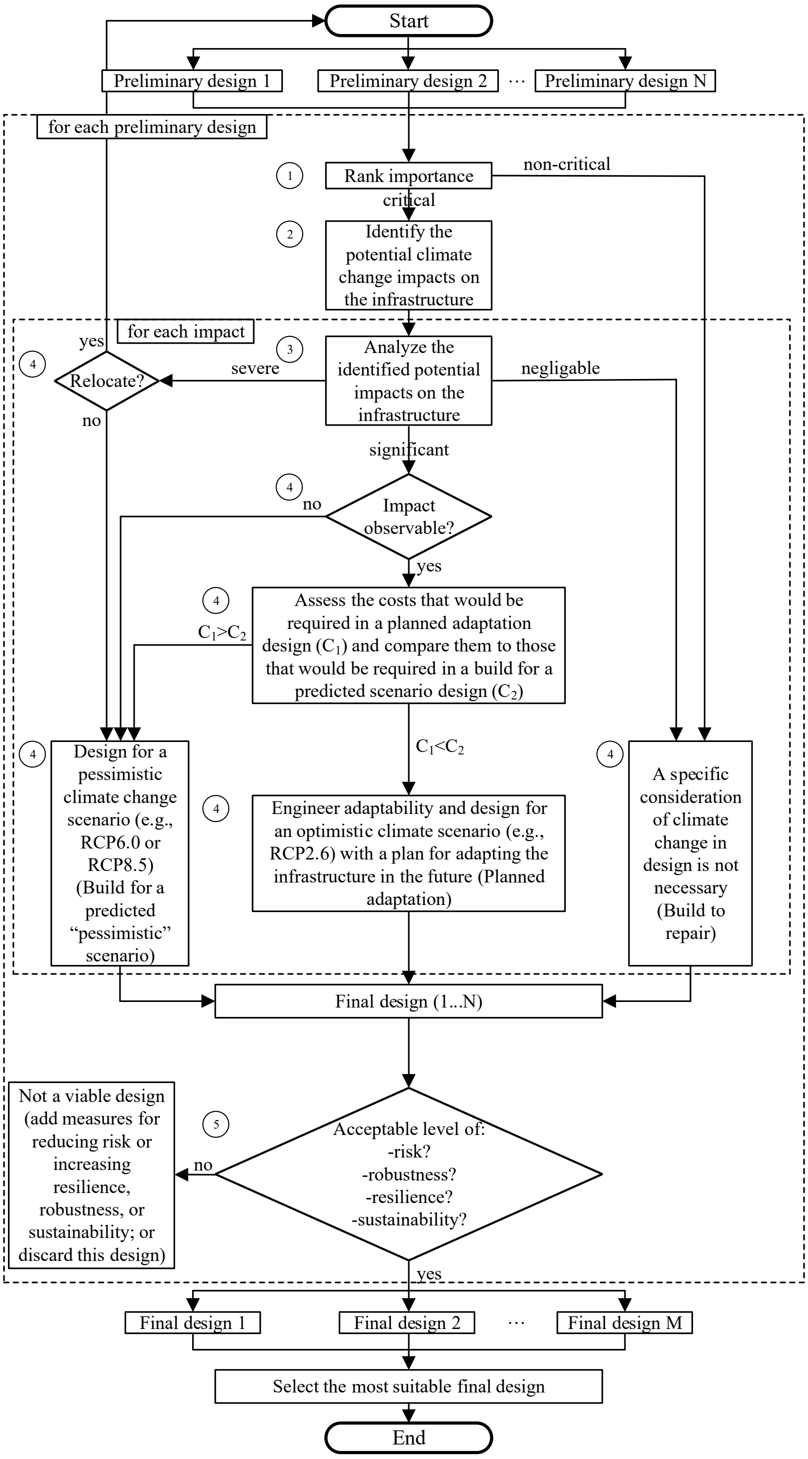

Figure 2. Conceptual framework for considering the risks of climate change in the design of built infrastructure assets; circles on the top left of each node represent the stage the node belongs to.

3.1. Stage 1: Importance Ranking

The first stage of the proposed framework is to rank the importance of the infrastructure asset being designed. Several methods for establishing this ranking for bridges exist and are already being used by varying departments of transportation. For instance, Rowshan et al. and Smith et al. [112,113] proposed a method that can be used for ranking the importance (or criticality) of highway infrastructure assets such as bridges and tunnels. Their suggested method is based on 14 different importance criteria, e.g., military importance, replacement cost, and replacement time. To reflect the relative significance of each criterion, a value ranging from 5 to 1 is assigned to each of them and the score of each infrastructure asset is calculated by adding up the values of the criteria it satisfies. A screening criterion can then be used to select the most important infrastructure assets based on the obtained scores. Another example is provided in [114], which proposed 22 different criteria that can be used to rank the importance of a bridge infrastructure; for example, whether it lies on a hurricane evacuation route or not, whether it supports urban centers or not, and the average daily traffic (ADT). In their study, it was shown that the ADT is a good indicator of bridge importance. Other criteria that have been proposed include the detour length and the symbolic significance of the infrastructure [113,115]. Table 1 presents some of the commonly used importance ranking criteria for bridge infrastructure which have been proposed in previous literature. These criteria are suggested to fulfil the aim of this stage of the framework.

Based on the output of the importance ranking stage of the proposed framework, it is decided whether a specific consideration of climate change is needed or not. For assets deemed non-critical, a specific consideration of climate change in design is considered unnecessary and hence a build to repair design strategy is chosen based on current design provisions. On the other hand, assets deemed critical require direct consideration of climate change in their design.

Table 1. Commonly used importance ranking criteria for bridge infrastructure, examples.

Criterion	Reference(s)
Average daily traffic (ADT)	[1,2]
Detour length	[2]
Replacement cost	[3,4]
Replacement time	[3,4]
Military importance	[1,3,4]
Hurricane evacuation route (yes/no)	[1]
Hazardous materials route (yes/no)	[1]
Evacuation route for nuclear incident (yes/no)	[1]
Supports urban centers (yes/no)	[1]
Symbolic importance	[3,4]

3.2. Stage 2: Identification of the Potential Climate Change Risks

Several methods of risk identification can be found in the literature [116]. Kaplan et al. [116] summarize five such methods, namely: failure modes and effects analysis (FMEA); hazard and operations analysis (HAZOP); event trees (ET); fault trees (FT); and anticipatory failure determination (AFD), and additionally introduce hierarchical holographic modelling (HHM) as an alternative method. As stated in [116] the risk scenarios identified during the risk identification process should be "complete". Providing an as-complete-as-possible list of risks at this stage of risk assessment has been highlighted by several other researchers [117,118]. For instance, Chapman [117] mentions that risk identification should aim at "identifying as exhaustively as practicable" risks. It should be noted that there is no single "best method" for risk identification [119] and to meet the "completeness" criterion an appropriate combination of different methods is often needed. Failure to meet the "completeness" criterion can lead to so-called ontological uncertainties (i.e., uncertainties arising from the unknown and the unexpected [120]).

Nasr et al. [3] identified potential climate change risks to bridges in general. The authors used a combination of three methods for identifying the potential climate change risks: (1) reviewing the relevant published literature; (2) reviewing documented cases of bridge malfunction, damage, or failure and investigating possible connections between these cases and the projected climatic changes; and (3) trying to elaborate scenarios in which the projected climatic changes would affect the performance and/or safety of bridges. Examples of the climate change risks for bridges identified in [3] include accelerated deterioration, increased scour rates, permanent inundation due to SLR, and increased drainage problems. Examples of other studies that aimed to identify the potential risks of climate change on infrastructure assets are [2,121,122].

3.3. Stage 3: Analysis of the Potential Climate Change Risks

After identifying the potential climate change risks for the infrastructure asset under consideration, the next stage of the proposed framework is the analysis of these risks. The aim of this analysis is to distinguish between severe, significant, or negligible risks. A prioritization method which can be used for this purpose is proposed in [123]. In this method, the following representation to describe climate change risk for bridges is adopted [4,123]:

$$R = P(H) \cdot P(E|H) \cdot P(D|E \cap H) \cdot C(D) \tag{1}$$

where R is the risk value, $P(H)$ is the potential change in a climatic parameter within a certain reference period (referred to as hazard), $P(E|H)$ is the probability of an adverse impact caused by the hazard (referred to as impact), $P(D|E \cap H)$ (referred to as vulnerability) is the probability of a damage or a reduction in performance and/or safety given the hazard and the subsequent impact, and $C(D)$ is the consequences of that damage. In [123], the four components of Equation (1) are represented using indices that are then aggregated to establish a semi-quantitative ranking of the various risks. In that work the authors demonstrate the applicability of the proposed method for bridges but also mention the possibility of extending the method to include other infrastructure asset types. Other examples of climate change risk analyses for specific risks can be found in, e.g., [124–129]. It is worth noting, however, that the unavailability of climate change data often hampers the analysis of climate change risks.

3.4. Stage 4: Design Strategy Selection

Following the analysis of the potential climate change risks and categorizing them into severe, significant, or negligible, a decision can be made on which of the three design strategies (i.e., build to repair, planned adaptation, or build for a predicted "pessimistic" scenario) should be chosen. As previously stated, for risks viewed as negligible, a build to repair strategy should be selected as the effect of climate change on these risks is considered insignificant [19]. For non-negligible risks, the framework directs the designer to select one of the other two design strategies.

For risks considered to be severe, relocating the infrastructure asset is recommended. If this is deemed unfeasible, a build for a predicted "pessimistic" scenario strategy should be opted for. On the other hand, for risks categorized as significant, the framework first considers whether the risk is observable or not. Observability, in this context, refers to whether the risk (1) can be detected and (2) whether intervention is possible before damages occur to the infrastructure asset. For instance, risks caused by gradual changes (e.g., sea level rise, melting permafrost) are considered observable while risks of sudden extreme events (e.g., storms, floods) are considered unobservable [111]. If the risk is found to be unobservable, then a planned adaptation strategy is not appropriate. This is since, as previously mentioned, this strategy requires continuous monitoring. Thus, for significant unobservable risks, a build for a predicted "pessimistic" scenario strategy should be selected. Alternatively, if the risk is observable, the designer should assess and compare two costs: (1) the cost of the planned adaptation design (C_1) and (2) the cost associated with a predicted "pessimistic" scenario design (C_2). C_1 should include the cost for engineering adaptability in the initial design (C_{11}), based on an optimistic scenario (e.g., RCP2.6), and the estimated cost of upgrading to accommodate a more pessimistic scenario which unfolds in the future (C_{12}). Noting that C_{12} depends on the climate scenario which unfolds in the future, it should be assessed as a weighted average for the different possible climate scenarios. However, as there is no consensus on the probabilities of the different climate change scenarios, expert elicitation [130] may be used for assigning plausible weights. Furthermore, as this cost is projected in the future, a suitable discount rate should be used in assessing C_{12}. If C_1 is found to be more than C_2, the build for a predicted "pessimistic" scenario strategy is favored. On the contrary, if it is found to be less than C_2 a planned adaptation strategy is selected. If both costs are approximately equal, neither of the two strategies is favored over the other and other relevant factors may determine which design solution should be chosen. Following the choice of the design strategy, the final design of the infrastructure asset is carried out. It should be highlighted that, irrespective of the chosen design strategy, the final design should have sufficient robustness/resilience to withstand unforeseeable risks that were possibly missed in the identification stage (see Stage 5).

3.5. Stage 5: Evaluating the Final Design

The last stage of the proposed framework aims at evaluating the final design considering the different climate change scenarios (i.e., RCP2.6, RCP4.5, RCP6.0, and RCP8.5). Traditionally, codes of practice have been developed to ensure that structures have an acceptable prescribed level of safety in a cost-efficient manner. However, it has been recently highlighted that current code provisions do not address important issues related to long-term infrastructure management and performance [131]. Hence, Sánchez-Silva [131] proposed that code provisions should be supplemented with additional requirements (see Section 2). In line with this proposal, the final design in the current framework is evaluated with regards to the following complementary perspectives: (1) risk acceptance requirements (is the infrastructure asset safe enough?), (2) robustness requirements (is the infrastructure asset robust enough?), (3) resilience requirements (is the infrastructure asset resilient enough?), and (4) sustainability requirements (is the infrastructure sustainable enough?).

Evaluating the final design of the structure results in several acceptable final designs, as shown in Figure 2. These possible final designs should be compared in terms of their costs, risk, robustness, resilience, and sustainability and the most suitable alternative should be selected. In practice, other factors which cannot be explicitly accounted for may also be of significance (e.g., construction traditions, access to materials). The different stages of the proposed framework are detailed in Figure 2.

4. Challenges and Research Needs

The current article proposes a conceptual framework for considering climate change risks in the design of infrastructure assets. However, there are several challenges that impede the application of this conceptual framework in practical settings. The following challenges and recommended research directions are identified (the relevant stages of the framework which are impacted by these challenges are also indicated):

- A major challenge in designing infrastructure assets for an uncertain climate is data availability. This problem applies to climate change projections as well as other data needed in the proposed framework. For example, data availability has been highlighted as a major problem in assessing the sustainability (e.g., using LCA) and resilience of infrastructure assets [77,132] (Stages 1, 3, 4, 5).
- Meeting the "completeness" criterion mentioned in the identification stage is a challenging and unverifiable task. Hence, some potentially significant climate change risks may go unidentified and be consequently unaccounted for in the design. Kaplan and Garrick [133] cite the criticism of a reactor safety study [134] (in which probabilistic risk assessment was first applied to large technological systems [135]) to exemplify

this issue. Assuring that the infrastructure asset has an acceptable robustness and resilience can control the consequences of such unforeseeable risks (Stage 2).
- Large uncertainties characterize climate change risks on infrastructure assets. Reducing these uncertainties can significantly facilitate the consideration of climate change risks in the design of infrastructure assets (Stage 3).
- For the planned adaptation design strategy, ways to engineer adaptability in the initial design of different infrastructure asset types for the different climate change risks need to be identified and further researched (Stage 4).
- Noting that, as mentioned in the discussion under risk acceptance requirements, rational risk acceptance criteria can be formulated based on the LQI concept which depends on, e.g., the GDP per capita [52–56] and considering that the different RCP scenarios portray drastically contrasting images of the future in terms of, e.g., population growth and economic development [14], the following question arises: Should uniform acceptance criteria be used across the different climate change scenarios when assessing climate change risks on infrastructure assets? (Stage 5).
- Establishing probabilistic robustness, resilience, and sustainability acceptance criteria is needed [77,91]. It should be noted that the challenge concerning the suitability of uniform acceptance criteria mentioned in the previous point is also relevant here (Stage 5).
- It has been observed that there is a gap in communicating resilience from research to practice which often results in inevitable subjectivities [78,136–138]. Furthermore, existing gaps in resilience assessment are still being addressed by the scientific community (e.g., resilience assessment of infrastructure assets subjected to multiple hazards [139]). We presume that these issues also apply, at least to some extent, to both robustness and sustainability. Therefore, refining these concepts and their consideration in standards is needed to remove possible ambiguities and subjectivities as well as to facilitate their transition into practice (Stage 5).
- It has been mentioned that existing LCA standards allow for the use of various LCA tools and approaches and hence the results of LCA are often difficult to compare [132]. Furthermore, societal aspects of sustainability are difficult to capture and often impose choices which contradict the better environmental and economical solutions [95]. Other limitations of LCA can be found in [132,140,141]. Hence, further research addressing these limitations is needed (Stage 5).
- Clarifying the relationship between risk, robustness, resilience, and sustainability is required. For instance, although it has been mentioned that the objectives of resilience and sustainability may, in some cases, be in conflict [77,91], it has also been noted that some design solutions can improve both objectives simultaneously [91,142,143]. Identifying these design solutions can be very valuable (Stage 5).
- Practical guidelines on which design choices are more/less robust, resilient, and sustainable are needed for the different infrastructure asset types (Stage 5).
- Developing innovative designs, construction techniques (e.g., accelerated bridge construction (ABC)), and materials that increase the sustainability of infrastructure without compromising its safety, robustness, and resilience is desirable. For example, the use of high strength materials (HSM) for the main load carrying members has been recommended in [105] to increase the sustainability of bridges. However, Skoglund et al. [144] recently observed that, in comparison to previous regulations, current regulations may be more discouraging to the use of such materials (Stage 5).
- Methods for increasing the recyclability of infrastructure and increasing the use of recycled materials in their design should be further investigated and promoted [105] as options for improving sustainability (Stage 5).
- Relevant concepts such as planned obsolescence, which advocates the shortening of infrastructure lifetimes and is defined in [145] as "planning practices based on the view that conditions may change, and an awareness of potentially creating path dependencies that may complicate future adaptivity in light of potential changes

regarding functions, demands, and Earth systems" should be further investigated. Ongoing important discussions in this regard can be found in [145–148] (All stages).

5. Conclusions

Climate change renders some fundamental built infrastructure design assumptions, e.g., climate stationarity, invalid to a large extent. In addition, large uncertainties characterize climate change projections and their potential risks on the built environment. This imposes a challenge to infrastructure designers and makes the task of delivering reliable and safe infrastructure in the light of a changing climate more difficult. First steps towards addressing this challenge should include: (1) developing a conceptual framework that captures the different possible design choices and gives guidance on how the problem can be approached in a rational manner and (2) identifying the challenges hindering the application of this conceptual framework in practical settings. This study proposes a five-stage conceptual framework that addresses the first of these important issues, currently lacking in the literature. The five stages of the proposed framework are: importance ranking, identification of the potential climate change risks, analysis of the identified climate change risks, design strategy selection, and evaluation of the final design. The study also addressed the second issue by outlining important challenges and feasible research directions to facilitate the application of the proposed conceptual framework in practical settings, and its further development, in the future for improved built infrastructure design in an uncertain climate.

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