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Key challenges and opportunities in transitioning towards road bridges with reduced carbon emissions – Perspectives in Switzerland

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Abstract

The construction sector is a major contributor to CO_2 equivalent emissions, responsible for approximately 37% of global and 23% of Switzerland's total emissions. Addressing this substantial carbon footprint requires innovative and sustainable materials, advanced construction technologies, and comprehensive stakeholder engagement. This paper discusses the key challenges and opportunities in transitioning towards reduced carbon emissions within the construction sector, focusing on the Swiss industry and road bridges as a case study. An extensive dataset of Swiss road bridge infrastructure is assessed to understand the current state in Switzerland. An engineering-oriented critical review of high-performance materials such as non-metallic reinforcements, lower impact concrete mixtures and timber products is made in comparison to established construction materials. Circular principles and design for disassembly are explored as strategies for reducing environmental impact. This paper identifies the critical role of availability of early-stage information regarding environmental impact, standardization of emerging materials and technologies, and stakeholder engagement in driving the construction sector towards practices with reduced carbon emissions. Emphasis is put on the requirements and alternatives for achieving reduced carbon emissions in newly constructed bridges, while the potential for extending the service life of existing bridges and its importance for achieving net-zero infrastructure goals is acknowledged but not explored.

Keywords: Net-zero construction, Transportation infrastructure, Road bridges, Structural engineering, Net-zero emissions.

1 Introduction

Climate change is becoming an increasingly pressing global concern and the impact of civil infrastructure on CO_2 equivalent (CO_2-eq) emissions and greenhouse gas (GHG) levels cannot be overlooked. According to information currently available, the construction and operation of civil infrastructure is responsible for 37% of energy- and process-related CO_2-eq emissions globally each year, 11% of which resulted from manufacturing building materials and products such as cement and steel [1].

Within a Swiss perspective, the construction sector has been responsible for about 23% of the total CO_2-eq emissions [2] of 41.6 Gt CO_2-eq in 2022, as illustrated in Figure 1, and is therefore a primary target in the transition to circular, net-zero processes. When presenting GHG emissions, the term CO_2-eq is used where the source is not solely due to direct CO_2 emissions, e.g. limestone calcination.

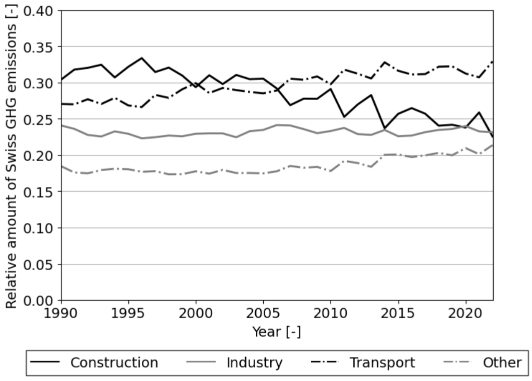

Figure 1. Evolution of the relative amount of greenhouse gas emissions in Switzerland since 1990 in four major sectors in accordance with the CO_2 Ordinance [3].

The construction industry is a vast and multifaceted sector, comprising various stakeholders of manufacturers, owners,

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engineers, architects, contractors, and regulatory bodies. Each stakeholder group operates within its own set of dynamics, decision-making patterns, and priorities, which can sometimes lead to conflicting interests and challenges in implementing sustainable practices. Moreover, the industry's high reliance on emission-intensive materials such as concrete, steel, and asphalt further complicates efforts to reduce its carbon footprint. These materials not only contribute substantially to CO_2-eq emissions during manufacturing but also pose challenges in terms of disposal and recycling at the end of their service life.

Despite growing awareness of the need for sustainability in construction, the cost and speed of construction and the cost for maintenance remain primary determinants in decision-making processes. However, achieving a paradigm shift towards sustainable construction practices requires overcoming these barriers, despite the fact that the construction products regulation (CPR) of the European Union has stated sustainability as a "basic requirement" [4] already for quite a time. According to the CPR, sustainability is considered equally important as other basic requirements, such as mechanical resistance, safety in case of fire or safety and accessibility during use.

In order to drive change, there needs to be accelerated development and adoption of low-CO_2 materials that offer performance comparable to traditional materials but with reduced maintenance requirements or initial costs. Additionally, rethinking design concepts to prioritize sustainability and longevity can also play a significant role in reducing the carbon footprint of construction projects. In recent years, innovative solutions such as Carbon Capture, Utilization, and Storage (CCUS) technologies have emerged as promising tools for mitigating CO_2 emissions. CCUS involves capturing CO_2 from industrial processes, such as cement production, and either utilizing them for beneficial purposes or storing them underground or in man-made materials to prevent their release into the atmosphere.

In response to the urgent need for decarbonization of the construction sector, the Board of the Swiss Federal Institutes of Technology and Research Institutes in the ETH Domain (ETH-Board) has established the Swiss Center of Excellence on Net Zero Emissions (SCENE[#1]). As part of its six action areas, the action area "Efficient Technical Cycles" aims to support the decarbonization of the construction sector by providing decision-making tools and strategies, including design for disassembly and materials/component reuse, to building authorities and designers.

The action area aims to investigate various technical, environmental and societal aspects of existing and emerging technological trends and possibilities to reduce the environmental impact of the construction sector, or even potentially reach net-zero emissions. Since the sector comprises primarily national clusters with distinct regulatory frameworks and supply chains (with only certain suppliers and supporting industries having international components) [5] the project narrows its scope, starting with Switzerland as an example focus area. With appropriate adaptation of inputs, the adopted methodology described in the following section, namely inventory characterization, technology review, and synthesis for decision-making, can analogously be applied to other national or regional contexts.

Within the SCENE action area "Efficient Technical Cycles", solutions for the following topics are investigated with a focus from an engineering perspective:

i. a reduction in the use of CO_2-eq-emitting materials (e.g. concrete, steel) by advanced manufacturing processes and replacement with sustainable timber-based materials, by changing materials chemistry and processing and storing carbon in construction materials;
ii. material savings by using topologically optimized geometries for structural components instead of conventional prismatic geometries [6];
iii. use of digital fabricated components serving as permanent parts of the structure and allowing complex geometries [7, 8].

To illustrate the efficiency and suitability of existing and emerging construction materials, road bridges were chosen as examples. In the studies, it is assumed that building a new bridge is the only viable solution and all other alternatives with lower emissions [9], such as retrofitting existing infrastructure, have been assessed and found not feasible. While bridges may offset embodied emissions through use-phase savings by eliminating detours [10] , such benefits are location-specific and may potentially be counteracted by induced traffic. This study focuses on construction-related emissions and use-phase considerations are not addressed.

Road bridges were chosen due to their strict requirements regarding loading resistance and durability. The minimum strength requirement for bridges according to EN 1992-2:2005 [11] is C30/37, a grade also commonly used in building construction. Studies [12] have shown that some early 20th century road bridges remain in service despite having concrete strengths below this threshold, with durability governed in large part by construction detailing such as clear cover. Nevertheless, generalization of conclusions drawn from road bridges to conventional building construction is still only possible to a limited extent, as modern bridge construction typically employs higher material grades and is subject to more demanding durability provisions than buildings, where cladding and façades protect the load-bearing structure from weathering.

This paper addresses the question of how the characteristics of an existing infrastructure inventory combined with an assessment of available established and emerging materials and construction technologies regarding their environmental impact can be used to support early-stage decision-making towards designing infrastructures with reduced embodied

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[#1] www.scene-project.ch

carbon emissions. The approach is demonstrated on Swiss road bridges as a case study and follows three steps, as illustrated in the flowchart in Figure 2, which can also be applied to other structural systems and national/regional contexts.

First, bridge inventory datasets of the Swiss Federal Roads Office (ASTRA) and of 14 cantons are analysed to characterize the existing road bridge stock in terms of construction material, structural system, span, and width, and to identify representative bridge configurations that cover the majority of the Swiss road bridge inventory. Second, an engineering-oriented review of established and emerging construction materials and construction technologies is carried out, with the reviewed technologies selected based on their applicability to the identified configurations, their maturity, and their potential to reduce carbon footprint. Third, the findings from both steps are brought together to identify which options are most relevant for the dominant bridge types and to support decision-making by stakeholders involved in early project phases.

2 State of practice

To identify where decarbonisation efforts would have the greatest impact, a systematic understanding of past practice and current trends is essential. To this end, an analysis of the Swiss road bridge stock is presented in this section. By characterising the most common structural types, materials, and span ranges, the analysis establishes which configurations represent the majority of existing infrastructure in Switzerland and sheds light on which types of construction materials and technologies should therefore be prioritised for decarbonisation in future research. Established materials and stakeholder decision-making processes are also reviewed to provide context for the discussion of emerging technologies in Section 3.

2.1 Established methods and materials

Infrastructure, including road bridges, has strict regulations for constituent materials to ensure structural integrity, safety, serviceability and durability. The choice and treatment of materials such as concrete, reinforcing steel, construction steel, and timber play a vital role in determining the durability and robustness of a bridge subjected to environmental influences and mechanical actions for a service life of 80-100 years.

Concrete is the most widely used construction material globally, with estimated annual production volumes exceeding 10 Gm^3 worldwide [13] and approximately 16 Mm^3 in Switzerland [14]. In addition to its mechanical properties, such as strength and stiffness, which are defined in standards like SIA 262 [15], concrete must maintain these characteristics over time, especially when exposed to harsh environmental conditions. Standards such as SN EN 206 [16] define material, design, and construction detailing requirements to ensure satisfactory performance of concrete structures throughout their life cycle. These standards establish exposure classes, which consider factors like reinforcement degradation and concrete deterioration, to guide the selection of optimal material compositions and design-related requirements for each project.

Recycling concrete and using it as an aggregate for new concrete is a well-established practice specified in standards like SIA 2030 [17]. The use of recycled concrete as an aggregate for new concrete is subject to the same design requirements defined for new concrete in SN EN 206 [16] and SIA 262 [15].

Structural steels come in various shapes such as rolled profiles or sheets and have been used extensively in bridge construction. Their application is regulated by standards such as SIA 263 [18], which provide extensive information on strength and stability, but also corrosion protection for ensuring the durability of structural components. Attention to structural details such as air-tightness in inaccessible elements is crucial for durability and minimal efforts in maintenance. Structural detailing is also an important criterion for the fatigue performance of welded connections.

Mechanical requirements for structural timber are defined in SIA 265 [19] and in a series of European standards, such as SN EN 338 [20] and SN EN 14080 [21]. Shielding timber from weathering and humidity by covering the members is essential for durability [22]. As of today, softwoods, and softwood-based laminated veneer lumber (LVL) and glued-laminated timber (GLT) dominate the market. The future trend is assumed to change related to the changing climate conditions in Swiss and European forests. Both species, Norway spruce (*Picea abies*) and European larch (*Larix decidua*) are expected to strongly decrease in forest stocks, whilst fir (*Abies alba*) and deciduous species generally are expected to increase their share in stock during the current century [23].

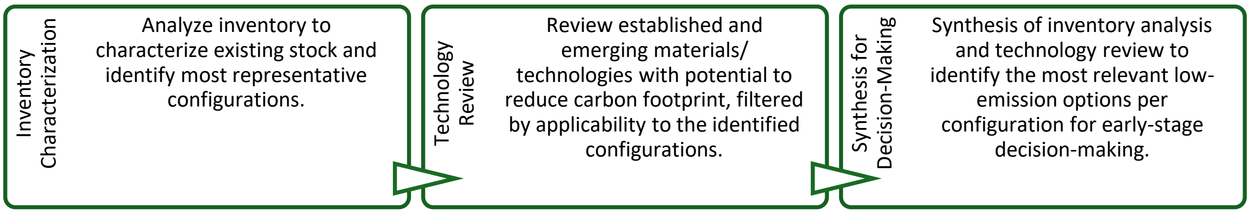

Figure 2. Analytical approach followed in this work, with Swiss road bridges as a case study. With adaptation of input, the same steps can be applied to other national or regional infrastructure inventories.

2.2 Design alternatives available to stakeholders

The construction of road bridges involves numerous stakeholders, including but not limited to government agencies, local communities, architects, transportation companies, engineering companies and construction firms. Studies have shown that emission reductions of up to 80% are achievable when decisions are coordinated across the complete chain of stakeholders, namely from material producers to engineers and construction companies, rather than concentrated on any single actor [24]. In the early stages of construction projects, high impact decisions (and relevant parameters) from the so-called direct stakeholders, organizations that have substantial managerial responsibility or financial investment in the project [25], can be listed as follows:

- where the bridge is situated (bridge length, span length, expected traffic volume, actions on the structure),
- dimensions of the bridge (purpose and number of lanes, bridge length, clearances over/under the bridge),
- properties of the bridge (structural system, choice of materials, maintenance concept, span length, number of spans, speed and cost of construction, environmental impact).

Decisions on where the bridge is situated and the dimensions and properties of the bridge have a direct impact on the necessary bridge length and bridge width. The influence of the bridge's size on costs and emissions is rather clear as larger bridges require more materials, assuming similar substructures. However, the influence of structural system and material choice on costs and emissions, despite having a high impact, is not as clear since it depends on various factors. Especially early cost estimates during pre-design stages, that also form the basis for feasibility, comparison, budgeting and early-stage decision making, are generally made without detailed plans and specifications [26]. Easy-to-use and reasonably accurate methods for preliminary cost estimation have been developed for infrastructure projects by using data from previously completed projects and from expert opinions [27]. The relationship between the level of available information and the influence of decisions on the total costs can be qualitatively described by the cost-influence curve [28] qualitatively shown in Figure 3.

It can be postulated that the life cycle environmental impact committed follows a comparable trend to costs committed, with the chance to influence being highest in the conceptual design phase and strongly decreasing as the project progresses. This by no means implies that costs and environmental impact are correlated with each other but implies that stakeholders hold a similar level of influence along the project development stages not only regarding the costs, but also the environmental impact. However, due to the lack of established environmental impact data and experience of completed construction projects, this information is not yet available to key decision makers as readily as cost-related information. To this end, it is important to produce indicative data from computational and lab-scale experimental research.

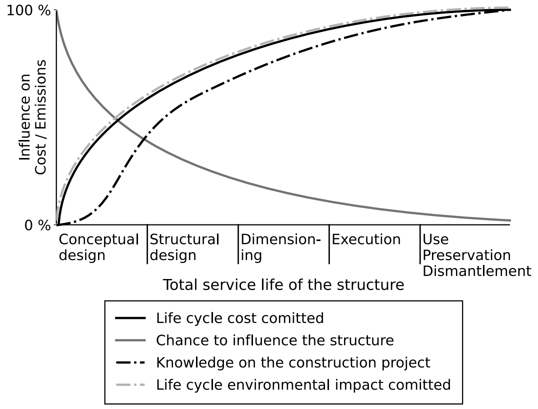

Figure 3. The relationship of existing knowledge about and possible influence on construction cost [28] and environmental impact during different project development stages.

2.3 Swiss road bridge stock

To identify the potentially most widely applicable tools, methods, and decisions towards road bridges with reduced carbon emissions and to have a starting point for further analyses, it is crucial to understand the existing practices, including the choice of materials, bridge typologies, and frequently encountered spans. To this end, bridge inventory datasets of the Swiss Federal Roads Office (ASTRA) and of 14 cantons (administrative divisions) were analyzed, containing more than 3600 entries of highway bridges (> 255 km) from all around Switzerland, and more than 4800 entries of cantonal road bridges (> 145 km) covering roughly 75% of the Swiss road network, with information on material, bridge type, span, bridge length and width, road type, and other general features for each bridge. The spatial distribution of these bridges is shown in Figure 4. It has to be noted that the information available in these datasets is not detailed enough to carry out a Life-Cycle-Assessment (LCA).

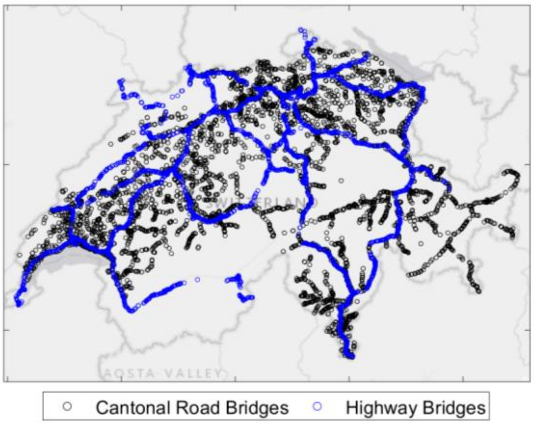

Figure 4. Spatial distribution of the analyzed cantonal (in black) and highway (in gray) road bridge inventory databases available in Switzerland.

As a first step, the very heterogeneous dataset was prepared for statistical analysis. For this purpose, inaccurate or missing entries were identified**,** removed and definition of material and structural systems were all collected under unified categories. At the end of this process, around 2000 entries of highway bridges (> 160 km) and around 4800 entries of cantonal road bridges (> 125 km) were available for statistical analysis.

The average age of the investigated highway bridge dataset is roughly 47 years, whereas the cantonal road bridge dataset reveals an average of 76 years. It can be seen from Figure 5 that almost 95% of the highway bridges and 85% of the cantonal road bridges were constructed before the introduction of the modern[#2] SIA 261 (2003) standard specifying the actions to be accounted for the design of structures [29], as well as of most of the modern standards covering the aspects related to the construction materials. Interestingly, the percentage of both "old" and "new" bridges are substantially higher within the cantonal road bridge inventory. The investigated dataset features cantonal road bridges from as early as the 16th century, but only a narrow window of rapid development for highway bridges between 1950-1990. Expansion of the Swiss local road network and replacement constructions induce a substantially higher percentage of new bridge constructions within the cantonal road network than within the highway bridges.

Figure 6, depicting bridge types based on typology and material, reveals that nearly 90% of the investigated highway bridges and 80% of the cantonal road bridges in Switzerland have been constructed using either reinforced or prestressed/post-tensioned concrete. A significant number of (natural stone) masonry bridges in the subset of cantonal bridges are attributed to the older age of the cantonal road infrastructure.

Among the main bridge typologies, girder and frame bridges emerge as the most common within the highway bridges dataset. Moreover, a significant number of simple beam, slab, and strut-frame bridges exist in the Swiss highway bridge landscape. Despite major similarities, the cantonal roads differ by featuring a significant amount of arch bridges yet again owing to the age difference. In any case, steel and composite bridges are notably less common compared to reinforced concrete, prestressed/post-tensioned concrete and (natural stone) masonry. While examples of such bridges exist, they constitute a minority in the overall bridge inventory. This emphasizes the prevailing "concrete culture" in Swiss bridge construction as opposed to the steel-dominated US landscape [30], likely attributed to concrete's proven durability and cost-effectiveness for small to medium spans.

Henceforth, simple statistical values, such as sample mean values and highest (probability) density intervals (HDI) are provided here to form a basis for discussion. HDI is defined as the narrowest interval containing a given probability density [31] and is shown by vertical lines in the histograms to cover 80% of the analyzed samples. Within the investigated cantonal road and highway databases, reinforced concrete (RC) bridges have an average span of about 13 and 18 meters respectively, while prestressed concrete (PC) bridges tend to have a longer average span of about 27 and 33 meters, respectively (Figure 7). Similarly, based on Figure 8, the average widths of cantonal road and highway bridges stand at 14 and 17 meters, respectively.

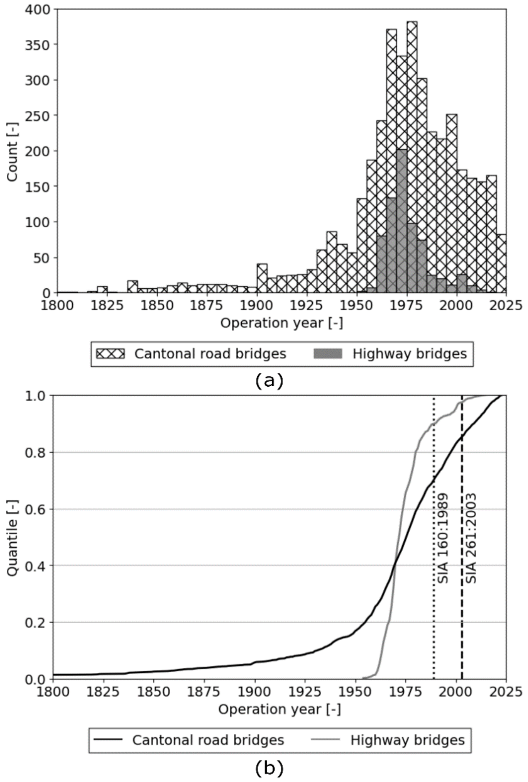

Figure 5. Histogram (a) and cumulative distribution function (b) of age of cantonal road and highway bridges. The two vertical lines represent the publication year of the relatively modern Swiss standards for actions on structures.

Relying on these results, the most common value range for various parameters are laid out, which will serve to understand the Swiss road bridge infrastructure landscape. A representative cantonal road bridge would possibly consist of a two-lane bridge deck, likely out of reinforced or prestressed/post-tensioned concrete, with one-to-two spans and a span length ranging between 10-40 m. Similarly, a highway bridge would likely consist of a three-to-four-lane bridge deck, likely out of prestressed/post-tensioned concrete, with one-to-two spans and a span length ranging between 10-50 m.

[#2] Dynamic amplification factors were for the first time implicitly considered as a constant in the acting forces in this standard, opposed to previous span-dependent or explicitly defined constants. This implicit definition has resulted in higher vehicular traffic loads and also greatly limited the possibility to reduce this factor in the bridge design.

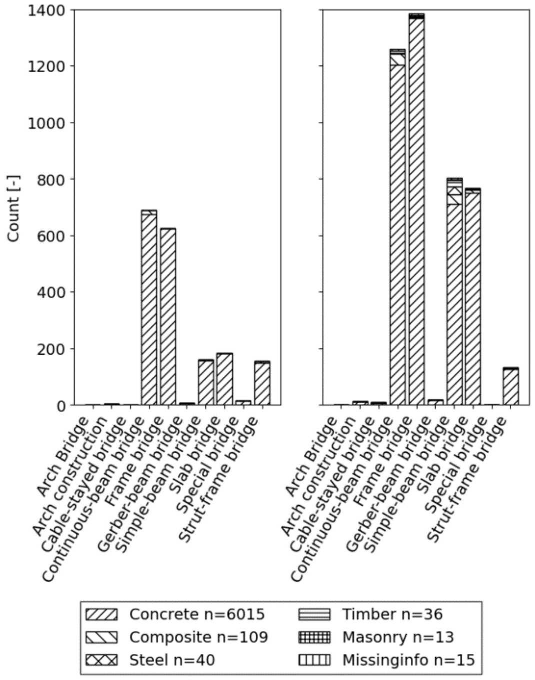

Figure 6. Distribution of material and typology of the available highway (left) and cantonal (right) road bridge stock.

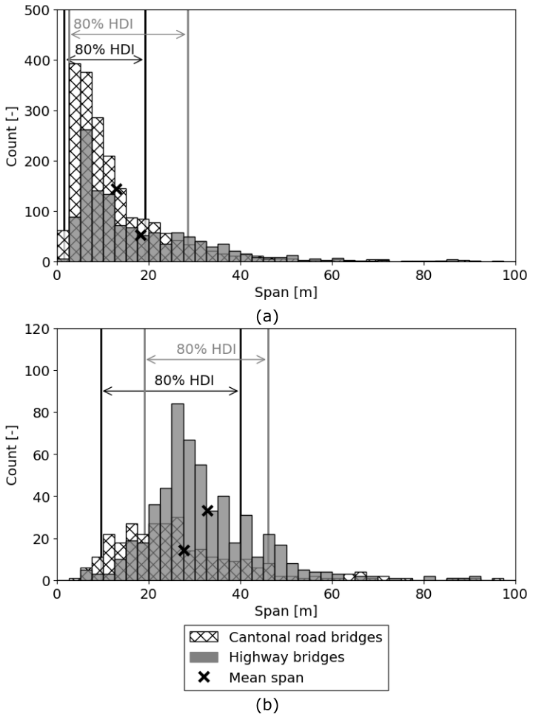

Figure 7. Histograms of span lengths of cantonal and highway road bridges made of (a) reinforced concrete and (b) prestressed concrete.

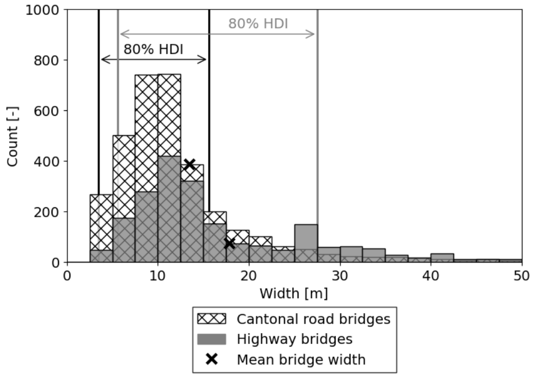

Figure 8. Histograms of bridge widths of cantonal and highway road bridges.

In addition to the above provided analysis, a total of 99 timber road bridges are currently in use in Switzerland, all with a vehicle load limit of at least 10 t, as shown in Figure 9 [34 - 42]. The spans of these bridges range from 9.5 m to 51 m, with the majority being shorter than 35 m. The vehicle load limits are predominantly concentrated at 28 and 40 t. Notably, no bridge built prior to 1990 is rated for vehicle loads of 40 t or above.

The majority of the timber road bridges currently in use in Switzerland were constructed after 1970, as can be seen in Figure 10.

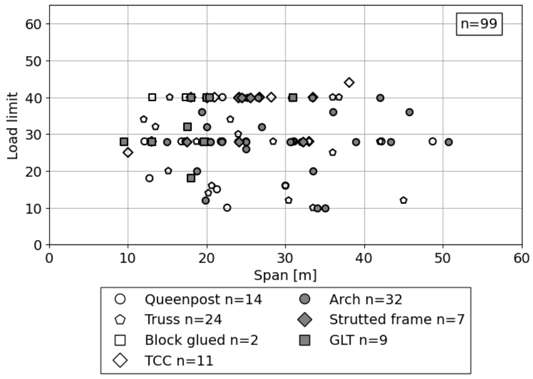

Figure 9. Span and load limits of timber road bridges in Switzerland with various structural systems.

The average span of the timber road bridges in Switzerland, which is approximately 26 meters, is comparable to that of cantonal prestressed concrete bridges. Interestingly, the difference between all bridges and those with a vehicle load limit of 40 t or more does not vary substantially, as shown in Figure 11. The average width of timber road bridges, between 5 m and 6 m is smaller than the one of concrete bridges, as shown in Figure 12. This indicates that timber road bridges comprise a larger proportion of one-lane bridges compared to the overall Swiss road bridge inventory.

It should be noted that bridges with one or two lanes differ significantly from an engineering perspective, with single lane bridges having loading scenarios with smaller eccentricity of acting traffic loads. Therefore, only existing two-lane bridges are considered in the following analyses. Even though a vehicle load limit of 40 t is highly desired within the road network, two-lane bridges that do not satisfy this criterion were also included in the analysis. The criteria are marked and shown with grey background in Figure 13. In total, out of the 12 Swiss timber road bridges, which match the aforementioned criteria, there are four timber concrete composite (TCC) bridges, one truss bridge, two GLT bridges and five arch bridges.

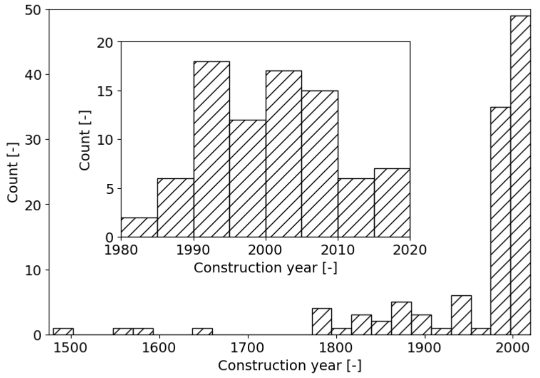

Figure 10. Year of construction of timber road bridges still in use in Switzerland. Four bridges were built before 1700, most bridges were built after 1980.

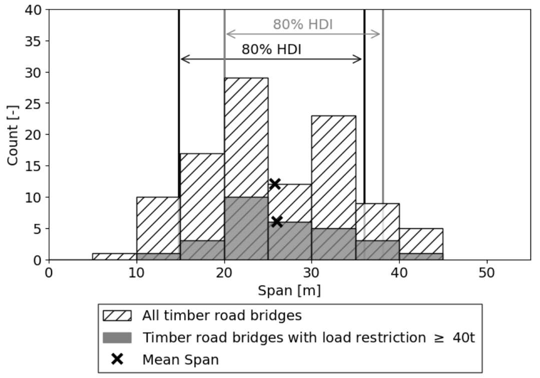

Figure 11. Span of Swiss timber road bridges still in use: all bridges and bridges with a vehicle load limit of at least 40 t.

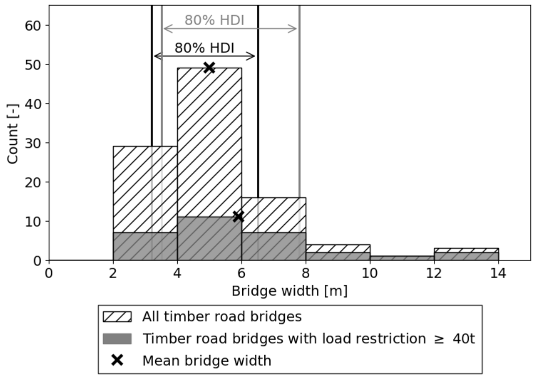

Figure 12. Width of Swiss timber road bridges still in use: all bridges and bridges with a vehicle load limit of at least 40 t.

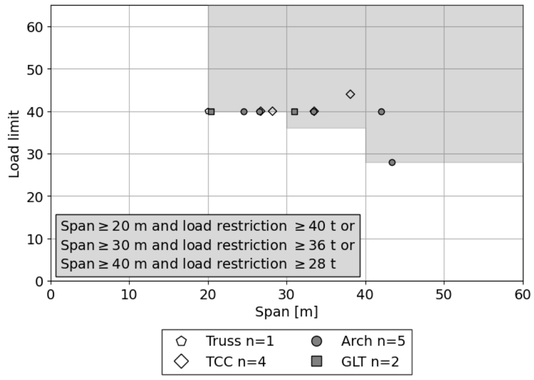

Figure 13. Span and load limits of Swiss two-lane timber road bridges with high performance, characterized by the grey shaded area, disaggregated by structural system.

Due to the risk of accidental vehicle impact, bridges supported by a load bearing structure, which is situated below the bridge deck are given preference to. The load bearing structure of most of the existing Swiss timber truss bridges and arch bridges is located at least partially above the bridge deck. The load bearing structures of TCC bridges and GLT bridges are generally located below the deck. Such typologies are considered advantageous with regard to a possible accidental impact.

3 Advanced technologies and prospective engineering options

The requirements in the construction materials when designing road bridges were explained in Section 2.1, highlighting the essential properties and the criteria necessary for ensuring the structural safety, serviceability and durability of road bridges.

The utilization of high-performance materials and advanced technologies has the potential to reduce material consumption and/or accelerate construction times. However, a reduction in material use does not necessarily guarantee lower CO_2-eq emissions, as the embodied carbon of advanced materials may be higher due to changes in material composition and production methods. Therefore, a reliable quantification of CO_2-eq emission reductions or cost impacts would require a full structural design and life cycle assessment tailored to specific project conditions, which falls outside the scope of this investigation. Thus, this section provides an overview of materials and concepts that may help in decarbonisation of road bridge construction.

The following subsections cover materials and construction concepts that are either already established with possibilities for wider adoption, or sufficiently mature to be considered for near-term application in road bridge construction. The presented concepts are organized along major areas, recycled materials and carbon capture, higher performance materials, digital fabrication, and circularity, and aim to provide a feasible range of options rather than an exhaustive catalogue. Three considerations guided the selection: i) applicability to at least one of the representative bridge configurations having been identified in Section 2.3, ii) demonstration at a minimum of pilot scale or commercial availability, and iii) potential to reduce embodied CO_2-eq emissions through lower emissions per functional unit or through lower material use. Within each area, the review goes into sufficient depth to allow an assessment of practical applicability, including current limitations. Where relevant, examples from Swiss practice are highlighted to reflect the national context of this study.

3.1 Carbon capture, utilisation and storage via recycled materials

As a sustainable construction practice, the reuse of materials serves an important role in promoting resource efficiency. Today, substantial effort is being made to develop and further refine various strategies for employing recycled materials. The integration of recycled concrete as an aggregate for new concrete is actually not an emerging idea and standardization in Switzerland is already established with SIA 2030 [17]. It was reported that by using recycled concrete aggregates, carbon emissions of concrete can be reduced by 7% [43] and maximize utilization of waste [44], although benefits may be partially offset if mix adjustments are required to compensate for reduced aggregate quality. Despite its environmental benefits, the industry adoption of recycled concrete as an aggregate for major load-bearing components is not established yet. Some concerns still remain, such as the uncertainty of potential contaminants from extracted materials and the lacking maturity of standardization.

Recycled aggregates can be even further utilized through mineral carbonation in concrete [45] or asphalt [46]. This process involves recycled concrete aggregates absorbing atmospheric CO_2 naturally during storage [47] or through accelerated carbonation under concentrated CO_2 conditions [48], already commercialized in Switzerland [49]. Besides aggregates, concrete slurry waste can also be carbonated and used as supplementary cementitious material [50]. A key advantage of mineral carbonation is that the bound CO_2 is considered permanently fixed as it becomes part of the mineral aggregates within the concrete. This process induces an improvement of concrete's mechanical properties [51] and can lead to an overall reduction of the geogenic CO_2 emission of 10–14%, however, carbonation also causes a reduction of the alkalinity which may lead to the corrosion of steel reinforcements [52]. These materials are potentially applicable across all representative bridge configurations identified in Section 2.3, as they do not require altering the structural system and are compatible with the concrete grades commonly used in road bridge design.

3.2 Higher performance materials

The integration of higher performance materials (i.e. materials with superior properties such as increased strength, durability, and robustness compared to conventional materials) within the construction industry practice can further enhance the shift towards low-emission and sustainable infrastructure development by minimizing material consumption, prolonging structure lifespans, and reducing maintenance demands. Moreover, materials that provide the same level of performance with lower environmental impact can also be classified as "higher performance" materials. A selection of such materials is presented within the following paragraphs.

3.2.1 Low-emission concrete

The main contribution of emissions from concrete stem from geogenic emissions [53], while the remaining emissions mainly originate from fuel consumption. In Switzerland, the yearly production of 40 Mt of concrete leads to 3.1 Mt CO_2 emissions (3.2% of all Swiss emissions) [54, 55]. These emissions are considered "hard to avoid" and are expected to remain steady until 2050 [55]. Although concrete has lower CO_2 emissions per unit mass compared to other building materials like steel, its lower strength-to-weight ratio means that larger quantities are required to achieve equivalent structural performance. When evaluated on a functional basis such as per unit load-bearing capacity, concrete does not necessarily outperform other materials, depending on the structural configuration and design efficiency [56]. This, combined with its extensive use results in a substantial overall environmental impact, as more concrete is used than any other building materials combined [57].

To reduce limestone calcination in cement production, new cementitious materials with clinker replacements like fly ash, burnt shale, slag, calcined clays, and ground limestone have been emerging. However, the supply of supplementary materials like fly ash and blast-furnace slag is limited and expected to decline. A promising composite cement blend includes clinker, calcined clay, and ground limestone, achieving high-performance concrete with reduced clinker content [58, 59]. Innovations like using carbonated wollastonite and alternative slags [60, 61] or integrating pyrolytic carbon from biomass (biochar) are also being explored. Despite possessing slightly lower compressive strength and stiffness compared to conventional concrete, preprocessing biochar into lightweight aggregates can produce concrete with adequate strength classes with net-zero emissions [62], which has already been commercialized as a product in Switzerland [63].

Another strategy relies on using cements that are not based on calcined limestone which do not cause geogenic emissions, i.e. MgO-based cements. Similarly, cements based on calcium-sulfoaluminates [64] have lower specific emissions from the raw materials and require lower temperatures for calcination [65, 66]. Despite the potential to become a negative CO_2-eq alternative to limestone-based cements, these materials are at a relatively early stage of development [67].

These alternative cement and concrete formulations are in principle applicable to all concrete road bridge configurations. However, for prestressed concrete bridges with higher strength requirements and stricter durability provisions, the available evidence on their long-term performance under the relevant exposure classes is limited, which currently restricts their use.

3.2.2 Fiber-reinforced polymers (FRP)

The high strength-to-weight and stiffness-to-weight ratio, corrosion resistance, light-weight nature, ease of handling and high durability [51] of FRPs reduce the need for heavy structural components, resulting in decreased transportation and workmanship [68] emissions during construction. Although the GWP of carbon-FRP rebars per unit mass is more than eight times that of steel reinforcement (19.7 vs 2.3 kg CO_2-eq/kg), considering the higher strength and lower density of CFRP, the reduced material quantities required can lead to approximately 30% lower total environmental impact in practical applications such as e.g. pedestrian bridges [69].

FRPs have been employed both internally and externally to constructions. Internal FRP reinforcements involve the use of fibers such as glass, carbon, or basalt, instead of the conventional steel reinforcement. These reinforcements are highly advantageous due to their exceptional resistance to corrosion and high strength [70], which makes them ideal for use in aggressive environments where traditional steel reinforcement might deteriorate and cause maintenance-based emissions, which have been estimated to amount to 40% of a bridge's emissions during its service life [71]. However, potential drawbacks include higher initial costs compared to conventional steel reinforcement, lower modulus of elasticity and their linear elastic brittle nature.

External FRP reinforcements, are typically composed of carbon fibers, and are often attached to the exterior surfaces of existing structures to enhance their strength and durability. External FRP reinforcements have been implemented to improve flexural, shear, and axial capacities of structural elements [72] and provide a lower environmental impact compared to the replacement of an existing structure [73].

3.2.3 Shape memory alloys (SMA)

Reinforced concrete structures often face limitations in span length due to cracking and long-term deformations (creep), as deformations reach unacceptable levels in slender structures with long spans. These problems can be solved by prestressing, where the stress from permanent loads is counteracted by forces from prestressing tendons [74].

As a promising emerging high-performance material, the incorporation of SMAs in bridge construction provides the potential to accelerate the prestressing process in concrete structures when compared to conventional tendons. The prestressing phenomenon in iron-based SMAs, termed the "shape memory effect (SME)," involves a reversible phase transformation between martensite and austenite phases, allowing the material to recover its initial shape post-deformation upon exposure to thermal stimuli, typically applied via resistive heating, or gas torch to temperatures of approximately 160°C. In situations where deformations are constrained from returning the material to its original state, it results in the creation of "recovery stress" [75 – 77]. With the development of low-cost iron-based shape memory alloys (Fe-SMA) [78] that perform well under short-term [79], as well as long-term [80] conditions, their financially feasible uses in civil engineering applications have significantly increased. A recent study substituted vertical reinforcements with Fe-SMA in a concrete truss bridge, which resulted in a reduction of the embodied carbon footprint by 25.9% compared to the reference specimen [81].

3.2.4 High strength steel

High-performance steel brings forth improved fatigue and corrosion resistance, leading to reduced material usage without compromising structural integrity [82] provided all stability verifications are satisfied. Such materials have already been employed in bridges worldwide, as e.g. the Akashi Kaikyo Bridge in Japan [83] and the Nesenbachtal Bridge in Germany [84]. Given the low share of steel bridges in the Swiss road bridge stock, the direct impact of high-strength steels on the overall studied inventory is limited. Their relevance increases for longer spans or in contexts where steel and composite bridges are more common, such as in the United States [33].

3.2.5 Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC)

UHPFRC provides a possibility to reduce overall material usage due to its very high compressive strength (150-200 MPa) and high tensile strength (7-15 MPa). Moreover, it performs very well under severe environmental conditions due to its low porosity and crack bridging properties and acts simultaneously as a waterproofing layer [85]. It can be used as a service life extending retrofit measure such as in the case of the Chillon Bridge in Montreux, Switzerland [86], as well as for new bridges, such as the Sempach Bridge in Luzern, Switzerland [87]. UHPFRC also seems to work well together with timber, the first examples of single-lane timber-UHPFRC composite bridges been already built. The Fruttli bridge (2020) spans 10 m and the Rigiaa bridge (2021) spans 16 m [88]. For new construction, the advantages of UHPFRC would be more pronounced for bridges where substantial reductions in cross-section dimensions can be achieved.

3.2.6 Hardwood products

The performance of timber bridges can be enhanced by using timber products of a higher strength class [20]. The strength classes used most frequently are GL24 and GL28 [36], which are made from Norway spruce (*Picea abies*) or white fir (*Abies alba*). Higher GLT strength classes available on the market are made from hardwood [19, 89]. European beech wood (*Fagus sylvatica*) is currently the most common hardwood in Switzerland [90]. Consequently, the properties of beech wood and beech GLT have been widely studied [91, 92] and have shown to offer promising mechanical properties. However, products from beech are not suitable for bridges which are service class 2[#3] according to current Swiss or European codes for the design of timber structures [93, 94]. A viable option for structural members of bridges is GLT made from European ash wood (*Fraxinus excelsior*), whose strength

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[#3] Service class 2 is characterised by a moisture content in the wood materials corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 85% for a few weeks per year. In service class 2 the average moisture content in most softwoods will not exceed 20% [93].

and stiffness properties have been investigated [95]. Structural European ash GLT members in higher strength classes such as GL40 and GL48 are already commercially available. Based on the spans of existing Swiss timber road bridges, hardwood GLT and timber-concrete composite systems are applicable to short-to-medium span cantonal road bridges, with spans of up to approximately 40 m. Their applicability to wider, multi-lane highway bridges has not yet been demonstrated in practice.

3.3 Digital fabrication

Digital fabrication technologies offer the means for reducing material consumption and enabling optimized novel structural geometries that would be impractical with conventional construction methods. For complex geometries, construction with digitally fabricated elements can achieve up to 50% reductions in environmental impact compared to conventional construction [96], though such findings are largely based on building components and their applicability to bridge infrastructure remains to be demonstrated. A key challenge for digitally fabricated concrete structures lies in reinforcement integration, as conventional steel reinforcements are incompatible with most additive processes. Currently, there are three main strategies available, namely printing with fibre-reinforced materials to eliminate discrete reinforcement, incorporating reinforcement during printing, and adding reinforcement in a separate step [97]. Early applications in bridge construction include the Gemert bicycle bridge in the Netherlands [98], which is a 3D-printed segmental structure connected via post-tensioning. Hybrid approaches that combine digital and conventional methods, such as digitally fabricated stay-in-place formworks, could offer a more immediate pathway to industry adoption for road bridges.

Formworks constitute a non-negligible part of material consumption and construction process for concrete structures. The prevalent industry standard for formworks primarily depends on timber or the so-called "reusable" formworks, with timber variants offering limited usability ranging between 2 to 10 times and "reusable" types allowing reuse of their surface 20 to 30 times [99]. The extent of reusability is constrained by the presence of inserts and additional components that necessitate modifications to the formwork surface. Furthermore, recycling these formworks becomes challenging in cases of material contamination.

While various digitally fabricated formwork technologies exist, their applicability to bridge infrastructure remains limited, primarily serving architectural purposes [100]. The inception of digitally fabricated permanent concrete formworks traces back to the late 1990s [101, 102], some commercialized services/products already rely on this principle. By printing a permanent in-place concrete outer shell as formwork, the conventional reinforcing and concreting processes can follow, leading to an idea that is familiar and thus more likely for industry acceptance compared to other methods [6, 7]. While the concept is not much different than conventional formworks, optimized geometries [103] can be built easily and present a lighter [104] and cost-efficient alternative to today's prevalent "high material use for lower workmanship cost" mentality [105]. Despite current challenges in design, production and quality control regarding reinforcements, interfaces and joints [98], real-world example of such a mixed-use bridge already exists in China [106]. The potential for digital fabrication would be highest for road bridges with high variations within the cross-section geometry, where digitally manufactured components and formworks could compensate the complexity of traditional methods.

3.4 Circularity of road bridge components

The circular economy is a promising approach to reduce the environmental impact by disassembling products in a manner that allows the reuse of parts in new products of the same quality [107]. After prevention of construction and retrofitting existing structures, reuse is considered to be the second best option according to the waste hierarchy [108]. From a structural engineering perspective, key aspects for a circular economy include the ease of disassembly and reuse, as well as the estimation of the residual capacity of disassembled components. Disassembly for reuse can be challenging if not already considered from the conceptualization phase of a structure's design. Additionally, the current condition of the component may be unknown if the influences on the structure were not documented and/or design information was not stored. To address this, the concept of Design for Disassembly (DfD) is gaining traction within the industry, which aims to facilitate the design of structures that can be easily disassembled, and conserving and curating detailed information about specific elements to facilitate their reuse [109, 110].

Despite an increasing rate of literature being published in this topic, there are still not too many works available dedicated to the reuse of existing structures and DfD of new structures in bridge engineering. Although each bridge is a unique infrastructure object, which may limit direct reuse, studies show that reusing existing bridge components, in certain cases, can still be a more sustainable and economically viable option than demolition [111]. However, the reuse of existing bridge components remains challenging in practice, as the load history, especially important for bridges due to fatigue, is often unknown. For new structures, research on DfD emphasizes the importance of joints as the most critical component for future reuse [109, 112 - 114]. Hence, in current practice, DfD might prove feasible for structurally simpler bridge configurations, where the number and complexity of joints is limited.

While keeping a similar DfD mentality in mind, but also considering robustness of bridges in seismically active areas, researchers have proposed bridge columns with replaceable plastic hinges made of engineered cementitious composite (ECC) or rubber reinforced with unbonded SMA bars, which was able to withstand drift demands exceeding 6% in shake-table tests [115]. As a next step, system level shake-table tests were conducted both before and after dis-/reassembly with minimal-to-no-repair, in order to demonstrate the feasibility of such an approach [116].

Despite being a relatively new concept, another promising technology that could allow new potential for DfD is through the use of 3D-printing. Segment-wise printing of components allow an easy reuse due to the dry-assembled construction, glue-free connections, and thus non-destructive disassembly that is not possible in many other construction technologies [117, 118]. Such a concept has been materialized in the case study of the "Striatus" pedestrian bridge [119], which features enabled circularity through the dry assembly of unreinforced 3D-printed concrete segments, as well as reduced material consumption and eliminated formwork waste due to its compression-only geometry. Similar concepts have been further implemented since then [120, 121].

Research on DfD of timber construction works is still in its infancy, as research on demountable connections is generally still done without physical loading of the connection between assembly and disassembly [108, 122]. Additionally, advances in strength grading of disassembled GLT were only made recently in research [123]. Methodologies for non-destructive testing aiming at estimating allowable load levels and residual service life are being developed [124].

4 Conclusions

Stakeholders involved in early-stage decision making currently do not have sufficient information to incorporate environmental impact into their choices of structural systems and materials. Although stakeholders currently possess comprehensive tools for making decisions based on engineering performance, costs, and construction time, there is a clear deficiency in tools that integrate environmental considerations, despite sustainability being a basic requirement under the CPR.

The bridge inventory analysis presented in this study reveals that the majority of Swiss road bridges are concrete structures with spans below 40 m. Hence, decarbonisation efforts for materials and systems optimally targeting this span range would address the largest share of both existing and future road bridge infrastructure.

Combining the representative bridge configurations identified in Section 2.3 with the assessment of available and promising technology in Section 3, a number of conclusions can be made regarding which technologies are most relevant for which parts of the bridge stock. Short-span reinforced concrete bridges on cantonal roads offer the widest range of options, including recycled and carbonated aggregates, low-clinker cements, biochar-based concrete, internal FRP reinforcement, timber-concrete composite systems, and hardwood GLT, several of which are already commercially available in Switzerland. The high number of bridges in this category means that even moderate per-bridge reductions in GWP can have a substantial cumulative effect. For medium-span reinforced and prestressed concrete bridges, the applicable options include recycled and carbonated aggregates, low-clinker cements, Fe-SMA prestressing, UHPFRC, and digitally fabricated formworks, although some of these are still at pilot stage of development or require providing further evidence on long-term performance. For longer-span prestressed concrete bridges, the options are more limited, with UHPFRC and high-strength steel being the most relevant for new construction. These observations do not replace project-specific LCA, but they can serve as an indication for stakeholders involved in early project phases, where the influence on environmental impact is highest, to identify which low-emission options are worth to be considered for a given bridge configuration.

Several observations are likely to hold beyond Switzerland. The observation that environmental impact, like cost, is largely committed during early project phases applies regardless of the national context. The finding that the majority of road bridges are short-to-medium span concrete structures is consistent with bridge inventories across much of Europe [32]. In such contexts, a similar set of technologies could be directly considered worth investigating. In bridge stocks with differing preferences of systems and materials, such as in the United States with a higher share of steel or composite structures [33], the relevant technologies could shift towards high-strength steels, and potentially to a higher importance of circularity concepts.

By advocating the use of existing and emerging low impact materials and technologies that have been discussed herein, the construction industry can make substantial progress towards reducing its carbon footprint. The combination of innovative and sustainable materials, advanced technologies, circular economy principles, and collaborative stakeholder engagement can form a promising framework for sustainable construction practices. To advance towards reduced carbon emissions in road bridge construction, the following actions are recommended:

1. Provide environmental impact data specifically tailored for early project phases to enable sustainable decision-making during conceptual design,
2. Prioritize decarbonization efforts on short-to-medium span bridges to maximize impact,
3. Promote the adoption of high-performance, low-emission materials and technologies, as well as circularity and design for disassembly principles,
4. Address stakeholder conflicts by emphasizing the long-term benefits of sustainable construction practices,
5. Apply the presented approach to bridge inventories in other national contexts to enable comparison of decarbonization priorities across different material traditions and regulatory environments.

Authorship statement (CRediT)

Yunus Emre Harmanci: Conceptualization; Methodology; Software; Formal Analysis; Visualization; Writing – Original Draft; Writing – Review & Editing. **Lukas Kramer:** Methodology; Software; Formal Analysis; Visualization; Writing – Original Draft; Writing – Review & Editing. **Moslem Shahverdi:** Conceptualization; Writing – Original Draft; Writing – Review & Editing; Supervision. **René Steiger:** Conceptualization; Writing – Original Draft; Writing – Review & Editing; Supervision; Lead of SCENE Action Area; Project Administration; Funding Acquisition.

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Data availability

Data will be made available on reasonable request.

Declarations

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

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