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FINAL REPORT

NACOE S73: Navigating Sustainability for Structures

NTRO Project No.:	24-02865
Project Leaders:	TMR: Stephen Rae NTRO: Georgia O'Connor
Quality Manager:	Dr James Grenfell
Author/s:	Georgia O'Connor, Daniel Ainalis, Matthew Bond, Brook Hall & Dr James Grenfell
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Executive Summary

The quest for sustainable infrastructure practices gathers apace as whole-of-government emissions reduction goals (e.g. net zero carbon targets) are applied to strategy and tangible actions. To respond to these imperatives, it is recommended that the Queensland Department of Transport and Main Roads (TMR) applies a strategy that enables discrete actions to achieve policy and the legislated targets.

The National Asset Centre of Excellence (NACOE) S73 Project: *Navigating Sustainability for Structures* investigates and advises on TMR's opportunities to reduce the embodied carbon emissions of road transport structures (bridges and culverts, etc.) and improve overall sustainability outcomes. Key opportunities surround sustainable materials, sustainability estimation and assessments and implementation of emissions reduction initiatives.

This report has been developed to provide information on directions that can measurably reduce the carbon footprint of TMR's structural assets through data-driven planning, design and monitoring considerations. Such considerations allow for optimal life cycle management practices in the construction and maintenance of the asset.

The report presents discrete sections in order to provide information around available and emerging initiatives to improve the sustainability of TMR's infrastructure. These include an overview of:

- **Concrete decarbonisation technologies:** An overview of existing and emerging technologies and provision of contextual information regarding their technical and market maturity within Queensland and TMR's ability to implement these technologies. Of the technologies reviewed, carbon reductions are available now through driving utilisation of high supplementary cementitious materials and geopolymer concretes in precast concrete manufacturing.
- **An innovation assessment process:** An overview of the innovation assessment procedure which has been developed to assess innovative products and solutions with a claimed sustainability benefit.
- **Implementing low carbon concrete solutions:** Development of a draft TMR Technical Note 59 *Low Carbon Concrete*. This technical note provides an overview of available and emerging technologies under the banner of low carbon concrete. It then briefly discusses how embodied carbon can be measured in order to compare these technologies.
- **Materials usage data:** An examination of the quality of various sources of data available for estimating material quantities and embodied carbon for TMR's structures, focusing on the relevant structural materials of concrete, reinforcing and structural steel, and structural timber. The assessment found that, in general, TMR has access to good quality material type and quantity data, and the embodied carbon factors are all of low to medium quality.
- **Defining sustainability in design:** Strategies for integrating sustainability considerations into the design of structures by directing designers to sustainability measures and criteria, and guidelines for sustainable practices and outcomes.
- **Support for sustainable decision-making in structural design:** Development of guidance aimed to support designers to improve the sustainability of structural design decisions. This guidance is focused on early-stage design, where designers have the most significant impact, and developed methods to estimate embodied carbon and other sustainability factors. The guidance aligns with the National Measurement Guidance and provides tools and methods to support informed decision-making throughout the project life cycle.

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1.1 Background

The quest for sustainable infrastructure practices gathers apace as whole-of-government emissions reduction goals (e.g. net zero carbon targets) are applied to strategy and tangible actions. To respond to these imperatives, Engineering and Technology: Structures within the Queensland Department of Transport and Main Roads (TMR) needs to navigate an operational course to measurably improve and embed the sustainability of design, construction, maintenance and life cycle management of structural assets.

1.2 Objectives

This project has been developed to provide direction to TMR's decision-makers on how sustainability practices can be realised and championed, within the Directorate's sphere of influence. This direction will enable a coordinated and strategic approach, preventing inefficient use of available resources. Each discrete works package has a unique defined scope and objectives, which are described in the relevant sections of the report.

This project provides a coordinated framework and approach to determining sustainability practices for structures for the efficient realisation of benefits. It provides direction such that discrete, tangible actions can be taken with engineering judgement, knowledge and confidence.

This project was completed over 2 years of the National Assets Centre of Excellence (NACOE) research program. Year 1 focused on research into the decarbonisation aspect of sustainability. Year 2 focused on developing practical and implementable solutions, based on the outcomes of the Year 1 project. The benefit of this is creating a more well-rounded perspective of sustainability for TMR structures as well as providing TMR with opportunities to mitigate their impacts on climate change.

1.3 Structure of this Report

Navigating Sustainability for Structures delivered discrete areas of research, each with a unique objective. These research elements and the sections of this report are as follows:

- **Lower carbon concrete** (Section 2) – examines the current proposals for significant reductions in embodied carbon of concrete and their place in the sustainability landscape and compares them with TMR's current practices.
- **Innovation assessment** (Section 3) – produces an administrative process to receive, assess and approve new materials, products and methods under the umbrella of sustainability (undertaken by TMR).
- **Implementing low carbon concrete solutions** (Section 4) – enables practical implementation of low carbon concrete research opportunities through the development of a draft new technical note.
- **Material usage data** (Section 5) – examines existing sources of data for estimating material quantities and embodied carbon for TMR structures.
- **Defining sustainability in design** (Section 6) – produces recommendations for TMR to include in design criteria or guidelines, directing designers to incorporate sustainability into design.
- **Support for sustainable decision-making in structural design** (Section 7) – provides guidance for a sustainability assessment process for structures, indicating in which project phases designers can make more informed decisions towards sustainability.
- **Research summary** (Section 8) **–** summarises each of the areas of research presented in the preceding sections and provides final conclusions.

2. Lower Carbon Concrete

This section provides an overview of concrete sustainability-focused technologies that may act to reduce embodied CO_2 emissions and improve environmentally sustainable outcomes. This list of initiatives is non-exhaustive; however, it reflects technologies that are understood to be developing in either technological or commercial maturity or that demonstrate considerable interest or potential. The initiatives under review have been selected based on several key resources and published pathways towards the decarbonisation of the cement and concrete industry. These include the *GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete* (Global Cement and Concrete Association (GCCA) 2022), *Decarbonisation Pathways for the Australian Cement and Concrete Sector* (VDZ 2021) and formal and informal representations from cement and concrete industry members.

Key initiatives that have been reviewed include:

- general purpose (GP) cement replacement by supplementary cementitious materials (SCMs)
- geopolymer concrete
- increased limestone in cement
- alternative limestone calcined clay cement binder (LC^3)
- alternative magnesium cement binders
- alternative fuels and increased efficiency in clinker production
- alternative fuels in transport
- carbon capture, usage and storage
- use of recycled materials.

2.1 Overview of Concrete Decarbonation Technologies

The major precursor to GP cement is Portland cement clinker which is manufactured by calcining limestone and other clay sources in a kiln. The calcination process is energy intensive, requiring materials to be heated (normally by fossil fuel combustion) in a kiln to approximately 1,450 °C. Limestone is the predominant raw material which emits CO_2 as a byproduct of the conversion of limestone ($CaCO_3$) to lime (CaO).

The clinker is ground through either a ball-mill or vertical roller mill with minor inclusions of gypsum and other minerals (typically limestone) to produce type GP cement. The mill grinding process is energy intensive and typically powered by electricity from the national grid.

Due to both the CO_2 emissions generated by calcination and the energy intensive requirements of cement production, GP cement has a high embodied CO_2 value. The Australian Life Cycle Inventory (Australian Life Cycle Assessment Society 2023) currently rates the average embodied CO_2 as 940 kg per tonne of cement, which is significant when considering the volume of consumption. The Cement Industry Federation estimated in 2020–21 Australia produced more than 10 million tonnes of cement per year (https://cement.org.au/australias-cement-industry/about-cement/australias-cement-industry/).

Due to the substantial scale of associated CO_2 emissions, most pathways to decarbonation focus on improving the emissions associated with GP cement manufacturing or reducing the rate of GP cement consumption.

2.1.1 General Purpose Cement Replacement with Supplementary Cementitious Material

Description of technology

A frequent approach to reducing the embodied CO_2 of concrete is to replace portions of GP cement with SCMs with lower embodied CO_2 values. The most commonly used SCMs currently used in Australian concrete are:

- fly ash
- ground granulated blast-furnace slag (GGBS)
- amorphous silica, frequently referred to as silica fume.

Fly ash

Fly ash is an industrial by-product generated by the combustion of coal in power stations. Fly ash is a non-crystalline material that is typically low in calcium and high in alumina-silicates. It holds pozzolanic properties and when used in concrete with a GP cement reacts with available calcium hydroxide to form cementitious minerals including calcium-silicate-hydrates and calcium-alumina-hydrates.

The use of fly ash as an SCM is common in the Australian concrete industry and has a decades-long performance history. A minimum fly ash proportion of 25% is specified for all TMR projects to mitigate against alkali-silica-reactivity, unless a cement blend containing greater than or equal to 60% GGBS is used.

Fly ash is commonly used in normal-class and non-TMR projects in Queensland at ranges between 15 and 30% of the total cementitious composition. It is generally understood that the use of fly ash above 30% exhibits diminishing strength performance benefits and becomes less economical to include.

Due to the distribution of coal-fired power stations and relatively high purity of black coal sources, fly ash is available in significant quantity within Queensland. In line with Towards Zero Emissions strategies, Queensland power stations are anticipated to progressively close by around 2035 when new sources of local fly ash will no longer be available.

Ground granulated blast-furnace slag (GGBS)

GGBS is a latent hydraulic binder which contains appropriate base minerals (calcium silicates and calcium aluminates) to produce a hydraulic cementitious reaction when in an alkaline environment. When blended with GP cement, the GP hydration reaction increases the pH of pore water solution which in turn activates the cementitious hydration of the GGBS.

GGBS is an effective replacement for GP cement in high proportions (60% and greater), although slower strength development during curing occurs. The rate of strength development is relative to the proportion of GGBS used.

GGBS blended concretes are desirable in marine exposure environments and offer excellent resistance to chloride penetration.

Though GGBS offers some reduction in alkali-silica reactivity potential, it does not perform as effectively as fly ash. GGBS is accepted in all grades of concrete on TMR infrastructure projects and can be used without fly ash when used in the range of 60–70% replacement.

Australia has limited supply of GGBS (Port Kembla NSW is the most prevalent source). In Queensland, GGBS is typically sourced from Asia in bulk shipments and ground in local mills.

Amorphous silica

Amorphous silica (also known as silica fume) is an ultra-fine pozzolanic material that is a byproduct of glass manufacturing. When blended with GP cement, during hydration the amorphous silica reacts with calcium hydroxide resulting from initial GP cement hydration phases. This calcium hydroxide interacts with silicates and aluminates within silica fume to form cementitious minerals. Due to its fineness and high reactivity, silica fume exhibits excellent strength and durability properties in concrete when used in small proportions. Due to its fineness and constant size, however, it is challenging to effectively produce concrete with silica fume proportions greater than 10%.

Silica fume is occasionally used in minor proportions to improve plastic properties of super-workable concrete (SWC) and shotcrete (sprayed concrete), or as a ternary blended cement with fly ash or GGBS to provide improved permeability and chloride resistivity properties.

Silica fume is only accepted for use on TMR projects when used with 65–71% GP, 25–31% fly ash and 4–8% silica fume.

Commercial availability

Most major concrete suppliers in Queensland's metropolitan areas carry bulk quantities of fly ash and GGBS to enable the production of concrete with varying cementitious blends. Additionally, cement suppliers in Queensland also sell blended cements which include fixed proportions of SCMs, such as 25% fly ash blend (FAB), which are more commonly adopted in regional areas.

Availability of GGBS can be restricted in some rural and regional areas, where concrete plants are frequently set up with a reduced number of cement silos and can therefore carry fewer cementitious products. Due to the absence of local sources of GGBS, the economics of transporting GGBS by road into rural areas and particularly north of Rockhampton is often cited as a major impediment to availability.

Though silica fume can be available in bulk, it is frequently sourced as a bagged product and added to concrete manually through the production process. Due to a relatively high cost and low proportions of use (typically less than 10%), amorphous silica is not typically selected for the purpose of CO_2 reductions, particularly when compared to fly ash or GGBS. Bulk sources of silica fume are typically imported by rail from Western Australia.

Potential future supplementary cementitious materials

As the energy sector is planning a transition away from coal fired power stations, available sources of fly ash will diminish. Therefore, the cement industry and specifiers have been looking to alternative sources of SCMs to continue to reduce demand of GP cement, to provide mitigation against alkali silica reactivity and to improve durability properties of concrete for certain exposure environments.

Whilst this report does not intend to explore all potential sources under investigation, the following have been identified as having reasonable future viability. The NACOE conducted a review in 2022–23 on the viability of fly ash and alternative SCM materials (Jayasooriya 2023). The report provides further details around materials including agriculturally derived biomass fly ash, metakaolin, recycled ground glass, pumice, diatomaceous earth and ash from power station waste dams.

Delithiated beta spodumene (DBS) is a byproduct of lithium refining and appears to have potential to supplement or replace fly ash as a pozzolanic SCM in concrete. Most prevalent sources of DBS are in Western Australia and would require transport by shipping, rail or road freight to a Queensland market. DBS is potentially able to be classified within AS 3582.4:2022 as a pozzolanic material; however, at present this standard is not recognised by cement standard AS 3972-2010, and therefore, its use in concrete is not covered by Australian Standards. There are no TMR specifications that provide for the use of DBS in concrete.

Dam ash or pond ash is the name provided for coal-combustion power station ash sources that have been stored as landfill waste. It is proposed that the ash sources are generally chemically stable and may be possible to mine and process for use in concrete in similar means that fly ash is currently used. The costs of extraction, processing and classification of ash will be substantially higher than processing of virgin fly ash, and it is therefore unlikely that a market will be established within Queensland whilst coal-fired power stations are still in operation and virgin fly ash is available. Similar to DBS above, pond ash has the potential to be classified within AS 3582.4 as an alternative SCM, which is presently not recognised as an alternative cement material according to AS 3972.

Chemically activated supplementary cementitious materials

Since 2018, concrete produced with chemically activated cementitious blends has been available in Queensland. These offerings use proprietary systems to activate SCMs, to enable concrete with very high GP replacement values. In addition to reduction of embodied carbon compared to GP cement concrete, many of the commercial market offerings claim engineering benefits compared to conventional concrete. These claims differ between suppliers and can include:

- neutral or enhanced early age strength development
- reduction of drying shrinkage
- improved durability and permeability performance
- improved or neutral placement and workability characteristics.

The current alkali-activated product offerings are sold under registered trade names including Boral Envisia®, Holcim ECOPact® and Hanson Ecotera® concrete products.

Cement Australia has also developed a geopolymer technology branded GreenCem which can be supplied as dry powder to typical concrete batch plants.

2.1.2 Geopolymers

Description of technology

Geopolymer concretes use alternative cementitious binders that do not contain any GP cement to produce concrete with a lower embodied carbon value than a conventional concrete. A geopolymer binder consists of alumina silicate precursors (typically fly ash and/or slag) and alkaline activator(s) as well as water and aggregate materials typical of a standard concrete mix. When assessing the potential embodied carbon compared to conventional GP or general purpose blended (GB) cement concrete, it is important to ensure the alkaline activators are considered.

Geopolymer concretes are generally produced through ordinary concrete manufacturing facilities; however, they have different behaviour regarding placement and curing requirements. The placement and curing of geopolymer concrete should not be treated in the same manner as Portland cement concrete.

A review of an Environmental Product Declaration (EPD) of a major supplier of geopolymer concrete in Queensland indicates a potential embodied CO_2 reduction of 89% compared to an average Australian ordinary Portland cement (OPC) concrete, as benchmarked by the AusLCI database (Noller 2020).

Commercial availability

In Queensland, Wagners Concrete has been the most prolific supplier of geopolymer concrete and markets their offering under the brand Earth Friendly Concrete (EFC). There is precedence of EFC being supplied into both precast elements and placed in situ.

Geopolymers are distinct from chemically activated or alkali-activated concretes as referred to in Section 2.1.1. These products claim low embodied carbon values, but due to the incorporation of GP cement, they are not classified as geopolymer concretes.

Status of standards and specifications

The use of geopolymer concrete is covered within Australian Standards through SA TS 199:2023. These standard details supplementary requirements to AS 3600 relating to the use of geopolymer concrete. SA TS 199:2023 is not considered applicable for marine structures, water-retaining structures or mass concrete elements.

TMR details how geopolymer concrete can be used in precast elements through TMR's technical specification MRTS270 *Precast Geopolymer Concrete Elements* (TMR 2018). Geopolymer concretes, for uses other than precast concrete elements, are not currently accepted within transport infrastructure works under TMR's specification MRTS70 *Concrete* (TMR 2022).

In addition to the abovementioned technical specifications, there are recognised general practice guides which provide detail and consideration around the specification, supply and use of geopolymer concretes. Of particular note are Z16-2011 *Geopolymer Recommended Practice Handbook* (Concrete Institute of Australia 2011) and *Specification of Geopolymer Concrete: General Guide* (Austroads 2016).

2.1.3 Increased Limestone in Cement

Description of technology

Portland limestone cement mainly consists of ground cement clinker and uncalcinated limestone. Direct substitution of clinker with limestone reduces clinker usage, resulting in lower direct CO_2 emissions and reduced fuel consumption associated with clinker manufacturing processes. This clinker replacement has the potential to reduce carbon emissions by up to 10% while maintaining concrete performance at an equivalent level.

Adding limestone up to a specific percentage can enhance or maintain concrete properties by promoting efficient particle packing and increasing cement gel production. Optimising the particle size distribution of limestone and the fineness of cement is critical in determining the reduction in porosity and achieving equivalent performance in general purpose limestone (GL) cement (Portland limestone cement, PLC). Extensive research in Canada and the USA has demonstrated that using GL with up to 15% limestone can produce concrete of equivalent performance, including similar strength and durability to that of conventional Portland or blended cement counterparts (CAC 2023).

Commercial availability

In October 2023, Adbri commenced commercial production of GL cements in Australia with limestone percentages up to 15%.

Status of standards and specifications

AS 3972 permits an inclusion of up to 7.5% limestone in Type GP cement, and up to 20% limestone in Type GL cement. AS 3972 does not permit the blending of GL cement with other SCMs.

Limestone percentage limits in international general purpose cement

The maximum permissible limestone percentages for GP cements, including those equivalents to Australian GP cements in the USA, Europe and Canada, are summarised in Table 2.1. Australian Standard AS 3972 permits the highest allowable limestone content, at 7.5%, for GP cement. In contrast, Canadian CSA 3001: 23, European EN197-1:2011, and ASTM C150/AASHTO M80:2013 standards all restrict GP Portland cements to a maximum of 5% limestone content as indicated in Table 2.1.

Table 2.1: Maximum limestone percentage in Australian and international GP equivalent cement standards

Standard	Cement	Maximum limestone %
Australia AS 3972	GP	7.5
Canada CSA 3001	GU	5
Europe EN197-1	CEM 1	5
US ASTM C150/AASHTO M80	Type 1	5

Limestone percentage limits in international GL (PLC) cements

Maximum allowable limestone percentages for various GL/PLC in Australia, Canada, the USA and Europe are outlined in Table 2.2.

Table 2.2: Maximum limestone percentage in Australian and international GL/PLC equivalent cement standards

Standard	GL/Portland limestone cement	Max limestone %
Australia AS 3972	GL	20
Canada CSA 3001	GUL	15
US ASTM C595/AASHTO M240	Type 1L	15
Europe EN197-1	CEM II/A-L and II/A-LL	6–20
Europe EN197-1	CEM II/B-L and II/B-LL	21–35

In Australia, commercial production of GL cement with up to 15% limestone recently commenced, and trial applications were launched in New South Wales and South Australia. TMR has also conducted trials within NACOE project P58 *Alternative Cementitious Binders for Cost-effective and Sustainable Transport Infrastructure*.

In Canada, the maximum limit for limestone in PLC is set at 15% to ensure its performance remains equivalent to that of traditional Portland cement concretes. GL is recognised within the National Building Code of Canada and has been applied in a wide range of construction projects in Canada. Although many transport authorities permit GL in construction projects, some restrict its use in structures or structural precast concrete. A comprehensive discussion on the use of GL in construction specifications can be found in Cement Association of Canada (2023).

In the USA, the maximum limit of limestone is set to 15% for Type GL. GL (Type IL) is permissible as specified by codes such as ACI 318-19, *Building Code Requirements for Structural Concrete*, specifications such as ACI SPEC-301-20, *Specification for Concrete Construction* and standards such as ASTM C94/C94M-23, *Standard Specification for Ready-mixed Concrete*. Most transportation agencies in the USA accept GL cement interchangeably with Type 1 cement (GP equivalent). There have been several successful applications of GL concrete pavements since the early 2010s in various transportation agencies. However, information on the use of GL in structural concretes is not available from transportation agencies. It is worth noting that some transportation agencies in the USA adopt a conservative approach for durability performances when allowing GL. This approach may include prescriptive or performance-based criteria when using higher limestone percentages. For instance, Caltrans permits up to 15% cement in GL (CPD 21-19) with an additional clause to ensure it meets moderate sulfate or high sulfate resistance performance criteria.

In Europe, PLC (GL) cements have been in use for the last 35 years (CAC 2023). The European standard allows for limestone percentages up to 35% under 2 different cement categories. CEM II/A-L with 6–20% of limestone is well-established and currently a standard cement for all normal building structures in European countries including Finland, Sweden, Ireland and Germany. On the other hand, CEM II/B-L & LL, containing 21% to 35% limestone, are used only for lower-grade applications such as plastering, flooring, masonry mortars and low-grade concretes.

2.1.4 Carbon Capture, Usage and Storage

The calcination of limestone during clinker production contributes approximately 60% of the total embodied CO_2e in cement (GCCA 2022). In all Australian cement kilns and most cement kilns internationally, these emissions are directly exhausted to the atmosphere.

Carbon capture infrastructure involves complete seizure of CO_2 exhaust gas from calcination and represents the highest potential of CO_2e reduction attributed to GP cement. There are several technologies in development (VDZ 2021), which hold some crossover with the electricity industry, including:

- Post combustion is the direct capture of CO_2 flu gas, usually through a medium such as amines.
- Direct separation involves initial calcination of limestone separately from other raw materials, enabling a more concentrated CO_2 gas to be captured.
- Oxyfuels are combusted in a near-pure oxygen environment, resulting in more concentrated CO_2 output for capture.
- Calcium looping employs using calcined lime (CaO) as a sorbent media to re-mineralise with CO_2 emissions.

If coupled with zero emissions fuel sources, the employment of carbon capture plants could result in a true zero-emissions cement and be one of the most significant contributors to CO_2e reductions attributed to concrete and infrastructure more broadly.

A number of pilot carbon capture plants are being developed internationally, including a scale pilot device established by Heidelberg Materials in Edmonton Canada in 2023 (Heidelberg Materials 2023).

Within Australia, major cement manufacturers Cement Australia, Boral and Adbri have all reported research and development projects to establish carbon capture capabilities in the future. Within Queensland, a scale pilot plant is programmed for commissioning in Cement Australia's Gladstone plant circa 2028–29.

Carbon capture is challenged by expensive development and operating costs. Successful development of carbon capture, usage and storage also relies on sufficient scale of utilisation and storage opportunities, as well as transportation capabilities to freight captured CO_2.

Carbon utilisation and storage are processes of repurposing or otherwise storing the CO_2 once captured, rather than emitting as greenhouse gases (GHGs). Once captured, CO_2 has potential avenues for reuse in agriculture, industrial chemical processing and e-fuel manufacturing. Within the concrete industry, avenues for reuse of captured CO_2 have been under investigation, by means of absorption into recycled crushed concrete aggregates, or in concrete elements where carbonation risks to steel can be managed.

There are no Australian Standards or specification requirements that are impacted directly by the proposed processes for carbon capture; however, some alterations to the clinker's chemistry could occur through oxyfuel or a calcium-looping mechanism. With the condition that any impact on chemical or performance properties can be addressed in the producer's quality management plan, cement should be able to perform in accordance with AS 3972 and be suitable for use within existing specifications.

2.1.5 Alternative LC^3 Cement (Limestone Calcined Clay Cement)

Description of technology

LC^3 allows for a reduction in Portland cement clinker by up to 50%. It is a combination of clinker, calcinated clay, limestone and gypsum.

Calcination of clays used in LC^3 do not emit CO_2, other than from the energy used for heating. During calcination, clays are heated at approximately 700–850 °C. This contrasts to Portland cement clinker calcination temperatures of approximately 1,450 °C, and the calcination causes additional CO_2 emissions due to the conversion of limestone to lime as explained in Section 2.1. These differences in energy demand and direct CO_2 emissions significantly reduce carbon emissions compared to Portland cement when used as a replacement up to 50%.

LC^3 offers high early-age mechanical performance, enabling higher substitution levels compared to other pozzolans such as fly ash and similar substitution levels to GGBS. This performance is attributed to the rapid reactivity of fine clay particles. Several reports (Dhandapani et al. 2018; Ejbouh et al. 2022) suggest that LC^3 has improved durability compared to ordinary Portland cement with improved resistance to alkali-silica reaction, chloride attack, sulfate resistance and reduced heat of hydration. The high fineness of calcined clay, especially when interground with clinker, may increase water demand and demand the requirement for superplasticisers.

Market availability

LC^3 cements are an emerging technology and are not produced or available within the Australian cement market.

Australia has large kaolinite clay reserves; however, the suitability of kaolinite clay for calcination in LC^3 production depends on its kaolinite content, which should be a minimum of 40% for performance equivalent to ordinary Portland cement (Scrivener et al. 2018). Therefore, it is essential to investigate different sources of kaolinite clay and assess their potential for LC^3 cement production. Clay availability near to the calcination unit and transportation are the key factors that determine reduction in carbon emissions and cost of LC^3 (Scrivener et al. 2019).

Other challenges to the establishment of LC^3 production capabilities relate to expensive capital investment required by cement producers, necessitating a separate kiln.

Internationally, anecdotal evidence has shown several examples of LC^3 production facilities that have been launched in Europe, South America and India.

Status of standards and specifications

There are currently no Australian Standards that recognise LC^3 cements.

However, LC^3 blending is feasible within several other standards. ASTM C595 permits LC^3 blending up to 40% pozzolan content, up to 15% limestone content, and a minimum clinker content of 45%, enabling LC^3 blends down to LC^3-45. In 2021, the European cement standard EN-197-5 began allowing LC^3-50, allowing up to 50% clinker replacement in the Portland-composite cement CEM II/C-M category. In August 2023, India introduced a new standard IS 18189:2023, specifically designed for LC^3 cement.

2.1.6 Alternative Fuels and Increased Efficiency (Cement Kilns)

Cement clinker, which is a precursor to GP cement, is produced by calcining raw materials at approximately 1,450 °C. The majority of Australia's clinker sources are produced in kilns fuelled by coal, natural gas or blended coal and gas sources, with minor proportions of waste-derived fuels which heat raw materials.

Commonly available alternative fuels include tyre rubber, residual waste oils, solid recovered fuel (biomass), waste timbers and waste industrial solvents. Utilising these alternative sources offers an approach to waste reduction and waste diversion from landfill. Both the energy density of fuel sources and relative CO_2 emissions are important considerations when compared to coal or anthracite.

Presently, modest proportions of alternative fuels are reported to be used within Australian clinker manufacturing plants including processed biomass, timber, tyre rubber, waste oils and solvents. The Cement Industry Federation (CIF) estimates that 18% of the fuel usage is derived from these alternative waste fuel streams (CIF 2023).

Biomass is used in the form of solid recovered fuel (SRF), which is a heterogenous mix of combustible fuels derived from either municipal or commercial and industrial waste streams. SRF is prepared for combustion through processes of separating, conditioning and shredding feed material before packaging and shipment to cement kilns. There is an established market for SRF biomass fuel production within most major Australian regional centres.

The GCCA (2020) provides default estimated CO_2 emissions factor values for common waste fuel streams in Table 2.3.

Table 2.3: Default CO_2 emissions estimation of fuel sources for clinker calcination

Fuel source	Relative emissions (kg CO_2/GJ)	% emissions compared to coal and anthracite fuels
Coal + anthracite	96	100%
Natural gas	56.1	58%
Waste oil	74	77%
Tyres	85	89%
Plastics	75	78%
Solvents	74	77%
Mixed industrial waste	73	76%
Dried sewage sludge	110	115%
Wood	110	115%
Paper, carton	110	115%
Animal meal, bone, fat	89	93%
Agricultural, organic, diaper waste, charcoal	110	115%
Other biomass	110	115%

Source: GCCA (2020).

Srivastava et al. (2023) conducted a multi-objective analysis of alternative fuel sources based on energy density (calorific values), and embodied carbon values relative to source availability. The modelling incorporated mixed fuel sources including coal, biomass, timber, tyres, residual oil, ethanol and hydrogen. The research indicated that tyres, residual oils and ethanol as blended fuels have potential to reduce the embodied carbon for cement kiln operations when compared to straight coal combustion.

Non-carbonate-based fuel sources are not available within the Australian cement market nor are they being procured internationally. Hydrogen is a high-potential alternative non-carbonate fuel source that has potential to contribute no embodied CO_2 through clinker production, with the condition that the electrical energy is derived from green energy sources.

The use of alternative fuels including waste oils, tyres, solvents and SRF biomass may provide a short- to medium-term solution to reducing embodied CO_2 in cement, whilst green hydrogen capabilities continue to mature. Fuel sources such as waste timber and agricultural waste act to divert waste streams from landfill, though they may not provide a decarbonation benefit.

There are no Australian Standards or specification requirements that relate to the fuel sources used during clinker production; however, co-firing of different fuel sources will result in some alterations to the clinker's chemistry. Managing the impacts on chemical and performance properties should be addressed in the producer's quality management plan, to ensure cements continue to perform in accordance with AS 3972.

2.1.7 Alternative Fuels (Transport)

The primary transportation modes across the manufacturing and supply of concrete in Queensland are categorised by the raw material in Table 2.4. Concrete and its bulk materials are mostly transported around Queensland via road, with some rail. Sea freight is only used for international imports, requiring onward transport of materials via both road and rail.

Table 2.4: Common transport mode of concrete raw materials

Raw material category	Common locations	Dominant transport mode
Aggregates	Typically sourced from local quarries	Road freight
GP cement clinker or ground powder	One local producer of clinker (Gladstone). Others imported internationally or from interstate with additional grinding facilities within greater Brisbane region	Sea freight to cement supply companies for grinding (if required) Road freight and some rail freight to dispatch to cement companies
Slag (GGBS)	Typically imported from within Asia (primarily Japan). Potentially available from Port Kembla NSW, though not a predominant source in Queensland.	Sea freight (import) to cement suppliers for grinding (if applicable) and dispatch. Road freight for supply to concrete plants.
Fly ash	Local sources (Millmerran, Gladstone, Callide, Tarong).	Road freight and some rail freight.
Amorphous silica	Western Australia or as bagged product in Sydney NSW.	Road freight and some rail (Western Australia origin).
Chemical admixtures	Complete admixtures imported, or imported as raw materials and manufactured locally.	Sea freight (import) Road freight for supply to concrete plants.
Plastic concrete	Distribution of premix concrete from batch plants to location of placement.	Road freight (agitator trucks).

The decarbonisation outcomes for each transport method will be linked to improvements made by the freight transport industry.

In this report, the following aspects of alternative fuels are not discussed in detail: the advancement of fuel technologies, the methods of production and the supporting refuelling/recharging infrastructure. The focus will be on alternative fuel technologies in road freight, but these will similarly extend to rail.

Before discussing the alternative fuels, it is worth mentioning another important factor in reducing the carbon emissions of freight transport is by improving the productivity of vehicles. This involves utilising high-capacity vehicles in the road freight sector and shifting freight from road to rail where possible. The importance of shifting freight via more efficient methods is demonstrated in Table 2.5, using emissions factor estimates from the Australian National Life Cycle Inventory (AusLCI) database (Australian Life Cycle Assessment Society (ALCAS) 2011).

Table 2.5: Comparison of emission intensity factors for road, rail and sea freight

Mode	Emission intensity factor [gCO_2-e/tonne-kilometre]	Emissions relative to road freight
Road	100 to 180	100%
Rail	20	11–20%
Sea	10	5–10%

Source: ALCAS (2011).

The main alternative fuels which are being investigated to reduce carbon emissions compared to conventional fuels (e.g. diesel and petroleum) include biofuels, electricity and hydrogen (Furtado 2018). All 3 fuels can provide a significant reduction of the GHG emissions associated with transport and distribution of concrete and its materials – dependent on the production method and grid emissions intensity. A brief overview and broad future outlooks are presented on each fuel type (and associated vehicles), and it should be noted that these outlooks may be subject to change with future technological developments.

Biofuels

Biofuels are produced from food crops or waste products and include biodiesel, biomethane etc. It is a drop-in solution that can be used in most existing vehicles and well-suited to long distance bulk freight applications and has the potential to significantly reduce GHG emissions. Drawbacks of biofuels include ensuring the source and traceability of feedstock, the competition and potential to displace agricultural crops (food vs fuel), the potential increased emissions due to land-use changes and tailpipe emissions which are still produced by these vehicles.

Market availability:

- Biofuels are unlikely to be deployed at a large scale (i.e. state or national) due to the limited availability and competition with food crops.
- They can play a small role now during the transition to zero emissions vehicles.
- The use of biofuels (outside of sea and air transport) is well-suited for decarbonising niche applications for individual vehicles/fleets, such as long-distance bulk freight transport.

Electricity

Electric vehicles have an on-board battery that stores electricity and provides it to the motors to propel the vehicle. Electric vehicles produce no tailpipe emissions and are the most efficient (in terms of energy use) of all alternative fuels – they can provide the deepest reduction in GHG emissions provided the source of electricity is low/zero emissions (via the grid or local generation). For bulk freight transport using electricity, there are several challenges that need to be addressed. These are generally focused around operational requirements (early models available now have limited on-board energy storage which currently limits their range and payload (small penalty) and charging infrastructure (in terms of both availability and power to minimise downtime for recharging).

Market availability:

- Electricity is likely to become the dominant alternative fuel source, already occurring for light and medium freight transport vehicles.
- Emissions reduction is linked to the electricity grid carbon intensity and will improve as more renewable energy generation is built. Local generation is also a possibility.
- Challenges to be addressed for long-distance bulk freight centre around feasibility due to loss of payload for bulk freight applications (due to increased vehicle mass of on-board batteries) and ensuring the necessary supporting charging infrastructure is in place.
- Due to these challenges, there may be an opportunity for hybrid vehicles to play a role in the future (i.e. an electric vehicle with a combustion engine that acts as a range extender).

Hydrogen

Hydrogen vehicles convert hydrogen to electricity using a fuel cell to propel the vehicle. They have the same basic powertrain as electric vehicles but with a smaller on-board battery and the addition of a fuel cell and hydrogen storage tanks. The benefits of hydrogen vehicles are centred around the ability to provide similar ranges and refuelling times to existing diesel vehicles. There are several ways to produce hydrogen and the method of production is very important to provide emissions reduction. If this is not carefully considered, then it is possible that more emissions are produced compared to current diesel vehicles. Green hydrogen is the only truly renewable colour of hydrogen, but there are concerns around its supply and cost.

Market availability:

- Hydrogen is unlikely to be used in urban and regional applications, but there is a potential role for their use in long-distance transport.
- Emissions reduction depends on the method of hydrogen production, only hydrogen produced by renewable energy sources will provide deep emissions reduction.
- Significant challenges remain around the viability of hydrogen in road transport due to the costs associated with their operations (capital and operating costs) and ensuring the infrastructure to generate and supply hydrogen to vehicles is in place.

Rail freight

For track segments that are not electrified, consider installing overhead line infrastructure. If it is unlikely that overhead infrastructure will be built, an investigation into intermittent solutions is needed. It is likely that some combination of diesel and batteries will provide the intermittent solution rather than hydrogen.

Sea freight

Research undertaken by UMAS (n.d.) outlined what fuels will help the shipping sector decarbonise. The shipping industry, through the International Maritime Organization, has committed to reducing GHG emissions by 'at least' 50% by 2050, with ambitions to zero emissions (UMAS n.d.). To achieve these targets, zero-carbon fuels and electricity (from renewables) is needed.

The pathways to decarbonising the shipping sector are broadly:

- electro-fuels (eFuels): hydrogen, ammonia, methane, methanol, gas, oil, etc. noting that all must be produced from sustainable sources
- electrification: utilising batteries to store electrical energy.

By application:

- Electrification is the most likely option for short-sea shipping (small tonnage and range requirements) for small barges, cargo ships and tankers, and ferries.
- Electro-fuels are the most likely option for deep-sea shipping (large tonnage and range requirements) for large vessels.

This is a significant challenge for the shipping sector, and the main challenges are to scale up the deployment of zero emissions vessels and ensure the necessary supporting infrastructure is in place to generate, store and supply these alternative fuels.

Roadmap for alternative fuels

For bulk freight where payload is important, the initial payload penalties for battery electric vehicles and hydrogen fuel vehicles may hinder their adoption. In the short term, battery electric and hydrogen fuel cell vehicles are significantly more expensive than current diesel vehicles, and it will be difficult to encourage operators to reduce road freight transport emissions significantly by purchasing these vehicles. This will change over the coming years, and in particular 2 key documents related to reducing emissions from transport in Queensland have been released by the Queensland State Government (https://www.qld.gov.au/transport/projects/electricvehicles/zero-emission-strategy) under the *Zero Emission Vehicle Strategy 2022-2032*, and *Zero Emission Vehicle Action Plan 2022-2024*. Early support is being provided for trials of zero emissions heavy vehicles that will help increase maturity and de-risk their deployment.

Recommendations include:

- Regardless of the alternative fuel, where possible shift the transport of bulk freight to more efficient modes, i.e. from road to rail.
- Encourage suppliers and contractors to increase their use of alternative fuels and ensure any alternative fuel used provides a reduction in CO_2 emissions.
- Alternative fuel production should be considered under the broader state targets for renewable energy generation.
- Identify opportunities for shared recharging/refuelling infrastructure at public sites to de-risk investment and operation of alternatively fuelled vehicles.

2.1.8 Alternative Magnesium Binders

Description of technology

Magnesium-based binders is a broad term which relates to several magnesium-based cementitious compounds that provide a potential alternative to calcium silicate-based Portland cements. Versions of magnesium-based binders have been patented since 1867 (Walling & Provis 2016) and research findings and the applicability in concrete are varied.

Magnesium-based binders in concrete have been subject to renewed interest due to potential reduction in CO_2 emissions by reducing calcining temperatures in production. In recognition of relatively low maturity of magnesium-based binders in research and in practice, in 2022 the International Union of Laboratories and Experts in Construction (Rilem) established a technical committee for the purpose of consolidating literature and further researching the potential of magnesium-based binder systems.

It is noted calcination of magnesia ($MgCO_3$) does emit CO_2 in similar proportions to limestone. Contention around the potential embodied carbon reduction is cited as a key historic barrier for the continued research and investment in commercialising magnesium-based binders in concrete.

Commercial availability

There is no availability of magnesium-based cements in Australia for the purposes of concrete manufacturing. Current industrial uses of magnesium binders in construction materials include enamels, thermal-resistant bricks, flooring compounds and coatings.

Status of standards and specifications

There is no provision within Australian Standards for magnesium-based cements to be used in concrete structures.

2.1.9 Use of Recycled Materials

In line with commitment to the Queensland Government's *Waste Management and Resource Recovery Strategy* (2019), TMR has been facilitating avenues to use recycled materials within transport infrastructure materials. These initiatives have multiple objectives and seek to balance positive economic and environmental impacts including reduction of landfill, reducing natural resource demand and minimising emissions.

Fly ash, silica fume and blast furnace slag are recycled from industrial byproducts and are referred to in Section 2.1.1.

Recycling materials as aggregates often require processes of inbound transit to a facility, crushing, separating, washing or shredding. Due to the additional processing, recycled aggregate materials typically have a higher embodied CO_2e value when compared to aggregate materials from traditional virgin sources. Due to balancing multiple environmental objectives, however, modest concessions to the embodied CO_2e may be preferable to achieving total positive ecological outcomes, such as diversion from landfill and reducing reliance on virgin material extraction.

Due partly to the introduction of Queensland landfill levies in 2019, a waste recovery market has seen a substantial rate of development within major geographic centres. Recycling from glass and construction and demolition waste (principally concrete) represents the most prolific sources of potential aggregate replacements due to relatively limited processing requirements, availability and anticipated mechanical stability.

NACOE conducted a literature review (Johannessen et al. 2021) of 3 main sources of recycled materials including recycled crushed aggregate, recycled crushed glass and recovered aggregate (from plastic concrete).

The research indicated that recycled crushed concrete coarse aggregate could be suitable for use in concrete when limited up to 30% replacement of virgin crushed aggregate, with diminishing strength and durability performance when higher quantities are used. Within MRTS70, recycled coarse aggregates are accepted for use in Normal Class concrete (non-structural) in quantities up to 20% of total coarse aggregate mass, with the condition that minimum water absorption and limits to contaminants are met.

Recycled crushed concrete fine aggregates are undesirable for use in concrete due to high water absorption impacting water demand, strength and durability performance even at modest proportions. These are not recommended for recycling back into fresh concrete.

Recycled crushed glass appears to present as mechanically stable and potentially suitable for use in concrete with the condition that contaminants including sugars are managed. Recycled glass sand at coarser size fractions is understood to represent potential alkali-silica reactivity, which is presumed to be mitigated due to TMR's mandated use of SCMs (25% fly ash or 60% GGBS).

Recycled crushed glass is accepted for use within MRTS70 up to 20% of the total fine aggregate composition, with the condition that the material complies with ATS 3050 – *Supply of Recycled Crushed Glass Sand* (Austroads 2022).

The NACOE study also reviewed aggregate recovered from waste plastic concrete, ferronickel slag from nickel refining as well as bottom-ash from coal-combustion power stations. Each of the above recycled materials appear to have some technical viability for use as a component in fresh concrete; however, insufficient research is currently available to facilitate incorporating them into specifications as an allowable material.

Crumb rubber

Interstate concrete barriers are being developed using crumb-rubber aggregate from waste tyres. Potential performance benefits indicated by research include a reduction of peak impact forces during vehicular collisions and greater deformation prior to failure when compared to traditional concrete traffic barriers (Karunarathna et al. 2023; Lyu et al. 2023). Whilst research is continuing, the use of crumb rubber aggregate is not presently accepted within TMR specifications.

3. Innovation Assessment

This section provides an overview of the innovation assessment procedure which was been developed to assess innovative products and solutions with a claimed sustainability benefit.

This includes an administrative process to receive, assess and approve new materials, products and methods under the umbrella of sustainability. However, it does not develop an assessment protocol or define criteria. It only defines broad categories rather than providing a method to develop the criteria.

3.1 Context

To achieve improvements in sustainability and the measures to assess it, changes need to be proposed and accepted. New materials, new designs, new ways of doing things will all need to be adopted, but change comes at a risk. There is a need to define what the impacts will be and if there will be unintended side effects. Therefore, it falls to TMR as the asset owner, to provide a governance framework that encourages innovation whilst mitigating unacceptable risks.

This section provides insights on what has been attempted in this space and a proposed pathway for considering sustainability initiatives in the future. A separate NACOE project, O20 Recycled and Innovative Materials Assessment Framework (Grenfell et al. 2024) further aims to produce a framework for assessment of recycled and innovative materials used in road infrastructure construction and maintenance projects.

3.1.1 Challenges

There are considerable challenges for the implementation of any agreed framework for assessing innovations. Some of the major challenges to be overcome include:

- **Unpredictability:** Innovations by their nature are new, and despite trying to keep up-to-date with the current trends in industry, TMR cannot predict exactly what will be proposed, when, or by whom.
- **Timeframes:** Innovations will often be proposed during a contract, increasing the pressure for speedy decision-making to avoid design/construction delays.
- **Long-term risk:** Bridges are planned with 100-year design lives, so any innovations will have a long-term impact, for good or bad. Testing and modelling are imperfect predictors of performance and so need to be planned and interpreted with care.
- **Industry acceptance:** Acceptance by TMR's Engineering and Technology (E&T) is only one step in getting an innovation into the field. Designers and contractors also need to be willing to experiment with change.

3.2 Approaches

Any pathway to accepting innovations must take into account the existing contractual and quality frameworks. Specifications[1] are, therefore, the key documents when it comes to having the most potential to support or hinder suggestions for the use of different materials or processes. If specifications are not written to anticipate alternative proposals, then navigating a pathway forward can become very complex and

[1] 'Specifications' here include Design Criteria and other mandatory manuals.

inconsistent from one project to another. The Transport Infrastructure Product Evaluation Scheme (TIPES)[2] process has been used within other disciplines, such as pavements and for some ancillary items, but is not seen as the way forward for structures, which are such safety critical components on the network.

Possible approaches to handling innovations are determined by asking questions at multiple stages. For example, a big-picture question is 'who initiated the innovation?' If the idea originated within TMR then the process followed would look completely different to one where a supplier comes to TMR with a new product. Before diving into these questions, some consistent principles are required. This question is considered in the work undertaken as part of the NACOE O20 Recycled and Innovative Materials Assessment Framework project (Grenfell et al. 2024).

3.2.1 Principles

Any governance framework needs to be founded upon strong principles to inform decision-making and focus attention on the overarching goals. When it comes to sustainability initiatives, the following principles are critical:

- **Net positive benefit** – innovations should be of value to the TMR as custodian and operator of the community's infrastructure. Usually this means that performance is equal to or better than the status quo, plus a sustainability or productivity bonus. There may be occasions where performance can be sacrificed as long as minimum specification and design requirements are still met, but the gains in a different aspect need to outweigh these losses.
- **Shared expectations** – proponents and the TMR should both understand how the innovation will be assessed and what it will be assessed against. These criteria may be developed early within the assessment process but shall always be communicated clearly. This aspect is being considered in the road infrastructure construction and maintenance sector through the NACOE O20 project (Grenfell et al. 2024).
- **Consistency** – innovations should be treated on their merits according to a fair process. Judgements should not be arbitrary but also accompanied by justification.

These key principles need to be taken into account along with other principles around the use of novel and recycled materials to ensure:

- equivalent if not better performance
- no work health and safety (WHS) issues for workers or the general public
- no long-term environmental impacts
- fully recyclable at the end of life.

3.2.2 Determinants

To develop or assess differing approaches to evaluating innovations, the following questions should be considered:

- Has TMR invited solutions to a specific challenge?
  - This is a popular methodology in the IT field and can also be used for narrow research questions (Transport for NSW 2024).[3] It requires significant involvement and active participation from the funding organisation and upends the more traditional innovation approach. The traditional approach has allowed industry to innovate, whereas this approach allows TMR to invite industry to provide

[2] The Transport Infrastructure Product Evaluation Scheme (TIPES) is a process aimed at providing an independent fit-for-purpose assessment of innovative road construction products. TIPES is intended for the evaluation of products that fall outside the scope of established standards and specifications. TIPES is a national scheme endorsed by all Australian state and territory road agencies as well as IPWEA (QLD), the Queensland Local Roads Alliance and WALGA.

[3] *Innovation Challenges Open Data Hub and Developer Portal* .

innovations to overcome a known challenge. This does require more TMR involvement upfront to ensure industry fully understands the problem they are trying to solve, which can facilitate better outcomes.

- Is this innovation within the intent of a specification?
  - This question creates the context of the innovation by defining the status quo that would be changed. Performance-based specifications are designed to allow innovation, should performance requirements be met. Any prescriptive elements of a specification would have to be changed to allow innovation if they were pertaining to materials to be used or processes to be followed.
- Is this actually an innovation?
  - This question tests how much of a change the proposal represents. If there is little or no change, then other assessment processes may be more appropriate.
- Does the specification prevent *carte blanche* use of the innovation?
  - Sometimes specifications are silent on the requirements for a product/process or have very clear criteria (with no assessment requirement). In these cases, there is nothing preventing the contractor/designer from doing something new and different. The move to performance-based specifications, will mean such documents will be materials or process agnostic provided that performance requirements are met.
- Does the specification anticipate this innovation by stipulating an approval process?
  - Many specifications include clauses permitting alternative or new materials and/or processes with approval. Depending on the complexity or criticality of the change, approval can be required from the Project Administrator, E&T – Structures section or even require the submission of technical documents to the TMR Director (Structures Design Review and Standards) for review and acceptance. This provides an opening for discussion and flexibility.

Whether the innovation should be classified as a 'sustainability' initiative is rather moot, since sustainability itself encompasses environmental, social and economic spheres, and even if the innovation did not fall into those scopes, the assessment process would fundamentally be the same – only the projected benefits would be different.

3.3 Examples

This section explores some classes of innovations that have been presented to the Structures Branch of TMR and how they have been managed. Details of specific products have been left undisclosed to avoid promoting (successful) and judging (unsuccessful) companies.

3.4 Proprietary Cementitious Materials (MRTS70)

When the 2018 version of MRTS70 was developed, industry had begun to explore concretes with 'activated' versions of cementitious material. These would not comply with the standard MRTS70 requirements, usually because the additives were not traditional AS 1478.1-compliant admixtures. So, a clause was added to allow some flexibility:

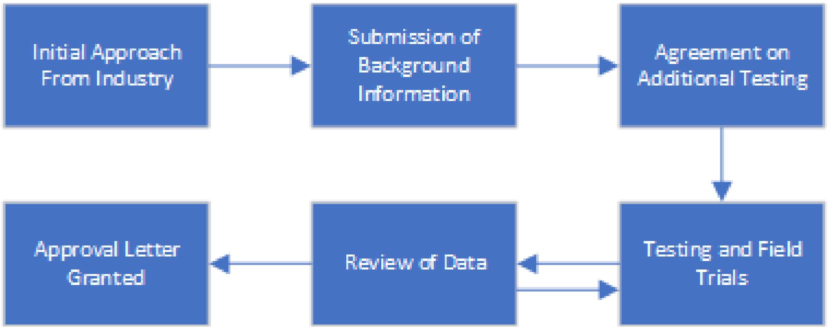
> Proprietary cementitious material systems, including any 'activators' shall be assessed for approval by the Director (Structures Construction Materials) on a case-by-case basis. Such activators need not necessarily comply with Clause 7.4 (TMR 2022).

This has proved to be a very useful clause to allow for innovation because it fits within the contractual governance framework and allows conditions to be determined when the innovation is assessed. At this stage, 2 different types of proprietary cementitious material systems have been considered, each from multiple suppliers:

- enhanced supplementary cementitious materials, permitted with relaxations to the usual cementitious blend requirements
- fast-setting concrete, permitted with cement types not included in AS 1379.

These assessments all followed a common, yet unpublished, workflow. This workflow is described in Figure 3.1.

Figure 3.1: Innovation workflow – cementitious systems



These approval letters contained precise instructions on what clauses of MRTS70 remained applicable and how others were relaxed. Similar text was used for new materials of the same type to ensure the same criteria were applied to each company.

These assessments can be considered a success in that the products have continued to be used; there have been only minor misunderstandings about what has been approved (e.g. cementitious systems vs mix designs), and the process itself went smoothly. It should be noted that the companies involved are large and experienced at dealing with TMR. Smaller companies are less likely to know who to talk to, have access to testing facilities or understand the governance framework in which the Department operates. Therefore, having formal assessment protocols will make the process transparent and ensure proponents speak to the right people to get the correct advice.

3.4.1 Durability-enhancing Admixtures (MRTS70)

The Structures Branch has been approached by several suppliers of innovative admixtures such as nano-fibres, internal curing agents and crystalline cementitious agents. These assessments have followed the flow in Figure 3.1 but have been less successful. When confronted with a net positive benefit requirement, the materials could generally not prove a sustainability benefit against existing concrete mixes.

As an aside, this is a common feature of innovations in concrete. Performance enhancement is observed when comparing mid-strength concrete (20, 25 MPa) with and without the additive, but gains are not significant against TMR-specification S40 and S50 mixes.

The bar set for TMR concrete is that equivalent mechanical and durability performance is met, and then the value is realised by reducing the overall cementitious content. Increasing the design life of the concrete over and above 100 years is not considered a benefit when the rest of the bridge does not consider this extended timeframe.

To date suppliers, have only been issued with letters of no objection, whereby the product is permitted in concrete mixes, but no relaxations are given to any other requirements and notice is given that TMR does not endorse its use.

3.4.2 Bridge Design (Design Criteria for Bridges and Other Structures)

Innovations that include a fundamental change to typical bridge designs are rarer but have the potential to achieve significant gains. Two recent examples stand out, one for a new girder cross-section allowing longer spans and one for a pre-fabricated super-structure shell allowing rapid construction of short bridges. As 'designs' these innovations faced significant challenges in their route to acceptance since the product assessment flowchart (Figure 3.1) does not apply.

The *Design Criteria for Bridges and Other Structures* has, since 2017, included a section for innovative materials and components (Clause 2.8, TMR 2024c) but this is focused on long-term inspection and maintenance with little detail about how innovative designs would be assessed; it simply states that they 'shall have relevant procedures and information prepared'. In 2020, a new clause on innovation was added (Clause 2.7, TMR 2022) which outlines the principles of equivalency and appropriate validation. It also warns that innovations should be addressed outside of contract since assessment will hold up project design.

The case of the new girder shape took place prior to this second clause appearing and there were issues with communication as to what was required to be proven prior to acceptance. Additionally, approval was granted in a conditional manner limiting where and how the design could be used creating uncertainty for designers wishing to consider it.

The second case proceeded more smoothly to design approval but has struck a barrier regarding fabrication due to the intersection of design approval and supplier registration. This was raised as a condition while the design was being assessed, but full ramifications were not understood.

These cases highlight the difficulties of assessing and adopting innovative design choices:

- Often the innovator will need to convince both the project designer and the E&T assessors of the benefits before it is implemented.
- 'Trials' may not be feasible as:
  - Bridges are inherently complex, long-term and costly.
  - A smaller scale may cancel out any possible benefits.
- Designs cannot be isolated from manufacture and construction.
- Larger teams are likely to be involved in the assessment.
- Acceptance will often come down to 'judgement' or 'comfortableness'.

3.5 Proposed Pathway

The elements to a strong pathway towards assessment and adoption of innovations, particularly those with sustainability benefits already exist within Structures documents and processes. However, they can be improved upon and expanded.

Most importantly, a clear overarching protocol would be advantageous to create shared expectations between industry and the Department. E&T published an *Engineering Innovation* document in 2014 (TMR 2014) that, as noted by TMR representatives, struggled to land on what it was trying to achieve and move past a simple flowchart to actionable guidance. Any developed document could be reviewed to bring together E&T's approach to innovation and provide better guidance to industry.

More specifications could take the approach of MRTS70 and provide avenues for flexibility where known areas of research and development exist. A key actionable step would be to identify and note known areas of research and development within specifications. The *Design Criteria* could also provide more details about how design innovations are managed and whether they are managed differently from standard departures.

The current product assessment schemes (e.g. the *Product Index for Bridges and Other Structures*) could be expanded, as part of an E&T-wide framework, to address innovation rather than simply be bounded by the Specifications.

Structures' internal processes for assessment and approval can be revised to provide stronger consistency and clearer communication and, therefore, hopefully reduce assessment timeframes.

4. Implementing Low Carbon Concrete Solutions

Alongside this research report, a new TMR Technical Note 59 *Low Carbon Concrete* has been developed to summarise the findings of Sections 2 and 3. The Technical Note provides an introduction to a range of materials and technologies that are discussed under the banner of low carbon concrete. This enables an understanding of what suppliers and researchers are proposing, assisting TMR decision-makers and delivery project teams to focus on reasonable innovations and place any claims in context. Efficient evaluation of these innovations requires clear pathways towards approval or trial, and a clear path to rejection to prevent unproductive investigations.

The Technical Note was developed with reference to the findings of this project and NACOE S67 *Future Availability of Fly Ash for Concrete Production in Queensland*, and the form of TN193 *Use of recycled Materials in Road Construction.* The opinions of potential readers were also sought to ensure the aims were being met and the level of detail was well-balanced.

5. Material Usage Data

This section examines existing sources of data for estimating material quantities and embodied carbon for TMR's structures. It includes:

- an introduction (Section 5.1)
- a description of the desktop review which was undertaken (Section 5.2)
- an overview of the data which was collected (Section 5.3)
- a summary of the data quality assessment framework and criteria which were developed (Section 5.4)
- a detailed description of the data quality assessment which was undertaken (Section 5.5)
- conclusions (Section 5.6).

5.1 Introduction

This section examines existing data sources for estimating embodied carbon in TMR structures. The objective was to seek to understand the availability and quality of data sources that will inform material usage and embodied carbon estimates on TMR structures. The materials of interest to TMR include concrete, reinforcing and structural steel and structural timber. Each data source has been assessed for its quality in accordance with the relevant ISO standard (ISO 14044:2006 and ISO 14025:2006). The assessment considers the accuracy of the data and its accessibility (including commercial sensitivities).

The types of data required for embodied carbon estimation assessments include:

- material types and quantities from project-level data
- embodied carbon estimates (i.e. emissions factors) for the relevant material types.

5.2 Desktop Review

In consultation with TMR, the National Transport Research Organisation (NTRO) identified a range of data sources for the type and quantity of materials used in TMR structures and sources for the embodied carbon emissions of materials. NTRO sought this data for 5 case studies that included significant structures. This section presents a desktop review of the data scope and availability of the data sources.

5.2.1 Case Studies

Based on these case studies, conclusions have been drawn on the suitability of TMR's and other available datasets for undertaking an estimation of the embodied carbon. The case studies and their regions/districts are outlined in Table 5.1.

Table 5.1: Case studies

Project	Region/District
Ipswich Motorway Upgrade, Rocklea to Darra (R2D)	Metro
Bruce Highway, Caloundra Rd to Sunshine Motorway (CR2SM)	North Coast
Bruce Highway, Edmonton to Gordonvale (E2G)	Cairns
Townsville Ring Road (TRR)	Townsville
Sumners Road Overpass (Western Freeway)	Metro

5.2.2 Sourcing of Material Quantities

The following sources of material type and quantity data were sought from TMR:

- Bills of Quantities (BoQ) and material tracking registers
- Infrastructure Sustainability (IS) ratings
- digital designs (e.g. TMR Building Information Modelling (BIM) drawings)
- contract documents and claims (e.g. TMR Portfolio, Program, Project and Contract Management (3PCM))
- stakeholder-supplied data from TMR concrete suppliers, contractors and consultants.

The sources are developed and revised throughout the life cycle of a project, as outlined in Table 5.2.

Table 5.2: Available sources of data at various stages of the life cycle of a project

Stages	Tasks	Available sources of material type and quantity data
Pre-planning	Initial design and costings Tendering	BoQ (initial) Contract documents and claims (initial)
Planning	Design Cost estimation	BoQ (revised) IS Materials Calculator 'Design' BIM (initial) Contract documents and claims (revised)
Construction	Building the structure	BoQ (updated throughout) Material tracking register (updated throughout) BIM (updated throughout) Contract documents and claims (updated throughout) Stakeholder supplied data
Post-construction	Quality and safety inspections	IS Materials Calculator 'As-Built' BIM (updated throughout)

Bills of Quantities and material tracking registers

BoQs are itemised lists of project costs for both labour and the various material types and quantities needed for construction. They are typically provided at the tendering stage of a project and are revised and updated throughout the project. Material tracking registers are used to monitor not only the type and quantity of materials used during construction of a project but also include the energy use associated with various construction and operational tasks.

Infrastructure Sustainability Ratings

The IS Rating Scheme evaluates sustainability initiatives and potential environmental, social and economic impacts of infrastructure projects and assets. The scheme can be applied across the planning, design, construction and operational phases of infrastructure assets (Infrastructure Sustainability Council ((ISC) 2023a). TMR mandates IS ratings on all projects valued at over $100 million in capital expenditure. The IS Materials Calculator is a free tool developed by the ISC for use on IS ratings (for the RSO-6 Material life cycle impact measurement and management credit). Where TMR has undertaken an IS rating, material information (type and quantities) is entered into the calculator.

Digital designs

Digital designs (i.e. structural drawings) are developed by structural designers to provide a digital representation of the structure prior to commencing construction. In some cases, they can provide an indication of the type and quantity of materials needed for the structure. Successive State Infrastructure Strategy documents have promoted a 'digital by default' approach (TMR 2023). This sets a clear direction for the progressive implementation of BIM into all major state infrastructure projects.

For bridges and structures, the bridge BIM model encompasses the structural design of the bridge asset in a complete 3D electronic model and is progressively developed through the asset's life cycle. The *BIM for Bridges Manual* defines the requirements and attribute definitions for all phases of the Bridge BIM life cycle (TMR 2024a). This includes the material types used on the structure. It is expected to include the material quantities in both the design phase and the construction phase (G Cairns, personal communication, 5 October 2023).

BIM is a strong candidate in future applications as the basis for materials passports for structures which supports resource efficiency, material selection and material circularity. However, at this stage, data cannot be shared for individual projects. TMR's E&T team noted that BIM models are developed by or for the project team and then submitted to E&T for review against TMR specifications. This means that the models rest with each district or project owner. Therefore, in order to access these models a request needs to be lodged with the project manager to start with, who may raise the request with the regional director. Further to this, TMR E&T noted that BIM data was not available for these specific case studies in the detail which was requested. Although these case studies may have basic volumetric data in BIM, the lack of maturity in this data means it would not likely provide value for the intention of this research.

Contract documents and claims

Contract documents provide an overview of the costs associated with all construction-related activities. One common type of data source highlighted is 3PCM, which is TMR's information communications technology (ICT) solution to deliver projects, contracts and programs. It is used to monitor and manage the costs related to all construction activities by categories such as construction, structures, pavements, etc.

Stakeholder-supplied data from TMR concrete suppliers, contractors and consultants

TMR requested information on all concrete which had been ordered in accordance with TMR specifications from 3 of its major suppliers. One supplier provided TMR's concrete order data, another cited commercial sensitivity and the third did not respond. The supplier data provided included concrete supply volumes by mix design. It was not entirely possible to break down the supply quantity data by project or project component in its provided form; however, it may be possible to draw conclusions, subject to further research, as specific mix designs are typically used for specific structural elements.

5.2.3 Sourcing of Embodied Carbon Factors

Embodied carbon estimation data for structural materials can be retrieved from:

- life cycle inventory databases (e.g. AusLCI, Ecoinvent)
- factors from within carbon calculators (e.g. IS Materials Calculator, Sustainability Assessment Tool for Pavements (SAT4P))
- EPDs.

Australian Life Cycle Inventory and the Constructions Emissions Database

The AusLCI provides a national, publicly accessible database to assist in undertaking LCA. The inventory database includes material and process flow data that can be used with standardised analytical methods to generate carbon emissions factors (ALCAS 2011). AusLCI includes a shadow database which is used to support gaps in AusLCI data. The shadow database is an Australianised version of the ecoinvent 2.2 database (described below) based on typical European/global practice but where all input flows have been changed to Australian inputs and process data where this is available e.g. all electricity, transport, natural gas etc. are changed to Australian inputs as well as any material data.

In May 2023 ALCAS released a new set of emissions factors specifically for the construction sector. The AusLCI Carbon Emissions Factors (AusLCI_1.42_EF_Contruction) contains emissions data in kg CO_2-e as an extract from the AusLCI database (ALCAS 2023). This new database includes key structural materials such as concrete, timber and steel. Figure 5.1 shows an extract of this database.

Figure 5.1: Extract from the AusLCI construction database

	A	B	C	D	E	F	G
1	Process name	Ur	Process type	Construction sect	Construction sector sul	Data source	Climate change – CN kg CO2 e
67	general purpose cement, imported clinker	kg	Material	Concrete and cement	Cementatious material	AusLCI	1.04
68	ground granulated blast furnace slag, at cement plant	kg	Material	Concrete and cement	Cementatious material	AusLCI	0.19
69	ordinary portland cement, at plant	kg	Material	Concrete and cement	Cementatious material	AusLCI	0.93
70	ordinary portland cement, Australian average	kg	Material	Concrete and cement	Cementatious material	AusLCI	0.97
71	ordinary portland cement, imported clinker	kg	Material	Concrete and cement	Cementatious material	AusLCI	1.09
72	concrete 20 MPa 30% fly ash, at batching plant	m3	Material	Concrete and cement	Concrete	AusLCI	225.66
73	concrete 20 MPa 30% GGBFS, at batching plant	m3	Material	Concrete and cement	Concrete	AusLCI	244.66
74	concrete 20 MPa, at batching plant	m3	Material	Concrete and cement	Concrete	AusLCI	305.73
75	concrete 25 MPa 30% fly ash, at batching plant	m3	Material	Concrete and cement	Concrete	AusLCI	253.60
76	concrete 25 MPa 30% GGBFS, at batching plant	m3	Material	Concrete and cement	Concrete	AusLCI	274.64
77	concrete 25 MPa, at batching plant	m3	Material	Concrete and cement	Concrete	AusLCI	342.22
78	concrete 32 MPa 30% fly ash, at batching plant	m3	Material	Concrete and cement	Concrete	AusLCI	290.02
79	concrete 32 MPa 30% GGBFS, at batching plant	m3	Material	Concrete and cement	Concrete	AusLCI	314.45
80	concrete 32 MPa, at batching plant	m3	Material	Concrete and cement	Concrete	AusLCI	392.91
81	concrete 40 MPa 30% fly ash, at batching plant	m3	Material	Concrete and cement	Concrete	AusLCI	348.37
82	concrete 40 MPa 30% GGBFS, at batching plant	m3	Material	Concrete and cement	Concrete	AusLCI	378.23

Source: ALCAS (2023).

Ecoinvent

The ecoinvent database is the international Life Cycle Inventory (LCI) database that supports various types of sustainability assessments. ecoinvent is regularly updated with version 3.10 containing more than 20,000 datasets modelling human activities or processes on global and regional levels. It covers a diverse range of sectors with information on industrial or agricultural processes, natural resource extractions from the environment, emissions to water, soil and air, product inputs from other processes (e.g. electricity), and the products, co-products and wastes produced (ecoinvent 2024).

Infrastructure Sustainability Materials Calculator

The Infrastructure Sustainability (IS) Materials Calculator is a support tool for the IS rating scheme developed and administered by the ISC. The IS Materials Calculator evaluates environmental impacts in relation to use of materials on infrastructure projects and assets (ISC 2023a). The IS Materials Calculator includes calculated embodied environmental impact factors for typical construction materials and is based on the AusLCI database and its shadow database, complemented with data from EPDs (ISC 2023a). This IS Materials Calculator (ISC 2023b) covers ready-mix concrete, precast concrete, binders, aggregates, steel and timber. Figure 5.2 shows an extract of the LCI worksheet from the IS Materials Calculator.

Figure 5.2: Screenshot of the IS Materials Calculator LCI data

Infrastructure Sustainability Materials Calculator
Life cycle inventories: IS EnviroPoints v2.0
Weighted, normalised and mid-point factors

Unit	Product group	Name	LCI Source	LCI process	Mid-point – Impact category: Global Warming (Unit: kg CO2 eq/unit)	IS EnviroPoints v2 (Pt/unit)
		1	2	3	4	5
t	Concrete Components	Additives	AusLCI Shadow database	Melamine formaldehyde resin, at plant/RER U/AusSD U + 250 tkm transport, truck, 3,5 to 16t,	4.25E+03	4.74E+01
t	Concrete Components	Alkali activator	AusLCI Shadow database	Sodium silicate, furnace liquor, 37% in H2O, at plant/RER U/AusSD U + transport to concrete p	1.10E+03	1.15E+01
t	Concrete Components	Cement	AusLCI	ordinary portland cement, Australian average/AU U + 200 tkm transport, truck, 40t load/AU U	9.74E+02	8.26E+00
t	Concrete Components	Coarse Aggregates	AusLCI Shadow database	Gravel, crushed, at mine/CH U/AusSD U + 50 tkm transport, truck, 28t, fleet average/AU U	9.52E+00	8.83E-02
m3	Concrete Components	Concrete production process	AusLCI	Concrete 40MPa, at batching plant/AU U (adapted from)	7.24E+00	6.93E-02
t	Concrete Components	Fibercon Emesh®	EPD	Fibercon E-Mesh and Macro Poly 2016 (EPD864)	2.50E+03	2.22E+01
t	Concrete Components	Fine Aggregates	AusLCI Shadow database	Sand, at mine/CH U/AusSD U + 50 tkm transport, truck, 28t, fleet average/AU U	3.84E+00	3.63E-02
t	Concrete Components	Flyash	AusLCI	fly ash, delivered to plant/AU U + 200 tkm transport, truck, 40t load/AU U	1.37E+01	1.46E-01
t	Concrete Components	GGBF slag	AusLCI	ground granulated blast furnace slag, at cement plant/AU U + 70 tkm transport, truck, 40t load	1.77E+02	2.08E+00
t	Concrete Components	Mains water	AusLCI Shadow database	Tap water, at user/RER U/AusSD/Link U	4.55E-01	4.22E-03
t	Concrete Components	Manufactured sand	AusLCI	Gravel, crushed, at mine/CH U/AusSD U + 50 tkm transport, truck, 28t, fleet average/AU U	9.52E+00	8.83E-02
t	Concrete Components	On-site recycled & captured water	NA	No impact	0.00E+00	0.00E+00
t	Concrete Components	Polymer fibre reinforcement	EPD	Fibercon E-Mesh and Macro Poly 2016 (EPD864)	4.80E+03	5.33E+01
t	Concrete Components	Recycled Aggregates	AusLCI	recycled aggregate, at plant/AU U + 50 tkm transport, truck, 28t, fleet average/AU U	7.30E+00	7.44E-02
t	Concrete Components	Steel fibres for concrete reinforcement	EPD	Low relaxation strand and wire - Australian	3.20E+03	3.31E+01
t	Concrete Components	BarChip 48	EPD	BarChip Inc BarChip 48, BarChip 54 and BarChip 60 Macro Synthetic Fibre 2020 (EPD2056)	1.99E+03	2.84E+01
t	Concrete Components	BarChip R50	EPD	BarChip Inc BarChip R50, BarChip R65 Macro Synthetic Fibre 2020 (EPD2056)	1.80E+03	2.46E+01
t	Concrete Components	BarChip R65	EPD	BarChip Inc BarChip R50, BarChip R65 Macro Synthetic Fibre 2020 (EPD2056)	1.80E+03	2.46E+01
t	Steel	InfraBuild Steel, Reinforcing Rod and Wire	EPD	InfraBuild Reinforcing Rod, Bar & Wire 2020 (EPD855): Reinforcing rod and wire	1.98E+03	2.03E+01
t	Steel	InfraBuild Steel, Low relaxation wire	EPD	InfraBuild Reinforcing Rod, Bar & Wire 2020 (EPD855): Reinforcing rod and wire	1.98E+03	2.03E+01
t	Steel	Low relaxation strand and wire - imported	EPD	Based on Australian factors; 5% increase due to lack of EPDs	3.36E+03	3.47E+01
t	Steel	ARC, Reinforcing Bar	EPD	Australian Reinforcing Company Reinforcing Bar & Mesh 2020 (EPD858): Reinforcing bar	1.67E+03	1.69E+01
t	Steel	InfraBuild Construction Solutions, Reinforcing Bar	EPD	InfraBuild Construction Solutions Reinforcing Bar & Mesh 2020 (EPD857): reinforcing bar	1.67E+03	1.69E+01
t	Steel	InfraBuild Steel, Reinforcing Bar	EPD	InfraBuild Reinforcing Rod, Bar & Wire 2020 (EPD855): Reinforcing bar	1.58E+03	1.59E+01
t	Steel	Reinforcement steel bars - imported	EPD	Based on Australian factors; 5% increase due to lack of EPDs	1.75E+03	1.77E+01
t	Steel	ARC, Reinforcing Mesh	EPD	Australian Reinforcing Company Reinforcing Bar & Mesh 2020 (EPD858): Reinforcing mesh	2.06E+03	2.10E+01
t	Steel	InfraBuild Construction Solutions, Reinforcing Mesh	EPD	InfraBuild Construction Solutions Reinforcing Bar & Mesh 2020 (EPD857): reinforcing mesh	2.06E+03	2.10E+01
t	Steel	Reinforcement steel mesh - imported	EPD	Based on Australian factors; 5% increase due to lack of EPDs	2.16E+03	2.21E+01
t	Steel	Reused Structural Steel	NA	No impact	0.00E+00	0.00E+00
mm	Steel	Steel Galvanised Coil - Steel BMT (per mm) only	EPD	Structural steel, hot rolled coil - Australian	1.87E+01	1.80E-01
g	Steel	Steel Galvanised Coil - Zinc coating (per g/m2 zinc) only	AusLCI Shadow database	Zinc coating, coils/RER U/AusSD U	8.51E-03	3.42E-04
t	Steel	Steel pipe and tube - Australian	EPD & AusLCI Shadow database	Steel, hot rolled coil - Australian & AusLCI: Sheet rolling, steel/RER U/AusSD U	2.80E+03	2.71E+01
t	Steel	Steel pipe and tube - imported	EPD & AusLCI Shadow database	Based on Australian factors; 5% increase due to lack of EPDs	2.93E+03	2.84E+01
t	Steel	Liberty Primary Steel, Rail product	EPD	Liberty Hot Rolled Structural and Rail 2020 (EPD1547): rail products	3.32E+03	3.46E+01
t	Steel	Steel rails - imported	EPD	Based on Australian factors; 5% increase due to lack of EPDs	3.49E+03	3.64E+01
t	Steel	Steel, hot rolled metal coated - Australian	EPD & AusLCI Shadow database	Steel, hot rolled coil - Australian & Zinc coating, coils/RER U/AusSD U	2.75E+03	3.78E+01
t	Steel	Steel, hot rolled metal coated - imported	EPD & AusLCI Shadow database	Based on Australian factors; 5% increase due to lack of EPDs	2.89E+03	3.97E+01
t	Steel	Steel, hot rolled powder coated - Australian	EPD & AusLCI Shadow database	Steel, hot rolled metal coated - Australian & Powder coating, steel/RER U/AusSD U	3.06E+03	4.08E+01
t	Steel	Steel, hot rolled powder coated - imported	EPD & AusLCI Shadow database	Based on Australian factors; 5% increase due to lack of EPDs	3.21E+03	4.29E+01
t	Steel	InfraBuild Steel Centre, Hot rolled structural sections	EPD	InfraBuild Steel Centre Hot Rolled Structural and Merchant Bar 2020 (EPD856): structural secti	3.72E+03	3.86E+01
t	Steel	Liberty Primary Steel, Hot rolled structural sections	EPD	Liberty Hot Rolled Structural and Rail 2020 (EPD1547): structural sections	3.32E+03	3.46E+01
t	Steel	Steel, Hot rolled structural sections, imported	EPD	Based on Australian factors; 5% increase due to lack of EPDs	2.99E+03	3.07E+01
t	Steel	BlueScope Welded Beams and Columns	EPD	BlueScope Welded Beams and Columns 2020 (EPD559)	2.75E+03	2.82E+01
t	Steel	Steel, welded beams and columns - imported	EPD	Based on Australian factors; 5% increase due to lack of EPDs	2.89E+03	2.96E+01
t	Steel	BlueScope Hot Rolled Coil – Low Carbon Steel	EPD	BlueScope Hot Rolled Coil 2020 (EPD557)	2.33E+03	2.24E+01
t	Steel	BlueScope Hot Rolled Coil – Medium Carbon Steel	EPD	BlueScope Hot Rolled Coil 2020 (EPD557)	2.38E+03	2.29E+01
t	Steel	BlueScope Hot Rolled Coil – Alloyed Steel	EPD	BlueScope Hot Rolled Coil 2020 (EPD557)	2.49E+03	2.55E+01

Source: ISC (2023b).

Sustainability Assessment Tool for Pavements (SAT4P)

NACOE, working in collaboration with the Western Australian Road Research and Innovation Program (WARRIP), have developed a user-friendly SAT4P to calculate life cycle GHG emissions and life cycle cost benefits of innovative road pavement designs and rehabilitation treatments. The SAT4P addresses the capability gap of existing tool limitations which do not have the flexibility to quantify innovative pavement materials (i.e. recycled), designs (e.g. crumb rubber asphalt), and processes (e.g. warm-mixes and in situ stabilisation) (Hall et al. 2020).

SAT4P is a specialised tool for road pavements and has not been enabled for structures. That said, where elements cross over between roads and structures, some elements of the tool may be able to be implemented for a representative purpose. The SAT4P materials database currently contains nearly 90 individual pavement materials with Queensland-specific carbon emissions (as well as other environmental impact) factors. Some of structural asset materials are also common to pavement materials, e.g. aggregates, reinforced concrete and some supplementary materials (e.g. concrete curing compound, set-accelerating/retarding mixtures, fly ash and slag). However, these structures may also contain additional materials not presently covered in SAT4P, such as structural concrete, steel and timber.

A sample extract of the SAT4P materials database is shown in Figure 5.3.

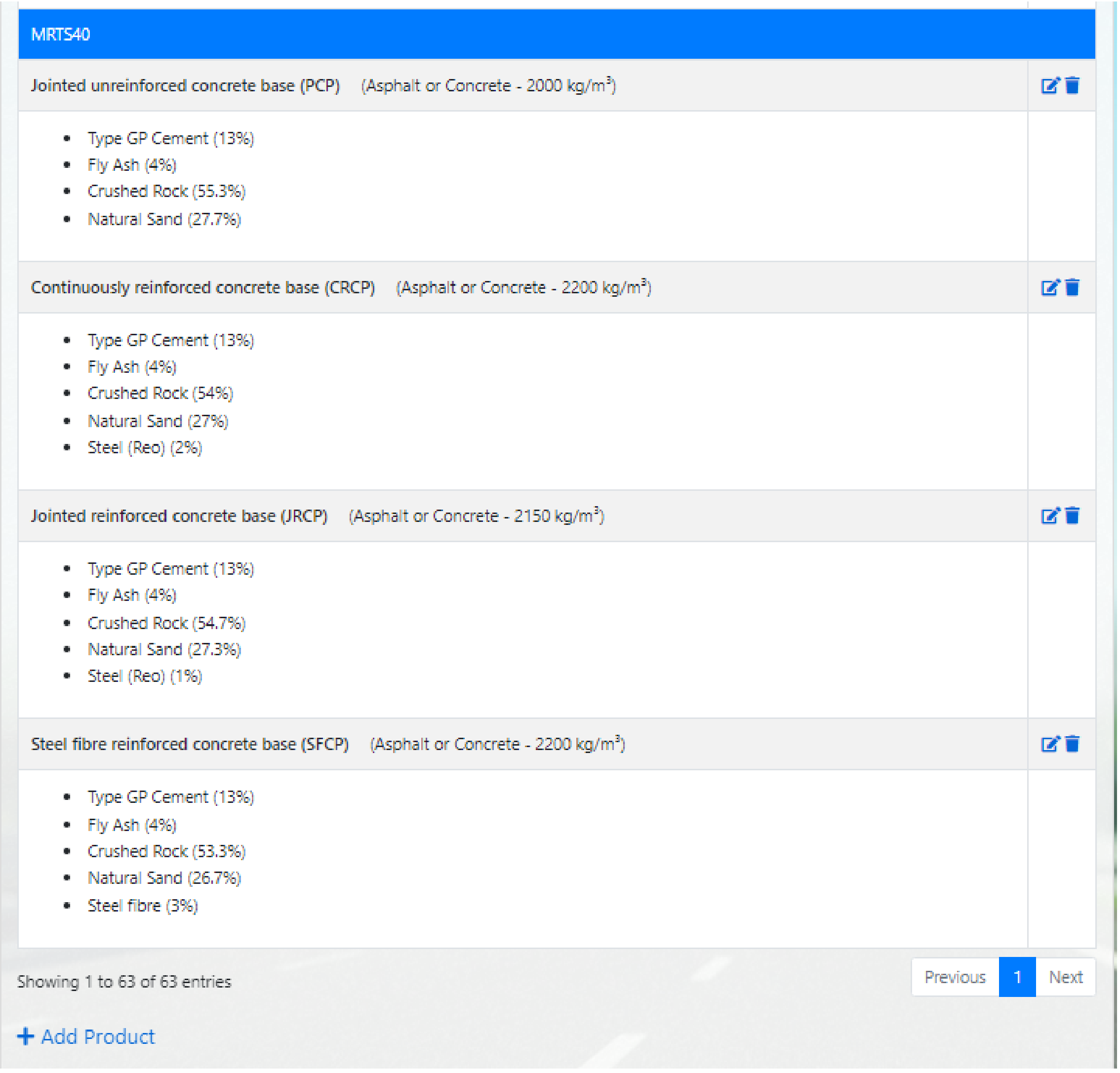
Figure 5.3: Sample extract from the SAT4P materials database

Concrete			
Steel (Reo)	7580 kg/m³	Virgin	1.95369336265315 tCO_2eq/tonne
Steel fibre	7580 kg/m³	Virgin	1.95369336265315 tCO_2eq/tonne
In-situ Material			
In-Situ Material	2000 kg/m³	Virgin	0 tCO_2eq/tonne
Supplementary Materials			
Air-entraining admixture	700 kg/m³	Virgin	4.22349716718234 tCO_2eq/tonne
Concrete curing compound	1051 kg/m³	Virgin	2.29798457068313 tCO_2eq/tonne
Fly Ash	2500 kg/m³	Recycled	0.01374763 tCO_2eq/tonne
Foaming agent	670 kg/m³	Virgin	2.3126364107935 tCO_2eq/tonne
Geotextile fabric	678 kg/m³	Virgin	2.4740412979351 tCO_2eq/tonne
Quicklime	3200 kg/m³	Virgin	1.00576358664428 tCO_2eq/tonne
Set-accelerating admixture	700 kg/m³	Virgin	4.22349716718234 tCO_2eq/tonne
Set-retarding admixture	700 kg/m³	Virgin	4.22349716718234 tCO_2eq/tonne
Slag (Ground Granulated Blast Furnace Slag)	3200 kg/m³	Recycled	0.168766305544627 tCO_2eq/tonne

Source: NACOE (2025).

SAT4P also contains a product library of pre-defined (MRTS specification aligned) road pavement products. Each product is made up of one or more of the materials from the material library. Structures such as bridges and overpasses will include pavement decking, so some pavement products may be relevant. Prior to implementation of this, a review would need to be undertaken of relevant TMR specifications to ensure alignment in pavement products, as SAT4P was intended to be for road pavements. This may include, but is not limited to, MTRS77 *Bridge Deck* (TMR 2019b), MRTS70 *Concrete* (TMR 2022), and MRTS72 *Manufacture of Precast Concrete Elements* (TMR 2019a). Figure 5.4 shows an extract of the SAT4P product library showing the MRTS specified material compositions of concrete pavements, as an example of the details possible within the tool.

Figure 5.4: Sample extract from the SAT4P product library



Source: NACOE (2025).

The NACOE Sustainability Stream has indicated an intent to further develop the SAT4P architecture and databases to enable embodied and life cycle emissions estimates of structural assets. This intent is not yet confirmed with dedicated funding or timelines and interim solutions for carbon estimation are necessary.

Environmental Product Declarations

EPDs outline the life cycle environmental impact of a company's specific products (EPD) and are becoming increasingly common among product and material suppliers and manufacturers. In Australia, EPDs cover a range of materials relevant to structures, including concrete, steel (reinforcing and structural), and wood and timber products. EPDs are often generated by a third party and always independently reviewed and verified according to ISO 14025. The data required to undertake an EPD include specific (or foreground) data that is sourced directly from the producer/manufacturer and generic (or background) data from life cycle inventory databases, such as AusLCI and ecoinvent.

5.3 Data Collected

This section summarises the data which was collected. This includes an overview of the availability and accessibility of the data requested (Section 5.3.2).

5.3.1 Overview

Table 5.3 provides an overview of the data that was provided to NTRO from the 5 case studies. The data varied across the different projects and it was not possible to obtain all data for the case studies (see the following section on data availability and accessibility). It should be noted that it is not possible to determine how the received data was generated; it is assumed that the data provided is accurate and has been compiled properly.

Table 5.3: Overview of data obtained across the 5 case studies

Project	Bills of quantities and material tracking registers	Infrastructure sustainability ratings	Digital designs	Contract documents and claims	Stakeholder-supplied data
Ipswich Motorway Upgrade, R2D	n.a.	IS Materials Calculator	n.a.	n.a.	n.a.
Bruce Highway, E2G	BoQs	IS Materials Calculator	n.a.	n.a.	n.a.
Townsville Ring Road (TRR)	BoQ and Material Tracking Register	IS Materials Calculator	n.a.	n.a.	n.a.
Bruce Highway, Caloundra Rd to Sunshine Motorway (CR2SM)	BoQ	n.a.	n.a.	n.a.	n.a.
Sumners Road Overpass, Western Freeway	BoQ	n.a.	2D drawings	3PCM	n.a.

Notes:

- n.a. indicates that data was not available or not provided.
- For the Bruce Highway (E2G) project 3 BoQs were supplied that cover the main contract and 2 major scope changes.

Some extracts illustrating the various data that was obtained are given in the Figures below. Sample data extracts obtained are presented for BoQ (Figure 5.5 and Figure 5.6), Material Tracking Register (Figure 5.7), IS Materials Calculator (Figure 5.8), 3PCM (Figure 5.9) and drawings (Figure 5.10).

Figure 5.5: Sample extract of bill of quantities data provided (Townsville Ring Road)

	DESCRIPTION	UNIT	PTU SUBMISSION (GRC QS REMEASURE) QTY
71707	Erection of prestressed concrete deck and kerb units, [depth 1000] mm deep, [length 25.13] metres long	each	19.00
71709	Holding-down bolts for prestressed concrete deck and kerb units, [l1500 1450] mm long	each	38.00
	Bridge Deck (MRS77 JUL 19)		
72000	**Concrete and Reinforcements**		
72002	Concrete Class S [compressive strength 40] MPa/20 in deck	m3	78.96
72004	Concrete Class S [compressive strength 40] MPa/20 in parapet and parapet terminal	m3	21.90
72006	Concrete Class S [compressive strength 40] MPa/20 in relieving slab	m3	55.20
72007	Reinforcing steel in decks, cross girders, kerbs and parapets, excluding parapet terminals	tonne	17.21
72008	Reinforcing steel in medians, insitu kerbs and parapets	tonne	3.46
72009	Reinforcing steel in relieving slabs	tonne	12.64
72011	Mechanical reinforcing bar splices, [diameter] mm diameter	each	
72030	**Cast-In Anchors**		
72031	Anchors for bridge rail (Anti-Throw Screens)	LS	1.00
72032	Anchors for guardrail terminals	LS	1.00

Figure 5.6: Sample extract of BoQs data provided (Bruce Highway E2G)

	SCHEDULE H - BRIDGES		
BRIDGES	**Pedestrian Overpass - Gordonvale**		
	DRAINAGE, RETAINING STRUCTURES AND PROTECTIVE TREATMENTS		
30555.01	Sheet filter drains	m^2	36.00
30556.01	Strip filter drains	m	18.00
30557.01	Sheet or strip filter drain outlet connection, [type]	each	4.00
30562 .01	Supply and installation of geotextile, Strength Class [strength class], Filtration Class [filtration class]	m^2	-
30671.01	Bridge abutment protection Type 1 rock spillthrough, [location] abutment (Dumped Rock)	each	1.00
30672.01	Bridge abutment protection Type 2 reinforced concrete over road embankment spillthrough, [location] abutment		
	Abutment Bearing Inspection	each	2.00
	GENERAL EARTHWORKS		
	Earthworks, Backfill		
32403.01	Backfill with free draining granular material to [description]	m^3	100.00
	Earthworks, Excavation		
32104.01	Excavation for structures, all materials [Blade Piers & Abutments]	m^3	310.50
32109.01	Blinding concrete, [thickness] mm nominal thickness	m^2	207.00
	BRIDGE SUBSTRUCTURE		
70302.01	Concrete Class [40] MPa/20 in pier pile cap	m^3	244.00
70302.01	Concrete Class [40] MPa/20 in blade wall	m^3	129.60
70303.01	Concrete Class [40] MPa/20 in pier above pile cap/cast-in-place pile/footing. **[Circular Columns]**	m^3	
70303.02	Concrete Class [40] MPa/20 in pier above pile cap/cast-in-place pile/footing. **[Y-Shape Columns]**	m^3	144.76
70304.01	Concrete Class [40] MPa/20 in pier headstock.	m^3	25.92
70311.01	Steel reinforcing bar in piers and abutments including parapet terminals.	tonne	92.53

Source: TMR (2024b)

Figure 5.7: Sample extract of material tracking register data provided (Townsville Ring Road)

Date	Docket #	Product	Product Code	Mix Code	Quantity	Distance (km)	Unit	Material	Material unit	Material Qty	Strength (MPa) updated	% SCM updated
12/6/2021	6122021	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	0.01	0	m^3	RM Concrete	m^3	0.01	40	30%
12/6/2021	40310064	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	2	12	m^3	RM Concrete	m^3	2	40	30%
12/7/2021	40310091	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	5	12	m^3	RM Concrete	m^3	5	40	30%
12/8/2021	40310107	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310108	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310111	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310113	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310115	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310117	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310119	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.2	12	m^3	RM Concrete	m^3	7.2	40	30%
12/8/2021	40310122	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.1	12	m^3	RM Concrete	m^3	7.1	40	30%
12/8/2021	40310124	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.1	12	m^3	RM Concrete	m^3	7.1	40	30%
12/8/2021	40310126	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310128	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310130	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/17/202	44897553	QLD STABILISED SAND 10%	137845	ZAR10PS00H	7	16	m^3	Portland Cement	tonnes	1.26		
12/8/2021	40310132	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310136	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.2	12	m^3	RM Concrete	m^3	7.2	40	30%
12/8/2021	40310143	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	6	12	m^3	RM Concrete	m^3	6	40	30%
12/8/2021	40310151	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	3	12	m^3	RM Concrete	m^3	3	40	30%
12/8/2021	40310093	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310095	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.2	12	m^3	RM Concrete	m^3	7.2	40	30%
12/8/2021	40310096	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.1	12	m^3	RM Concrete	m^3	7.1	40	30%
12/8/2021	40310098	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.1	12	m^3	RM Concrete	m^3	7.1	40	30%
12/8/2021	40310099	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310101	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310102	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.4	12	m^3	RM Concrete	m^3	7.4	40	30%
12/8/2021	40310104	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.3	12	m^3	RM Concrete	m^3	7.3	40	30%
12/8/2021	40310105	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	7.2	12	m^3	RM Concrete	m^3	7.2	40	30%
12/9/2021	40310159	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	5	12	m^3	RM Concrete	m^3	5	40	30%
12/9/2021	40310161	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	5	12	m^3	RM Concrete	m^3	5	40	30%
12/9/2021	40310164	ROAD AUTHORITY 40MPA 20MM MRS11:70	166111	ZPR40X210A	5	12	m^3	RM Concrete	m^3	5	40	30%

Figure 5.8: Sample extract of IS Materials Calculator data provided (Bruce Highway E2G)

Ready Mixed (in-situ) Concrete - default mix designs

For information on default concrete compositions, see "Default concrete compositions" tab.

	Amount	Unit	Transport mode(s)	Distance(s)	Material related GHG (t CO2-e)	Material related IS EnviroPoints v2.0 (Pt)	Transport related GHG (t CO2-e)	Transport related IS EnviroPoints v2.0 (Pt)
Default **Ready Mixed Concrete 1:**	54.12	m3	Concrete Agitator Truck	10 km	13.7	119.0	0.2	1.9
Strength grade	20	MPa	**Comments**					
SCM	20%	of total binder content						
Default **Ready Mixed Concrete 2:**	3312.221	m3	Concrete Agitator Truck	5 km	794.8	6950.4	5.1	58.9
Strength grade	20	MPa	**Comments**					
SCM	25%	of total binder content						
Default **Ready Mixed Concrete 3:**	2233.998	m3	Concrete Agitator Truck	9 km	705.7	6127.6	6.3	73.1
Strength grade	32	MPa	**Comments**					
SCM	20%	of total binder content						
Default **Ready Mixed Concrete 4:**	11701.015	m3	Concrete Agitator Truck	5 km	3326.2	29084.8	18.0	207.9
Strength grade	32	MPa	**Comments**					
SCM	30%	of total binder content						
If possible, enter the specific mix design, as this is probably not a standard concrete mix.								
Default **Ready Mixed Concrete 5:**	16199.347	m3	Concrete Agitator Truck	5 km	5590.7	48928.1	24.9	287.9
Strength grade	40	MPa	**Comments**					
SCM	30%	of total binder content						
If possible, enter the specific mix design, as this is probably not a standard concrete mix.								

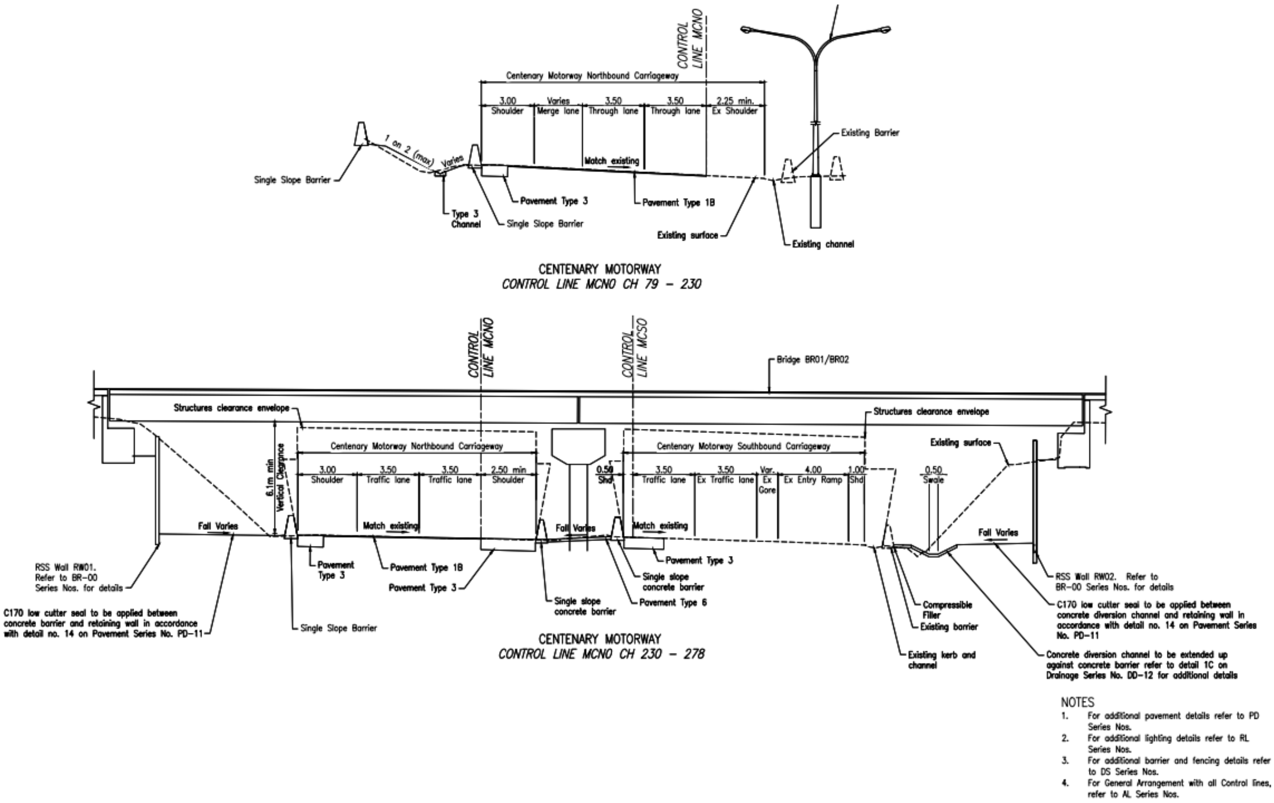
Figure 5.9: Sample extract of 3PCM data provided (Sumners Road Overpass)

Column: All

Note: This is for reference only and you cannot re-import the content of this file.

WBS Code	WBS Item	Actuals	Estimated Final Cos	Estimated Remaining Spend	Approved Total Budget
C~~C.IM~~C.IM.6	Construction	$49,068,287.54	$49,068,287.54	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Construction	$48,774,741.51	$48,774,741.51	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Construction	$48,774,741.51	$48,774,741.51	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Earthworks	$0.00	$0.00	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Earthworks-Place Holder	$0.00	$0.00	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Structures	$221,968.33	$221,968.33	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Structures-Place Holder	$221,968.33	$221,968.33	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Pavement	$53,913.25	$53,913.25	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Pavement-Place Holder	$53,913.25	$53,913.25	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Traffic management	$0.00	$0.00	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Traffic management-Place Holder	$0.00	$0.00	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Intelligent Transport Services (ITS)	$17,664.45	$17,664.45	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Intelligent Trans Ser (ITS)-Place Holder	$17,664.45	$17,664.45	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Surfacing	$0.00	$0.00	$0.00	$0.00
C~~C.IM~~C.IM.6~~C	Surfacing-Place Holder	$0.00	$0.00	$0.00	$0.00
C~~C.IM~~C.IM.7	Environmental and Cultural Heritage	$2,039.00	$2,039.00	$0.00	$0.00
C~~C.IM~~C.IM.7~~C	Environ and Cultural Heri- Place Holder	$2,039.00	$2,039.00	$0.00	$0.00

Figure 5.10: Sample extract of drawings provided (Sumners Road Overpass)



5.3.2 Data Availability and Accessibility

From Table 5.3, it is evident that there was some difficulty in obtaining data and there are several reasons for this. Firstly, it can be difficult to determine the right point of contact to obtain the necessary data for materials quantities. Secondly, as some of the data requested resides with (or needs to be approved for release by) individual project managers, rather than having a centralised repository or point of contact, it was difficult to compile all potential datasets across the selected case studies. Finally, the availability of data varies by project. For example, 2 of the case studies (Bruce Highway CR2SM and Sumners Road Overpass) did not conduct an IS ratings assessment because they preceded the IS ratings mandate or did not meet the capital expenditure threshold to mandate an IS ratings assessment. IS-rated projects are, however, centrally coordinated within TMR, and where data was available, it was easy to access. For some of the projects, the requested data was not available due to differing project and contract types (e.g. collaborative project agreements).

Several sources of data were provided and are described herein. TMR provided copies of completed IS Materials Calculators (used in the IS rating process) for all 3 case studies which included the base and actual cases. Each materials calculator contains the estimated project materials and quantities as well as a library of associated embodied carbon emissions factors. Each case study used a different version of the calculator, as below:

- Ipswich Motorway upgrade (R2D): v1.2 released 18 September 2020
- Bruce Highway (E2G): v2.0.08 released 15 December 2021
- Townsville Ring Road: v2.0.10 released 16 June 2022.

TMR provided 2D engineering drawings for the Sumners Road Overpass project. On review, although the drawings provided some information on structural dimensions, these did not provide usable/succinct material quantity information and were therefore excluded from consideration. BIM data was available within TMR but it was not adequate and available for the selected case studies (see Section 5.2.2). This project was unable to assess the quality of the BIM data, but it should be noted that the challenges associated with data accessibility, transferability and transparency could be issues for further investigation.

Contract documents (i.e. 3PCM) were only provided for the Sumners Road Overpass project and included the high-level costs associated with the project. In terms of estimates and schedule data, BoQs were provided for the Bruce Highway, Sumners Road Overpass and Townsville Ring Road projects. For the latter, a material tracking register was also provided.

5.4 Data Quality Assessment Framework and Criteria

A data quality assessment framework and criteria have been developed and applied to the obtained materials and emissions datasets. The framework provides a qualitative assessment of the material type and quantity, and emissions factors. Data quality criteria have been developed to assess the data sources, and each source is assessed against the criteria and given a score of high (3), medium (2) and low (1). If a source is considered between 2 criteria, such as medium to high, then the average value is assigned (2.5). From these scores, an average score for all criteria is calculated to provide an overall indication of the quality of the data source.

5.4.1 Data Quality Assessment Criteria

The data quality assessment criteria are based on Section 4.2.3.6 'Data quality requirements' of the ISO standard (ISO 14044). Table 5.4 describes the 10 key categories for assessing data quality.

Table 5.4: Data quality requirements: categories and descriptions

Category	Description
Time-related coverage	The age of data and the minimum length of time over which data should be collected.
Geographical coverage	The geographical area from which data for unit processes should be collected to satisfy the goal of the study.
Technology coverage	The specific technology or technology mix used.
Precision	The measure of variability of the data values.
Completeness	The percentage of flow that is measured or estimated.
Representativeness	A qualitative assessment of the degree to which the dataset reflects the true population of interest (i.e. geographical coverage, time period and technology coverage).
Consistency	A qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis.
Reproducibility	A qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study.
Sources of data	No description.
Uncertainty	The uncertainty of the information e.g. data, models, assumptions.

Source: ISO 14044:2006.

Although the ISO standard does not prescribe how to assess each of the categories, it is a useful starting point for a data quality assessment framework. A relevant subset of these criteria is adopted for use in assessing the data quality of TMR's datasets. Table 5.5 provides an overview of the data quality assessment criteria with descriptions of their applicability to the 2 data types to be assessed.

Table 5.5: Assessment criteria to evaluate the material type and quantity, and the emissions factors

Assessment criteria	Material type and quantity	Emissions factors
Time-related coverage	When was data collected for the structure? At what stage in the process are these data collected (e.g. was it during the scoping phase)?	When was the data for the emission factor published/last updated? Does it cover the actual time of the site production, is it an annual average? Are there seasonal variations that should be captured?
Geographical coverage	Is the data collected from the structure, or are estimates made from similar structures and where (e.g. state, national)?	At what scale does the emissions factor cover (i.e. site, local, state, national, estimate from shadow database)?
Technology coverage	n.a.	How well do the emissions factors accurately represent the materials and technologies used? Are the technologies to produce, transport and install the material known?
Precision and uncertainty	How precise are these values? What is the type and level of uncertainty in terms of the material type and quantity? e.g. are material quantities rounded up to the nearest tonne/1,000 tonnes?	How precise are these factors? What is the reason for the uncertainty? Can it be reduced to improve the precision?
Completeness	Are all materials accounted for?	Do these factors consider all processes in material?
Consistency	Were data collected in the same way for all materials?	Were emissions factors from the same source?

Table 5.6 and Table 5.7 provide a description of the data quality rating (high, medium, low) to be applied to TMR's datasets.

Table 5.6: Data quality criteria descriptions for material type and quantity

	High	Medium	Low
Time-related coverage	Data has been validated	Data was collected from initial planning stage estimates	Data was estimated well before or after construction
Geographical coverage	Data is project specific	Data is estimated from similar projects in the region	Data is estimated from state or national averages
Precision and uncertainty	Material type and quantity for the structure is well known and documented	Material type and quantity for the structure is mostly known and documented	Material type and quantity for the structure is estimated or not well known
Completeness	Comprehensive material details (i.e. detailed product mixes and designs)	Broadly defined material types and quantities	Indicative material type and quantity data
Consistency	Data collection is consistent for all materials	Data collection is consistent for most materials	Data collection is inconsistent and highly material dependent

Table 5.7: Data quality criteria descriptions for emissions factors

	High	Medium	Low
Time-related coverage	Data obtained within the last 3 years	Data obtained within the last 3–10 years	Data obtained more than 10 years ago
Geographical coverage	Data captured is site specific or from similar projects in the region	Data is estimated from state or national averages	Data is estimated from overseas
Technology coverage	Data reflects actual technologies used in processes	Data is estimated using validated technologies from similar processes	Data is estimated using generic processes
Precision and uncertainty	Estimates from site-or project-specific data, including specific product mixes and manufacturing processes.	Estimates from State/Australian data	Estimates from international data
Completeness	Data captures all processes/technologies for structural materials	Data captures most processes/technologies for structural materials	Data captures some processes/technologies for structural materials
Consistency	All data are captured from the same source/database	Most data are captured from the same source/database	Most data are captured from different sources/databases

5.5 Data Quality Assessment

This section presents the qualitative assessment of the material type and quantity data and the embodied carbon factors across the case studies. The assessment considers the completeness, accuracy and usefulness of the data and focuses on the relevant structural materials of concrete, steel (reinforcing and structural) and structural timber. As the sources of data are relatively consistent across the case studies, they are only assessed once.

5.5.1 Material Type and Quantity Assessment

Table 5.8 presents the assessment of the material type and quantity datasets provided. From the assessment, the IS Materials Calculator and material tracking registers scored the highest and both provide highly detailed information on material types and quantities. Both provide high-quality data about the material types and quantities used in the project and are suitable for use in providing the data to estimate embodied carbon emissions.

The BoQs overall provide a good level of information on the general material quantities used. A limitation, however, is that they do not provide detailed information on the type of materials used, for example the concrete mixes are not disclosed. For some components, insufficient information is provided to determine the actual material quantity. For example, for steel-reinforced concrete pipes, diameter and length are specified but the amount of steel and concrete per length is not. The 3PCM scored the lowest and does not provide any information on the material quantities used in the project. The 3PCM only has a high-level summary of the estimated and actual costs of Work Breakdown Structure (WBS) items (e.g. ‘construction’, ‘pavement’, ‘structures’ etc.). It is unsuitable for estimating material types and quantities used in projects and is not recommended for use.

Whilst not specifically aligned with the project scope, TMR sourced concrete supplier quantities from one of the main concrete suppliers in Queensland. This data provided specific quantities of different concrete mixes supplied to market by TMR mix designs. From this data TMR may be able to infer concrete use on Queensland structural assets by filtering by relevant concrete mixes. This analysis may be considered in year 2 of this project.

With statewide concrete quantity estimates by mix design in hand, it would be possible to estimate the embodied carbon on those relevant structural assets. This data source does not, however, have linkage with specific projects. Its value in this context would be dependent on the intended analysis. Regardless, this dataset is not comprehensive nor verified and should be treated with caution when making inferences.

Table 5.8: Assessment of provided data sources of material quantities across the case studies

Criteria	IS Materials Calculator	BoQ	3PCM	Material tracking register
Time-related coverage	**High** Base (design) and actual data	**High** Scheduled and remeasured data	**High** Estimated and actual data	**High** Data logged throughout the project
Geographical coverage	**High** Project-specific data	**High** Project-specific data	**High** Project-specific data	**High** Project-specific data
Precision and uncertainty	**High** Well-defined material type and quantity for all major components	**Medium to High** Good documentation of major material types and quantities, with some additional information (dimensions of components) required to estimate material quantities	**Low** No material type and quantity data, only high-level summary costs	**High** Well-defined material type and quantity for all major components
Completeness	**High** Well-specified data material type and quantity data for different structural materials and compositions	**Medium** Broadly well-defined for major material types. Lacking in comprehensive detailed material type and quantities (item, lump sums etc.)	**Low** No material type and quantity, only high-level summary costs provided	**High** Detailed quantities of materials used, and includes additional data such as mix codes and transport distances
Consistency	**High** Type and quantity data relatively consistent across all categories	**Medium** Data is generally consistent across materials, but deviations observed for smaller items and do not include the actual total quantities (item, lump sums etc.)	**Low** No material type and quantity, only high-level summary costs provided	**Medium** Data relatively consistent but not organised well to easily compare with other projects and requires further processing
Average rating	**3.0**	**2.5**	**1.8**	**2.8**

Note: Higher average rating is better (scoring: 3 = high, 2 = medium, 1 = low).

5.5.2 Embodied Carbon Factors Assessment

The assessment of the various data sources for emissions factors used to estimate embodied carbon is presented in Table 5.9. The IS Materials Calculator LCI database provides relatively good coverage of a broad range of structural materials from various data sources. The number of EPDs included in the database has increased in recent years, improving the transparency of the processes to generate the different materials. Despite this improvement, it should be noted that the emissions factors used in these EPDs are product-specific but modelled on data sourced from the AusLCI database and shadow database. As such, their accuracy is dependent on the background datasets.

Compared to the IS Materials Calculator, the SAT4P database provides a deeper coverage for pavement-related materials and has coverage of several new and innovative materials. It also provides a user interface to model new mix designs drawn from its extensive materials database. Most processes have been adapted to reflect Queensland-specific emissions intensities in electricity generation and transportation distances (e.g. for imported materials, from major export port to Brisbane). SAT4P and its database are focused on pavements with few structures-related materials, products and emissions factors. The NACOE SAT4P project team has identified that future expansion of the tool for structures is a priority in future years.

The AusLCI construction emissions database was specifically developed for the construction sector and is based on the AusLCI database (and shadow database to fill gaps in available Australian data). The AusLCI database and shadow database are used extensively in both the IS Materials Calculator and SAT4P databases and is the standard used in assessing the embodied carbon (and broader environmental impacts) for LCAs and EPDs in Australia. The data does not have a secure and sustainable funding source to ensure timely data updates. As an interim approach, the AusLCI database is complemented by the AusLCI shadow database, which is a localised version of the international ecoinvent v2.2 database, with input flows changed to AusLCI where process data is available (e.g. electricity, transport, natural gas, materials etc.). Despite its limitations, the AusLCI database is still considered the industry standard and is accepted as current best practice throughout the life cycle evaluation and sustainable infrastructure communities.

The ecoinvent database is a comprehensive source of embodied carbon factors across a wide range of sectors and receives annual updates. As the ecoinvent Association is based in Europe, there is a distinct lack of emissions factors for Australia, which are covered (if at all) under the ‘rest of world’ processes.

Overall, in relation to assessing the embodied carbon of TMR’s structures, the data sources are generally of low to medium quality with a significant amount of relevant background data based on international processes. Some individual materials or groups of materials have been more thoroughly reviewed and their emissions factors have been updated in the Australian context. Two good examples are concrete and asphalt products which were updated with funding from the Green Building Council of Australia and the Australian Flexible Pavement Association, respectively. Steel products on the other hand are heavily based on international.

Table 5.9: Data quality assessment for embodied carbon factors

Criteria	IS Materials Calculator	SAT4P	AusLCI database and construction emissions database	ecoinvent
Time-related coverage	**Medium** Relatively good, most data sourced within the last 10 years and a small number older than 10 years	**Medium** Relatively good, data has generally been sourced within the last 10 years	**Medium** Relatively good, data has generally been sourced within the last 10 years	**Medium to High** Relatively good, data has been sourced within the last 10 years
Geographical coverage	**Low to Medium** Generally representative for national, but no state- or site-specific emissions factors. Some product-specific data via EPDs (~30% of entries), and others based on international processes	**Medium** Relatively good, with custom processes and data, and some data from AusLCI modified to include state-specific and national values	**Low to Medium** Relatively good coverage at a national level, with some low-quality data adapted from international data (i.e. shadow database)	**Low** Minimal Australia-specific factors for structural materials, often covered under 'rest of world'
Technology coverage	**Medium** Good coverage of structures-related materials and related processes at a broad level	**Low** Good coverage for pavement-related technologies and materials but lacking coverage for structural materials	**Medium** Relatively good coverage of structural materials, except timber which is covered by the shadow database	**Medium** Relatively good coverage of broad range of technologies and material types
Precision and uncertainty	**Low to Medium** Low to medium estimates from national and international data, based on AusLCI database and shadow database	**Low to Medium** Some state-specific coverage, and national and international (adapted) estimates for processes	**Low to Medium** Low to medium national estimates of structural materials. Concrete from AusLCI database, while low quality data for steel and timber from the AusLCI shadow database	**Low** International data
Completeness	**Medium** Good coverage of most types of structural materials	**Low** Extensive coverage of pavements (improved over other sources), but no data for structures such as bridges	**Medium** Good coverage of most types of structural materials	**Medium** Good coverage of most types of structural materials
Consistency	**Medium** Generally consistent sources used (AusLCI database and shadow database), but a range of materials increasingly being covered by EPDs (often based on AusLCI database and shadow database). EPD coverage of materials used in Queensland's structural assets is currently low	**Medium** Data is well covered for the Australian context and includes novel and innovative materials, lacking in coverage of transport structure materials	**High** Good consistency, approximately 50/50 split to AusLCI database and shadow database for the construction emissions database	**High** Database in a consistent format
Average rating	**1.8**	**1.6**	**2.0**	**1.9**

Note: Higher average rating is better (scoring: 3 = high, 2 = medium, 1 = low).

5.6 Conclusions

A desktop review and qualitative assessment was undertaken to evaluate TMR's data sources for estimating the embodied carbon of structures. Embodied carbon emissions estimates are a function of material quantity (e.g. mass) and an appropriate carbon emissions factor (e.g. $kgCO_2$-e/kg). Where accurate estimates of material quantities (by material type) are available and these can be appropriately matched with relevant embodied carbon factors, the embodied carbon of structural assets can be estimated. Where data is lacking (due to availability, access or level of detail) or has low data quality, embodied carbon estimates are not possible or lack reliability.

Using 5 case studies identified by TMR, material quantity data was lacking, primarily due to availability and access. The availability of data is dependent on the project and contract types, and in some cases the requested data was not available (e.g. for collaborative project agreements). In some cases, it can be difficult to determine the right point of contact, and most of the requested data resides with (or needs approval from) the individual project managers. Two of the case studies did not have to conduct an IS ratings assessment, meaning there was no IS Materials Calculator data available. Data availability is therefore inconsistent across projects and is not easily accessible to all or relevant TMR staff or contractors. Issues with availability and accessibility limit the ability to estimate embodied emissions of TMR structures.

The data sources that were identified to be useful for estimating material type and quantity for structures are the IS Materials Calculator, BoQ, and the Material Tracking Register. The IS Materials Calculator and the material tracking register provide the best available data on material type and quantity, followed by the BoQ which requires some additional information of various components, for example the specific concrete mixes, or in some cases the actual material quantity, to convert into suitable material quantities. The IS materials calculator is only required when the project is undergoing an IS rating. Ratings can be done in planning, design and after construction ('as built') to update and verify the design inputs. Material tracking registers are produced during construction, while BoQs are developed early during the project development life and updated throughout to construction.

Sustainable outcomes are best influenced in planning and early design. While the material tracking register provides good quality materials data, key design decisions are likely to have been settled by the time the register is established. Therefore, the IS Materials Calculator is the preferred data source for materials data in the planning and design stages. In smaller-scale projects where IS ratings are not required, the BoQ is likely to be the best data source. In practice, the IS Materials Calculator inputs would be informed by the BoQ and the data has been somewhat processed through expert knowledge and assumptions to provide the necessary detail and matching with relevant embodied carbon factors.

Two data sources were identified to not be useful for estimating material type and quantity. Contract documents and claims were found to only provide high-level summary costs that provided no material type and quantity data. Digital drawings of the structures may provide some useful data on material types and quantities; however, they were not assessed as it is not practical to obtain estimates without processing to produce quantity outputs.

BIM data could address these issues, particularly if the detailed designs are regularly updated; however, no BIM data was available for assessment. Further investigation into BIM data would be beneficial and may support other resource efficiency and material circularity outcomes.

The sources of embodied carbon factors available to assess TMR structures are generally low to medium quality. For some materials or material groups (e.g. concrete and asphalt), extra effort has been given to review and update these materials for the Australian context. However, even these updates are based on data that is over 10 years old. Despite this assessment, the AusLCI and ecoinvent databases, which are used to populate the IS Materials Calculator and SAT4P databases and in EPD modelling, are the industry standards and considered of a reasonable quality to undertake embodied carbon estimations.

Embodied emissions estimates require matching the structure's materials with the most appropriate embodied emissions factor. In many cases, emissions factors are fairly generic (e.g. concrete 40 MPa), which allows for high-level carbon estimates; however, comparisons between different material sub-types, such as different low carbon concretes requires far greater data specificity and re-analysis by suitably skilled LCA experts. Use of generic embodied carbon factors is suitable for high-level carbon estimates but is unlikely to be useful for detailed design comparisons or optioneering.

EPDs offer a partial pathway to better, more accessible data as they are built off current-practice product-specific information and undergo rigorous validation testing prior to publication. EPDs, however, also rely on the aging AusLCI and ecoinvent datasets and have limited coverage of infrastructure materials with high development costs and long approval timelines constraining their expansion.

Ultimately, TMR produces and/or will continue to produce good quality material data that can be applied (broadly) to existing accessible carbon emissions factors to enable high-level embodied carbon emissions estimates. These estimates, however, should be interpreted appropriately, noting their limitations, and used with caution when informing or supporting critical decisions.

While this is often not practical (or feasible), there are a number of recommendations for improvements that can improve the estimation of embodied carbon emissions for TMR structures and help identify significant contributors. This could include:

- addressing data accessibility issues within TMR by, for example, developing a centralised repository to ensure access to the structural material types and quantities across the stages of a project
- incentivising or mandating suppliers of large quantities of materials (namely concrete and steel) to provide detailed product information, including identifying constituent materials and their composition or mixes, and/or EPDs for the quantity of each material supplied.

6. Defining Sustainability in Design

6.1 Introduction

Australia is one of the highest emitters of GHG emissions per capita in the world (Yu et al. 2017), and transport infrastructure is a significant portion of all development in Queensland. The transportation sector is integrating sustainability into technical standards in many areas, but progress is gradual. Therefore, it is essential that sustainable design principles are thoroughly implemented. Currently, there is limited guidance on how to incorporate sustainability into the design of TMR's structures (including bridges) or what measures can be used to assess acceptable sustainability impacts.

This section aims to improve the integration of sustainability parameters by informing upon:

- sustainability-focused actions that can be incorporated into designs
- methods for evaluating sustainability practices, including practice guides and assessment tools.

A literature review, presented in Section 6.2, was conducted to review sustainability design frameworks for common design choices, and sustainability measurement tools. Sustainability parameters identified from the ISC Ratings Tool formed the basis of the literature review. Details of the ISC Ratings Tool are provided in Section 6.1.1. Focus was given to areas that enable design engineers to impact upon sustainability.

A draft literature review was presented to designers experienced in TMR projects for comment. The findings of this stakeholder consultation are detailed in Section 6.3. Changes relating to governance and policy were not considered in this scope, as they are considered outside of the direct influence of the design engineers.

6.1.1 Infrastructure Sustainability Council Ratings Scorecard

The IS Rating Scheme is a comprehensive rating system to evaluate the economic, environmental and social performance of infrastructure across the planning, design, construction and operational phases. In this project, the elements in focus are limited to the 'Design & As Built' IS Rating Scheme (ISC 2024a). The ISC ratings scorecard (version 2.1) (ISC 2021) was refined to take account of the relevant list of criteria (Table 6.1) in consultation with the project team to use as a guide for considering sustainability in the design of TMR structures.

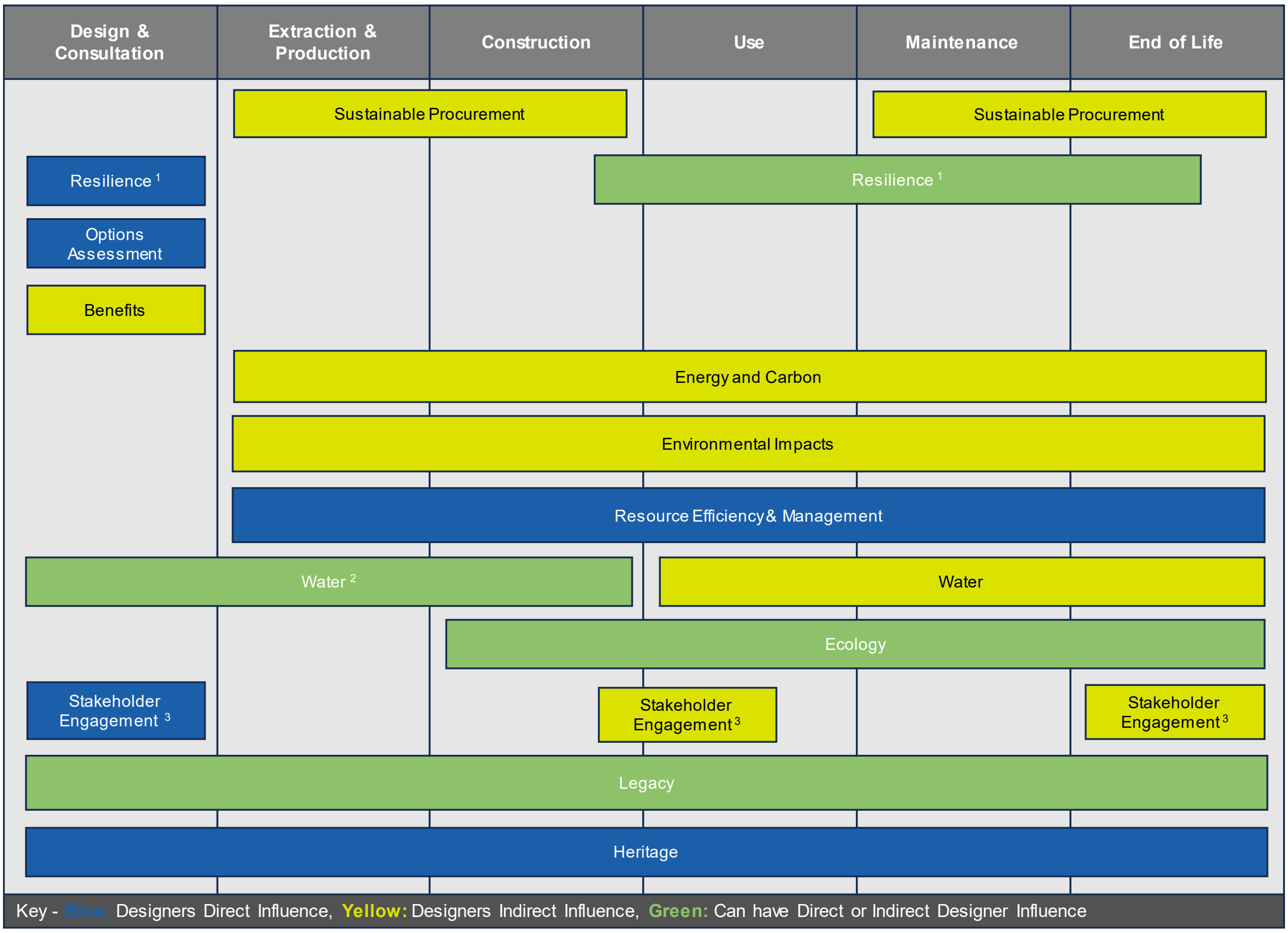
Table 6.1: ISC ratings scorecard criteria to be examined

Theme	Category	Criteria (IS code)	Designer control (Direct/Indirect)
Governance	Sustainable procurement	Supplier assessment and selection (Spr-2)	Indirect
	Resilience	Climate and natural hazards risks (Res-1)	Indirect
		Resilience planning (Res-2)	Direct
Economic	Options assessment	Options assessment and significant decisions (Ecn-1)	Direct
	Benefits	Benefits mapping (Ecn-4)	Indirect
Environment	Energy and carbon	Energy efficiency and carbon reductions (Ene-1)	Indirect
		Renewable energy (Ene-2)	Indirect
		Offsetting (Ene-3)	Indirect
	Environmental impacts	Receiving water quality (Env-1)	Indirect
		Noise (Env-2)	Indirect
		Vibration (Env-3)	Indirect
		Air quality (Env-4)	Indirect
		Light pollution (Env-5)	Indirect

Theme	Category	Criteria (IS code)	Designer control (Direct/Indirect)
	Resource efficiency and management	Resource strategy development (Rso-1)	Direct
		Resource recovery and management (Rso-4)	Direct
		Adaptability and end of life (Rso-5)	Direct
		Material life cycle impact measurement and management (Rso-6)	Direct
		Sustainability labelled products and supply chains (Rso-7)	Indirect
	Water	Avoiding water use (Wat-1)	Both
	Ecology	Ecological protection and enhancement (Eco-1)	Both
Social	Stakeholder engagement	Stakeholder engagement and impacts (Sta-2)	Both
	Legacy	Leaving a lasting legacy (Leg-1)	Both
	Heritage	Heritage protection and enhancement (Her-1)	Direct

From the identified criteria, Figure 6.1 was developed to pinpoint at what stage of the project's life cycle these categories cover and the level of influence a designer can have on each. This was presented to experts during the stakeholder workshop. The criteria and the measures designers can influence (either directly or indirectly) are examined in the literature review.

Figure 6.1: ISC ratings scorecard category coverage through the life of a structure and the level of influence a designer can exert



1. Resilience planning can be directly influenced at the Design and Consultation stage; however, as a project progresses, the ability of designers to influence resilience will depend on the nature of the project, such as whether the structure is new or is being repaired.
2. The designer's influence will depend on the responsibility the designer has for construction management of the project. Construction management might be considered by the designer when making design decisions.
3. Responsibility for stakeholder engagement will often shift to other roles during the construction and end-of-life stage of the project. The influence of the designer at the design and consultation stage, which will directly involve the designer, may continue to influence the stakeholder engagement at these later stages of a project.

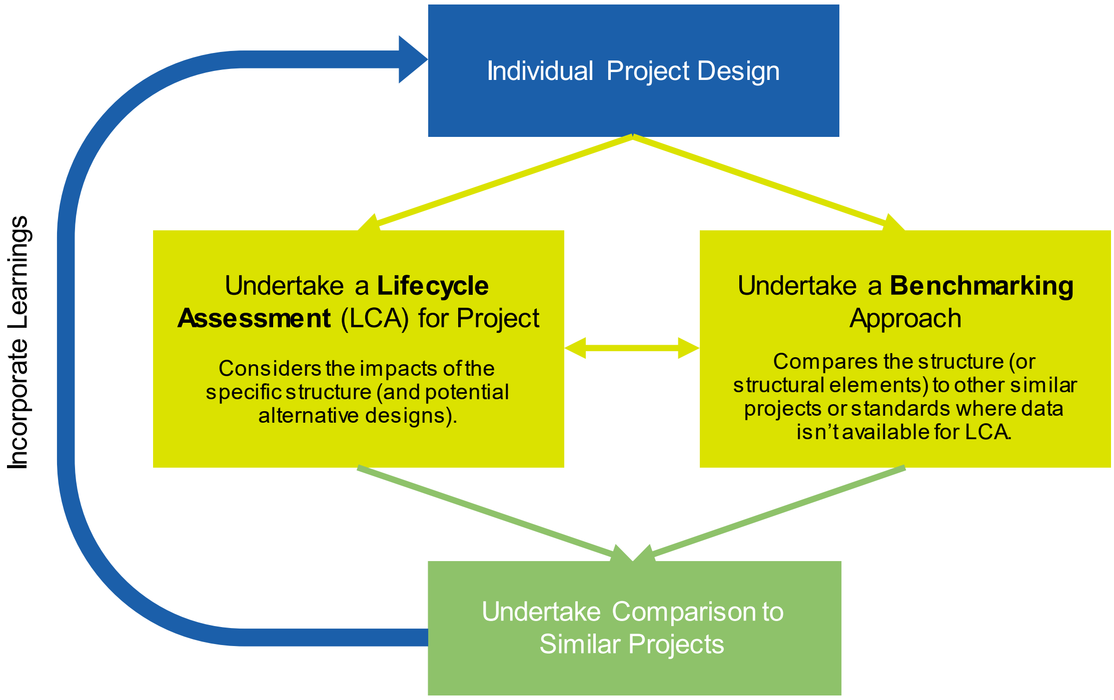
6.2 Literature Review

The literature review examined the refined list of criteria from the IS rating scheme to provide a broad range of best practice advice and recommendations for sustainable design in structures. The review will provide designers with measures and decisions to maximise sustainability (financial, environmental and social) in the design of bridges.

6.2.1 Sustainable Design Approaches

From the literature search, 2 stages of assessment were identified, as detailed in Figure 6.2. These methods, LCA and benchmarking may initially seem independent. However, for the most sustainable outcome, they work together. LCA assesses a design's environmental impact throughout its lifespan. When LCA data is missing, benchmarking steps in, comparing the design to similar projects. Understanding the advantages and disadvantages of both methods is essential to create truly sustainable structures.

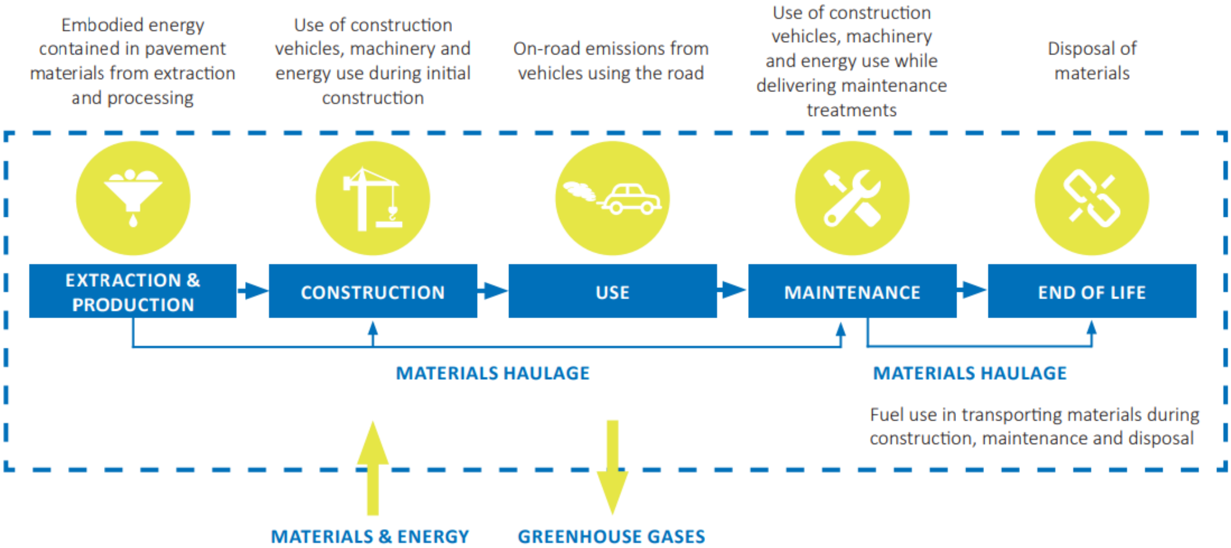
Figure 6.2: Sustainable design assessment approach



Life cycle assessment

LCA evaluates a structure's environmental impact throughout its life. It considers all stages from raw material extraction to the structure's end-of-life and can be used to identify priority areas for sustainability improvement. An overview of the LCA phases for a bridge is shown in Figure 6.3. LCAs can be time-consuming to develop: it can be difficult to collect the necessary data and it requires a careful balance to manage the LCA scope.

Figure 6.3: Overview of the phases of a transport asset's life cycle (using a road pavement example)



Source: Hall et al. (2020).

Benchmarking approach

If data is not available or accessible for an LCA, then an alternative approach to assess the sustainability of a structure is through benchmarking. Benchmarking, as defined in ISO 21678:2020, is a 'process of collecting, analysing and relating performance data of comparable buildings or other types of construction works' (Mattinzioli et al. 2022). To address the lack of material data in the early design stages, benchmarking can be applied to individual structural components. While there are varying methods available, this approach compares known information to industry standards or similar materials/components/projects and can be used to make a qualitative assessment of the sustainability of a structure or component.

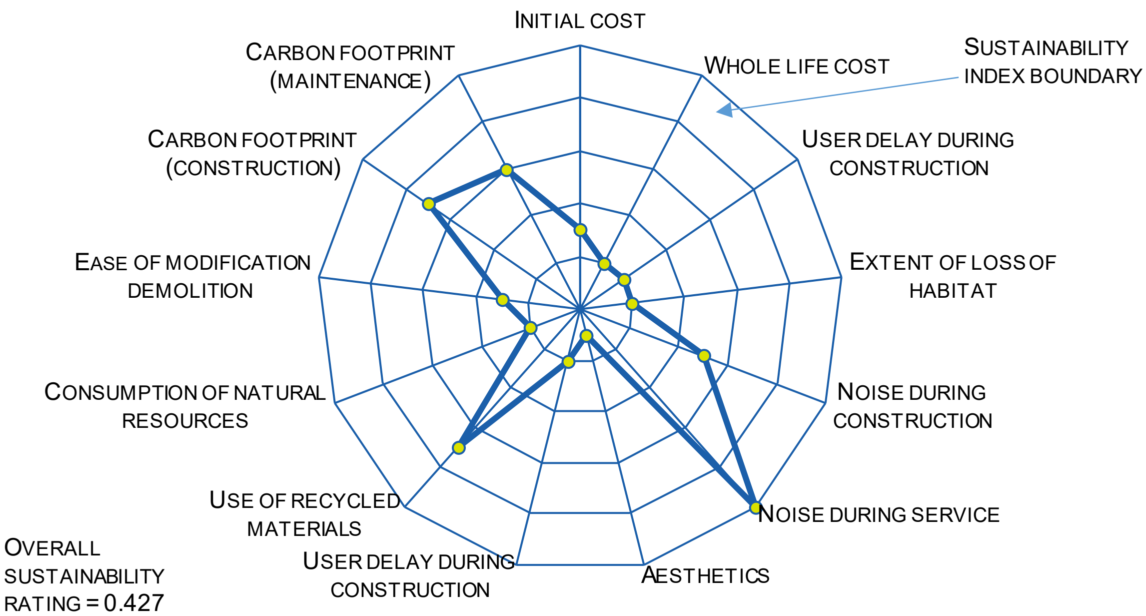
In the early design stages, where LCAs are difficult and time consuming to develop, benchmarking can be a useful alternative for designers. For example, information to guide whether *x tonnes* of embodied emissions is a 'good' or 'bad' sustainability outcome can be lacking, and so benchmarking enables comparison to known information to assist designers in understanding if a design choice offers a beneficial outcome (Hollberg et al. 2018).

Comparison to similar projects

Any assessment undertaken should not be conducted in isolation. The assessment should compare a bridge design's sustainability to industry standards (e.g. IS Ratings) or to similar projects. Of the various approaches available, one example illustrating a comparative assessment to similar projects is through the Sustainability Index proposed by Hendy (2011). The Sustainability Index provides a simplified method to compare projects of a similar nature across the various elements of sustainability (environmental, economic, etc.) throughout the life of a bridge. Indices such as these provide a consistent approach to rank projects and identify areas to improve their sustainability.

An example of the Sustainability Index output is provided in Figure 6.4, illustrating the sustainability rating of a bridge across the various elements, with the visualisation providing clear feedback on priority areas for improvement.

Figure 6.4: Example output visualisation of the Sustainability Index for a bridge design



Note: The smaller and closer the boundary line is to the centre of the circle the greater optimisation to a sustainable designed solution.

Source: Adapted from Hendy (2011).

One challenge with undertaking comparisons across projects (or potential proposals for a single project) is how to select appropriate criteria weightings to achieve the desired outcomes. The costs to construct and maintain a structure are often given significant weighting at the expense of other criteria (see Section 6.3). Several researchers have investigated the use of multi-criteria assessments (MCAs) and decision-making frameworks, but these usually focus on the economic costs (Penadés-Plà et al. 2016). To achieve the desired sustainability outcomes, TMR should consider making a clear decision on how to provide criteria weightings that do not prioritise costs.

6.2.2 Elements of Design Sustainability

This section explores elements that designers can influence directly and indirectly and the actions they could take to improve and manage sustainability across the categories identified from the IS ratings scheme (Table 6.1). While these elements are discussed separately, there are many interdependencies, and they should not be considered in isolation when designing a bridge. For further discussion on the interdependencies and the relative weightings, see Section 6.3.

Governance: Sustainable procurement

Sustainable procurement is focused on ensuring procurement practices are delivering positive outcomes across the other sustainability categories (environmental, economic, social) and achieving the overall project objectives throughout its life cycle (ISC 2021). The Queensland Government has developed guidance for procurement professionals that outline principles, approaches and actions to improve the sustainability of procurement (Queensland Department of Housing and Public Works 2018, 2024). This guidance can be used to assist in achieving goals such as reduced waste and by-products, increased use of recycled and recyclable materials, and prioritised product efficiency and longevity. Due to the broad nature of sustainable procurement, it is often difficult to quantify the sustainability outcomes. To address this, the Commonwealth has released new technical guidance on incorporating sustainable procurement in infrastructure projects (TfNSW 2025). The guidance is provided for use by Australian government, states and territories and is aligned with PAS 2080. It provides information to inform sustainable procurement during the design phase, such as minimum sustainability requirements and obligations for designers to ensure alignment with PAS 2080 (TfNSW 2025).

Furthermore, there are no requirements for designers as they only have an indirect influence on sustainable procurement. Despite this, designers should take an active role in understanding the procurement implications of their designs (i.e. material selection, construction and maintenance practices) across the life of a bridge to improve sustainability outcomes in procurement. Designers could set requirements for the supply chain to meet targets (e.g. carbon emissions or other) outlined by the asset owner (Infrastructure NSW 2024). Designers should collaborate with procurement and other cross-discipline professionals to help develop or inform the sustainable procurement objectives. For example, material selection could be adapted to utilise local materials and services, where possible.

Governance: Resilience

Resilience is the capability of a structure to be prepared for, respond to and recover from threats with the minimum damage to social well-being, the economy and the environment (PIARC 2015). Resilience is becoming increasingly important due to climate change impacts on the frequency and intensity of extreme weather events. The resilience of a bridge is critical for designers, who need to ensure that structures are designed (and constructed) to minimise any potentially damaging effects.

The AS 5100 bridge design standards have recently updated the requirements for bridges to meet the threats posed by natural disasters and flooding events. In addition, designers should conduct a thorough risk assessment in the design phases using available data to assess the sensitivity of a proposed bridge to the potential risks and develop appropriate mitigation strategies that are proportional to the risk. Depending on risks identified, this data will include air temperature, humidity, sea surface temperature, precipitation, sea level rise, wind and hail, fire hazards, coastal inundation, cyclones and storms, flooding, heatwave, drought, and frost (ISC 2021).

Economic: Options assessment

An effective options assessment enables designers to evaluate a range of approaches and solutions and compare their sustainability across social, economic and environmental factors. The sustainability (both positive and negative impacts) should be considered across the life of a bridge, from design to end-of-life. A broad options assessment during the early stages enables for not only the identification of potential issues, but also for opportunities to make improvements at the design stage, which is more effective than during construction or while the bridge is in operation.

A thorough options assessment requires the evaluation of the full range of benefits and drawbacks across social, economic and environmental factors. However, not all factors should be given equal weighting, and there is still considerable debate as to how these weightings should be applied. It was noted by Penadés-Plà et al. (2016) that, until recently, priority was given to the economic costs associated with constructing a bridge. Many academic studies have investigated and proposed various approaches to evaluating the sustainability of a bridge against multiple criteria or attributes across different life cycle stages (Penadés-Plà et al. 2016). These approaches are increasingly considering broader aspects of sustainability and can provide designers with improved methods for performing early-stage options assessments. This is an area that requires further research to determine suitable categories (and weightings) that align with TMR's priorities now and into the future.

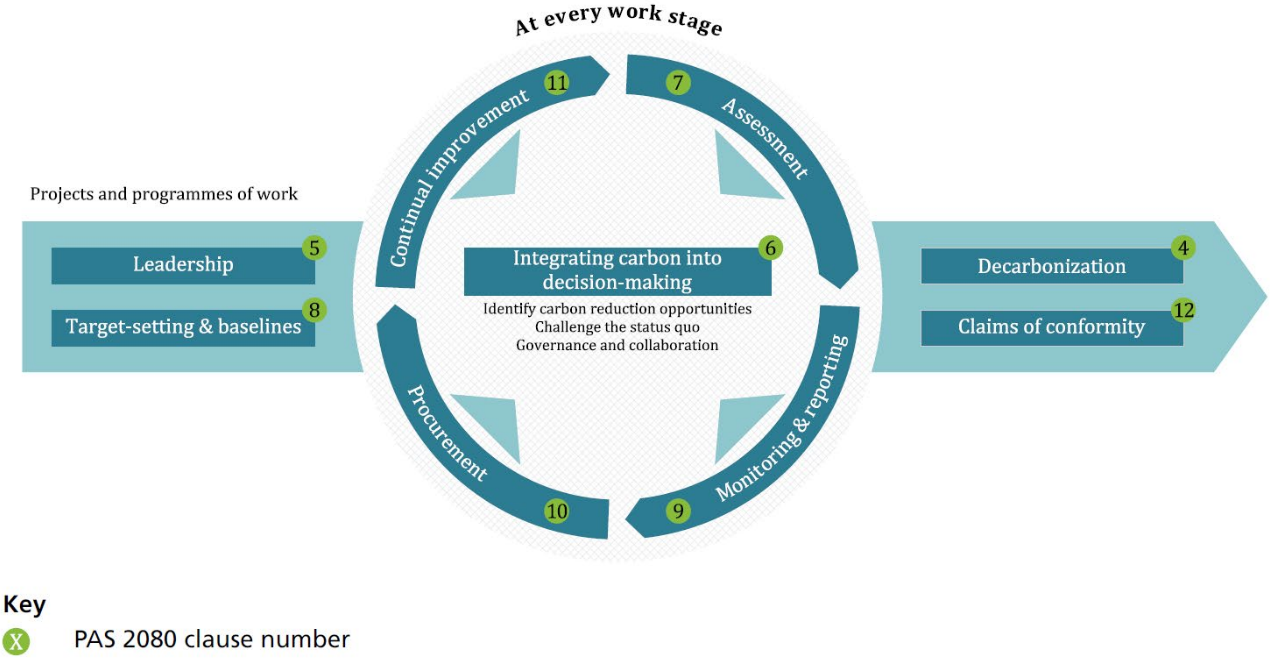
Environment: Energy and carbon

Designers have an indirect influence on the energy consumption and carbon emissions throughout the life cycle of a bridge. It is acknowledged that ISC Ene-credits (Table 6.1) only apply to emissions from the construction and use phase; however, designers have some capacity to influence these factors. Modelling during the planning and design stages enables designers to identify opportunities for reducing both energy consumption and carbon emissions (ISC 2021). There are tools and software available, such as CERCLOS' eTool (Cerclos 2024) for buildings and infrastructure, or the Sustainability Assessment Tool for Pavements (SAT4P) (Hall et al. 2020), which can be used to evaluate and benchmark the embodied emissions of various designs.

Design opportunities for reducing energy and carbon of a structure include reusing materials and components when replacing bridges, as well as extending service life of a bridge (Hilton 2022). An example is that of the Brisbane Gateway Bridge which had various features and enhancements added to increase its service life to 300 years for small additional costs. Reductions in emissions may also be achieved with renewable energy, such as incorporating solar panels to power electrical components. The overall goals and objectives should not be considered in isolation but balanced across the various elements of sustainability that align with community, industry and government priorities.

Resources such as British Standards Institution's' (BSI) PAS 2080:2023 *Carbon Management in Infrastructure and Built Environment*, and the New South Wales Government's *Decarbonising Infrastructure Delivery Policy* (Infrastructure NSW 2024), present approaches to considering decarbonisation in infrastructure. Adaptation of these policies and standards to a Queensland context may support designers in reducing carbon emissions, along construction and other phases. PAS 2080 considers decarbonisation across all project phases, as shown in Figure 6.5 and thus also relates to other categories including Governance: Sustainable and Environment: Resource efficiency and .

Figure 6.5: Overview of the PAS 2080 carbon management process



Source: PAS 2080:2023.

The PAS 2080 standard guides designers to:

- challenge the standards and prescriptive requirements that have an impact on whole-of-life carbon
- integrate whole-of-life carbon reduction opportunities in the design
- have governance structures in place that promote whole-of-life carbon reduction opportunities
- comply with and challenge targets defined by the asset owner/manager for the project
- align targets with net zero aims
- demonstrate reuse of materials, use of low carbon materials, use of energy efficient and/or renewable energy generation, and minimise overall resource use
- assess future adaptability and material recovery potential
- submit carbon reduction proposals to the asset owner/manager or other value chain members.

The *Decarbonising Infrastructure Delivery Policy* (Infrastructure NSW 2024) identifies the scope of control and influence of designers as:

- setting requirements for the supply chain to meet carbon reduction ambitions of the asset owner/manager
- encouraging the use of carbon reduction design methodologies
- encouraging cross-discipline coordination and innovation across the design process
- supporting the broader value chain with capability uplift.

Designers should complement considerations of material suitability and performance with knowledge of the energy demand and associated GHG emissions of the available materials and construction activities that are influenced by design choices. This includes evaluating material selection, reducing material use where possible and using local materials to reduce transportation impacts.

These aspects are discussed in further detail in Environment: Resource efficiency and , as Rso-6 (Material life cycle impact measurement and management) also considers the impact of changing design and using alternative materials to influence environmental and carbon impacts.

Environment: Environmental impacts

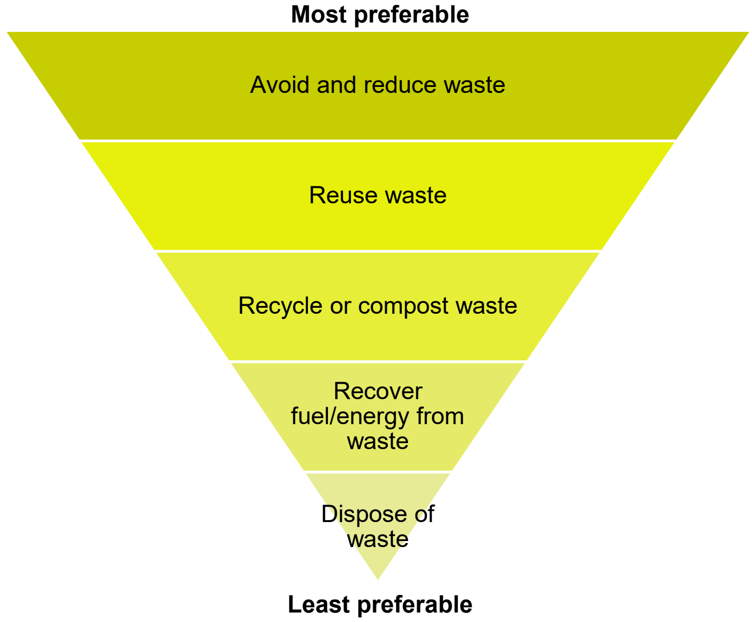
Another area of environmental sustainability is associated with reducing the life cycle pollutive impacts of the following 4 categories: water, noise, vibration and light. While many of these impacts can be considered in both the construction and use phases of a bridge's life, the impacts here are focused on the use phase over which a designer exert greater influence. To effectively reduce these impacts, designers should utilise data on the existing conditions of the site and perform modelling to assess the potential impacts and risks, and redesign to incorporate mitigation measures as appropriate. Measures designers can consider to reduce these environmental impacts (directly or indirectly) include:

- **Water:** AS 5100:2017 has been updated to mandate designers to consider the risk of pollutants entering watercourses and ensure they design for appropriate mitigation actions.
- **Noise:** the design should include effective noise reduction barriers or prevention systems as required.
- **Vibration:** the design should sufficiently dampen the vibrations generated from the passage of vehicles/pedestrians over the bridge, including transmission to nearby dwellings. Additionally, designs should aim to minimise vibrations during construction such as through selection of best available piling technologies e.g. bored piles, which can impact levels of noise and vibration (Level Crossing Removal Project 2023.
- **Light:** the design should ensure lighting installed on the structure is useful, targeted (i.e. only where needed), no brighter than necessary and uses warm colours where possible.

Environment: Resource efficiency and management

Resource efficiency is the sustainable use of natural resources by minimising the overall consumption of materials and ensuring they are utilised to their fullest extent. While zero waste might always be out of reach, designers should strive to minimise resource use and maximise resource recovery. This requires designers to have an appreciation of the impacts of material selection on the construction of a bridge and where material inefficiencies/losses occur. The Queensland Government's (2019) *Waste Management and Resource Recovery Strategy* presents the standard resource and waste management hierarchy (Figure 6.6). Designers should consider how their designs and material selections will impact on waste according to this hierarchy.

Figure 6.6: Hierarchy of waste and resource management



Source: Adapted from Queensland Government (2019).

One area of resource efficiency that has been gaining significant attention in recent years is the use of recycled materials to reduce embodied carbon and avoid wastage. For example, SCMs such as fly ash and GGBS in concrete can generate a reduction in GHG emissions by up to 60% (Singh 2022). Furthermore, the use of geopolymers offers significant reductions in carbon emissions, with Hilton (2022) demonstrating up to an 80% decrease compared to traditional Portland cement. Additionally, using material waste generated on site (or nearby) is another option that designers should consider, including identification of contaminated materials and consideration of reuse opportunities in early works. Alternative materials should be evaluated on a performance basis and be available for designers to use where possible.

Environment: Water

While designers have an indirect influence over avoiding water use, it is an important area of sustainability. Reducing water use can be done through modelling water demand during both the construction and operation phases, which can be used to identify opportunities for avoidance and reduction and implementing efficient water systems design. Utilising water modelling tools, designers can assess and plan for various water uses, including user or worker usage, dust suppression, moisture control, wash down or cleaning, landscaping irrigation and firefighting, among others. This could form part of the initial planning stages and assessment of design. Incorporating water conservation planning, reuse measures, and designing out the need for water (e.g. specifying drought-resistant plant species) are potential opportunities for designers to further the sustainability outcomes of a bridge.

In addition, incorporating a drainage system designed for water collection and reuse could be a valuable strategy. Water sensitive urban design (WSUD) considers planning and design to make use of stormwater as a valuable resource and reduce its harm to waterways (Melbourne Water 2017). For example, capturing rainwater runoff (and potentially greywater) reduces reliance on municipal water supplies. Varying techniques can be applied, including rainwater tanks, raingardens and swales. Additionally, designing to effectively channel water away from the structure may minimise water damage and extend its lifespan. Encouraging or mandating WSUD principles would showcase TMR's commitment to environmental responsibility.

Environment: Ecology

The design and construction of modern bridges should aim to protect and enhance terrestrial and aquatic ecology through an evidence-based identification and management approach (ISC 2021). While designers are not solely responsible for this, they can have some direct and indirect influence over the impacts during construction, operation and maintenance. Designers should consider the following key principles:

- maximising the retention of vegetation/habitats
- maintaining biodiversity
- ensuring access and connectivity for wildlife.

Designers should also evaluate the broader ecological impacts of their designs, for example the creation of necessary temporary structures during the construction process, and how these could be minimised (Seliverstov 2000). Considering the ecological impacts from the design stage will help improve the overall sustainability of a bridge and maintain or improve the local ecology.

Social: Stakeholder engagement

Stakeholder engagement has been mentioned previously but is significant enough in its own right to have a dedicated ISC credit. This credit revolves around engagement with the community who live around and will use the structure being built. Designers are usually not responsible for this function but can contribute in meaningful ways. Where feasible, designers should take an active role in stakeholder engagement to receive feedback on important aspects or outcomes of the proposed bridge and in return demonstrate to stakeholders where their feedback has been incorporated.

Social: Legacy

Leaving a lasting legacy is centred on delivering initiatives through the project that have a significant and long-lasting impact on societal or environmental outcomes (that have not been covered in the previous categories). Ideally, legacy initiatives should be aligned with and can seek inspiration from local government/community plans (ISC 2021). Designers can have a direct and indirect influence on this and should be involved in the identification and development of initiatives during the design process to ensure they are incorporated in the design. Initiatives could focus on societal benefits such as improved equity for the local community or setting a minimum requirement for using local resources to boost the economy.

Another aspect that extends beyond the local community where the structure is to be built is innovation and longevity in design. Designers should be encouraged by government to develop designs that are innovative, whether they be small changes or transformational designs.

Social: Heritage

The preservation and enhancement of a site's heritage is an area that designers have a direct influence over. To effectively protect and enhance a site's heritage, designers should first gain a thorough understanding of the location's cultural significance and heritage prior to developing designs. They should also be transparent about design decisions and engage the local community through effective stakeholder engagement (ISC 2021). This enables the development of designs that would effectively protect and enhance heritage.

6.3 Stakeholder Engagement

This section summarises key takeaways from an online stakeholder workshop held with the project team, TMR structural engineers and Australian bridge design experts on 30 April 2024. Discussions were focused on:

- incorporating sustainability considerations into infrastructure projects
- the role and responsibilities of designers
- the challenges and opportunities across various phases of a project's life cycle.

6.3.1 Summary of Discussions

The key discussion points and takeaways are summarised below.

Influence of structural engineers on design decisions

- Structural engineers may have limited influence compared to other designers or engineers in the project.
- Multi-Criteria Analyses (MCAs) often prioritise factors such as cost over sustainability.
- Standardising sustainable procurement practices and incorporating sustainability into design standards can be more effective, when compared with business as usual.

Balancing maintenance vs new construction

- Maintaining existing structures is generally more sustainable than building new structures.
- Increasing the design life can significantly reduce embodied energy over time.
- An alternative approach to extending design life could be designing for a shorter life using certain sustainable materials such as timber.

Broader considerations beyond design

- Decisions made during planning stages such as road width or bridge quantity, significantly limit and impact the design options and embodied carbon footprint.
- MCAs need to give greater weight to sustainability considerations relative to monetary costs.
- Procurement practices can be used to encourage sustainable design choices through project briefs emphasising sustainability goals.
- Structural engineers can play a more proactive role by advocating for innovative solutions during the planning stages.

Challenges in assessing sustainability

- Important that the entire life cycle is considered including maintenance and material reuse.
- Need to consider the source and environmental impact of materials and processes.

Limitations of current assessment tools

- Existing tools may have limitations in transparency and accuracy (e.g. input data for materials).
- Assumptions used in assessment tools can significantly impact the final outcome.
- Need for standardisation and transparency in tools and data to measure sustainability, from embodied carbon footprint to broader impacts.
- Common frameworks and data sources are useful for assessment (but do not necessarily need to be accurate/up-to-date which can be difficult and expensive to do)

Designer influence on construction practices

- Designers have limited ability to directly influence construction methods due to contractor discretion.
- There is a 'hidden' carbon footprint from construction mistakes and rework due to unforeseen conditions, outside the control of designers.
- Lack of understanding regarding stakeholder needs can also influence sustainability causing disruptions and delays.

Design criteria and sustainability efforts

- Relaxing current prescriptive design criteria towards performance-based standards might be beneficial but requires clear guidelines.
- Limitations are noted; however, sustainable techniques that may be considered such as partial pre-stressed beams, including pile liners as structural components and the embodied carbon footprint of permanent parallel lines.
- Designers face a difficult compromise to balance priorities such as durability, maintenance and sustainability considerations.
- Encouraging bridge rehabilitation and lifespan extension might be hindered by risk-sharing concerns between designers and asset owners.

Summary

From the workshop, the stakeholders emphasised the need for:

- optimising designs for sustainability outcomes
- integrating sustainable materials and technologies
- incorporating sustainability throughout the project life cycle including design phase
- standardising assessment tools and incorporating transparency into sustainability measurement
- assessing opportunities to rehabilitate existing structures and addressing culture of risk aversions
- revising design methods and specifications to promote sustainable design and construction methods
- encouraging or requiring LCAs to be developed during the design phase
- improving early collaboration between structural and design engineers
- facilitating knowledge sharing and education of sustainability principles, and applications and case studies
- using procurement processes to promote sustainability performance and apply weighted multi-criteria assessments
- facilitating ongoing research into sustainable materials, designs and construction technologies
- limiting over-design.

Recommendations from the stakeholder's feedback on the draft literature review and workshop have been included in Section 6.4.1.

6.4 Conclusions

When evaluating the sustainability of a structure's design, the whole life cycle of the structure needs to be considered. LCAs offer a comprehensive, quantifiable way to assess environmental impact across the life cycle of the structure, from material extraction and fabrication to construction, operation, maintenance and eventual demolition. However, LCAs may not capture all aspects of sustainability such as social impacts on workers or communities and they come at the cost of time and effort. In the absence of LCA data, benchmarking provides a valuable alternative. Benchmarking compares the sustainability performance of a structure against similar structures that have achieved positive environmental outcomes. This qualitative assessment offers a good indication of the structure's potential environmental footprint relative to industry standards and practice.

Comparing the structure's design to similar successful sustainable projects adds another layer of value. This transparency not only highlights areas for improvement but also acts as a reality check, ensuring proposed material choices, energy use estimates and other decisions are grounded in achievable benchmarks. It is crucial to recognise that sustainability elements are often interconnected. For example, focusing solely on minimising costs does not translate to sustainable outcomes. Sustainable materials and design techniques may initially be more expensive, particularly until they become more widely adopted. Criteria weightings need to be carefully considered to achieve the desired sustainability outcomes.

Stakeholder engagement is key to navigating these interdependencies. By including a diverse range of voices in the design process, all perspectives – environmental, economic and social – can be considered. This collaborative approach ensures that sustainable solutions are identified and implemented for the structure and enables adjustments to be made throughout the development phase, ultimately leading to a more sustainable and successful structure.

In terms of the broader sustainability of a bridge's life cycle, designers have direct and indirect influences over a range of aspects. Designers can:

- indirectly influence procurement but should take an active role and work with procurement professionals to understand the procurement implications of their designs (i.e. material selection, construction and maintenance practices) across the life of a bridge to improve sustainability outcomes
- directly influence the resilience of bridges and need to ensure they are able to withstand potential threats such as climate change and natural hazards, and maintain service
- assess bridge design options considering social, economic and environmental factors throughout the bridge's life cycle
- influence the energy use and embodied carbon of bridges by using less material, locally sourced materials and renewable energy sources; they can also consider the reuse of materials and components from old bridges
- indirectly influence water pollution, noise, air pollution, vibration and light pollution
- play an active role in resource efficiency according to the waste hierarchy, from minimising material use and waste by selecting appropriate materials, to exploring the use of recycled materials and geopolymers Early-stage modelling tools can be helpful for designers to assess the impacts of material, energy, and water use
- influence the impact on wildlife by considering habitat retention, biodiversity and wildlife connectivity in the design
- contribute to meaningful stakeholder engagement by incorporating community feedback into designs
- be involved in identifying and developing initiatives that benefit the local community or environment; this could involve using local resources or focusing on innovation in design
- consider the cultural significance of a bridge location and design in a way that protects and enhances its heritage.

6.4.1 Recommendations

Following the literature review in Section 6.2 and outputs of the stakeholder engagement workshop detailed in Section 6.3, the following actions are recommended in order to improve incorporation of sustainability into designs. These recommendations were further investigated in Year 2 of this project. The outcomes of Year 2 are provided in Section 7.

Project planning recommendations

It is well recognised that optimal sustainability benefits can only be achieved when considered from the earliest stages of the project life cycle. The following actions are recommended from ideation, inception and master-planning stages and are to be further developed throughout each project:

- Project appraisals and business cases must consider the sustainability costs of alternatives, including maintaining and rehabilitating existing infrastructure, to extend effective service life.
- Guidelines for planning and evaluating options to retrofit and maintain existing infrastructure should be developed. This may provide a range of sustainability benefits and provides a necessary baseline to compare against new construction proposals.
- Strategic procurement practices should be used to ensure sustainable design outcomes are achieved. MCA decision frameworks must give appropriate weighting to sustainability parameters. Project briefs should clearly outline sustainability requirements and incentivise the use of sustainable materials and construction methods.
- Sustainability considerations must be integrated into the planning stages. This includes optimising road layouts, minimising bridge needs and exploring the use of modular or adaptable designs to facilitate future modifications. Effective planning will require early consolidation of both civil and structural components.

Project design and specification recommendations

The following actions are recommended to implement sustainability criteria into designs by providing direction and supporting engineers:

- Contract specifications should be updated to require the assessment and reporting of key sustainability parameters alongside traditional design parameters. Proposed designs and tenders should be reviewed with prejudice if they do not effectively report on key sustainability criteria.
- Clear and comprehensive specifications should be developed that mandate minimum sustainable construction practices and incentivise maximum sustainability benefits. These specifications should address areas including decarbonisation, waste reduction and reuse, and energy-efficient construction methods.
- Accepted, standardised tools for assessing the sustainability of infrastructure projects should be developed or nominated. These tools should be transparent and user-friendly and should account for Australian conditions. A set of relevant input parameters for use within the models is also required. Such parameters may include, but are not limited to:
  - permitted assumptions and specifications, including life cycle scope and lifespan definition
  - accepted databases for use (e.g. performance, emissions factors, economic costs etc.)
  - guidance on weighting assessment criteria including comparing base cases to alternatives.
- Design criteria should be reviewed and work undertaken to remove Barriers to more sustainable designs, for example by including more performance-based (outcomes-driven) options.

Framework for designing for sustainability

Due to the rapid rate of development regarding sustainability options and the relative lag in practice, governance and specifications, it is recommended to develop guidelines for designing works for sustainability. Guidance documentation should address:

- stakeholder groups to engage at each stage of the design process
- practical guidance toward planning LCAs, and modelling alternatives
- a procurement strategy including defining sustainable targets and weighting MCA assessment criteria
- a framework for performance-based assessment for the use of recycled or low carbon materials, noting that safety-in-design and asset lifespans are to be maintained
- assessment of materials for end-of-life recyclability
- assessment for occupational health and safety and environmental impacts
- whole-of-life financial and non-financial costs.

General recommendations

The following list of general recommendations should be considered in order to support the continuous development of best practice in sustainability:

- Invest in research and development of innovative materials and construction techniques that minimise embodied energy and environmental impacts.
- Establish platforms for knowledge sharing and best practices related to sustainable infrastructure design and construction. This can involve workshops, training programs and online resources.
- Address risk-sharing concerns related to bridge rehabilitation and lifespan extension. Develop frameworks and incentives that encourage designers (or asset owners) to consider the long-term benefits of maintaining existing structures.
- Promote early collaboration between infrastructure owners, structural and civil engineers during the planning and design stages.
- Foster greater collaboration between designers and contractors throughout the construction phase. This allows for early identification and mitigation of potential sustainability issues arising from construction methods.
- Consider modelling the sustainability impacts of designing for different design-lives, optimised for different material choices and structural types. The whole-of-life embodied energy may be optimised, without over-design.

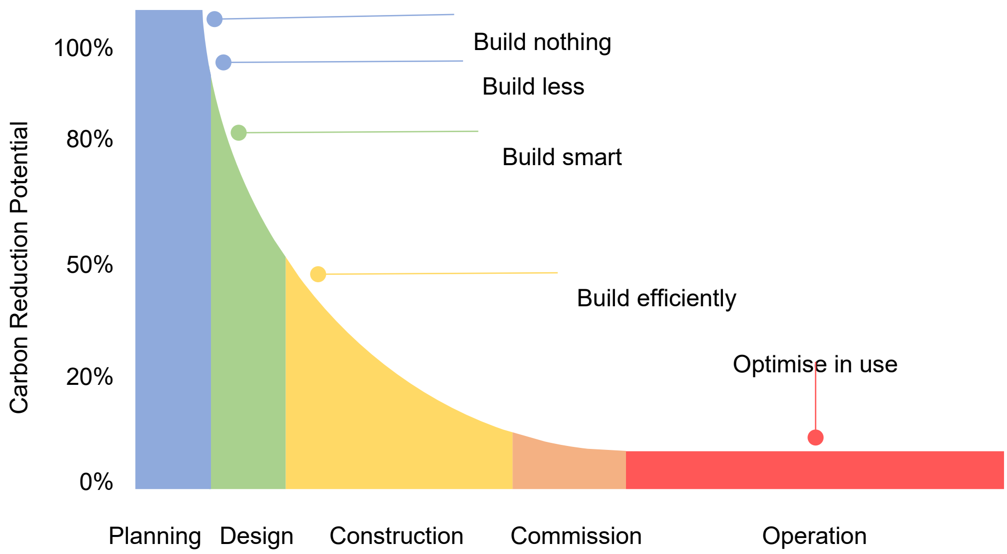
7. Support for Sustainable Decision-making in Structural Design

7.1 Introduction

Traditionally, structural designers have primarily been focused on ensuring their designs met durability, maintenance and service-level requirements. The quest for sustainable infrastructure practices gathers apace with various state and federal government policies and legislation around net zero GHG emissions and other sustainability targets. To respond to these imperatives, E&T Structures needs to chart an operational course to measurably improve and embed the sustainability of design, construction, maintenance and life cycle management of structural assets, to achieve GHG emissions reduction targets, on a pathway to net zero GHG emissions by 2050 and mitigate the impacts of climate change. Structural designers have many direct and indirect influences over a broad range of sustainability impacts, as demonstrated in Figure 7.1. They can influence not only the material type and quantity used but also the broader environmental, economic and social impacts that can make structures more sustainable and resilient.

There is a trade-off between when decisions are made and their impact on sustainability outcomes. As can be seen from Figure 7.1, the greatest opportunities to reduce GHG emissions (carbon), for any infrastructure project, are at the earlier stages. As the detail and accuracy of the project's design increases, the opportunities decrease and the cost of change increases. As a project moves through design phases and into detailed design, the ability to challenge, influence or alter the design solution reduces and the focus moves more to optimising the design (e.g. pavement types or concrete mix designs).

Figure 7.1: Ability to influence whole-of-life-cycle carbon emissions



Source: Adapted from Mott MacDonald and Arup (2016).

While the early stages of an infrastructure project (i.e. during the business case and planning stages) are when the greatest influence on sustainability outcomes can be made, there is significant project uncertainty due to the undefined scope. As the project progresses beyond the initial stages, more project details are confirmed which enables an increase in the accuracy of measurement and estimation. However, as the project progresses the scope to influence change reduces.

Despite the uncertainty during the early stages, designers need to be involved in making decisions and understanding their effects on sustainability using preliminary estimates. Making assessments during the early stages enables designers to significantly influence the design and materials selection to ensure sustainable outcomes are achieved.

7.1.1 Scope

This project aims to enhance TMR's ability to assess and mitigate the environmental impact of structural design decisions. By leveraging insights from previous research phases, the project has developed practical guidance for TMR staff to estimate embodied carbon and broader sustainability outcomes throughout the project life cycle, from initial concepts to completion.

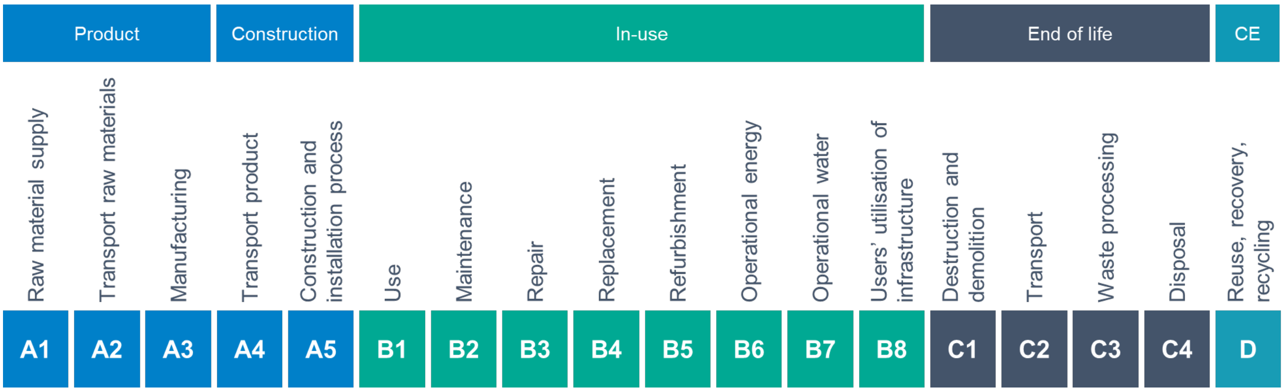
This guidance focuses on the stages of a structure when the designers are most involved and can greatly influence the sustainability outcomes. It will outline methods and information requirements for different project stages, and how and when to apply material and emissions factor data for embodied carbon measurement.

This guidance is aligned with and informed by the recently released Infrastructure and Transport Ministers (ITM) *Embodied Carbon Measurement for Infrastructure: Technical Guidance* which was recently approved by all states (ITM 2024). In this document, it will be referred to as the 'National Measurement Guidance'.

7.1.2 Life Cycle of a Structure and Carbon Terminology

The life cycle modules (Figure 7.2) of a structure cover the production of raw materials to the structure's end of life disposal and reuse as part of the circular economy. The modules cover the various stages of a project's life, from the production of the input materials (A1-A3), the construction of the structure (A4-A5), the use of the structure (B), its end of life (C), and finally any circular economy outcomes that occur beyond the structure's asset life (D).

Figure 7.2: The life cycle modules of a structure and the minimum inclusions as outlined by the National Measurement Guidance



Source: ITM (2024)

The different carbon terms and life cycle modules associated with the life cycle of a structure are defined in Table 7.1. Embodied carbon is the most important for TMR, and further details on the minimum inclusions for the embodied carbon of structures is discussed in Appendix A.

Table 7.1: Description of the various carbon terms used and the relevant life cycle modules

Term	Description	Life cycle modules
Upfront carbon	The carbon emissions associated with the product and construction stages up to the structure's practical completion.	A1-A5
In-use carbon	The carbon emissions associated with the processes and materials required to maintain, repair. Or refurbish the structure during its operational life.	B1-B5
End-of-life carbon	The carbon emissions associated with the structure's end-of-life deconstruction or demolition and the transport and processing required to dispose of any waste.	C1-C4
Embodied carbon	The carbon emissions associated with upfront carbon plus the emissions directly associated with the management of the structure and the end-of-life.	A1-A5 B1-B5 C1-C4
Operational carbon	The carbon emissions associated with the energy and water usage during the structure's operational life (e.g. lighting). Some elements of modules B1 and B2 may be included under operational carbon.	B6, B7
User carbon	The carbon emissions produced by users of the structure (i.e. the emissions produced by vehicles travelling over the structure).	B8
Circular economy	The potential carbon emissions that can be saved by reusing, recovering, or recycling materials and components from the structure at the end of its life.	D

While designers can have some level of influence on most of these modules, they will have the most impact on the upfront carbon and embodied carbon. Given that designers may have limited scope for drastically changing the design of the structure and adjusting maintenance schedules, the greatest area of impact for designers is around the materials (type and quantity) used in the structure. The materials are generally the largest component of a structure's carbon emissions, excluding the enabled emissions from the user's utilisation of the asset (B8), and will be the focus of this work.

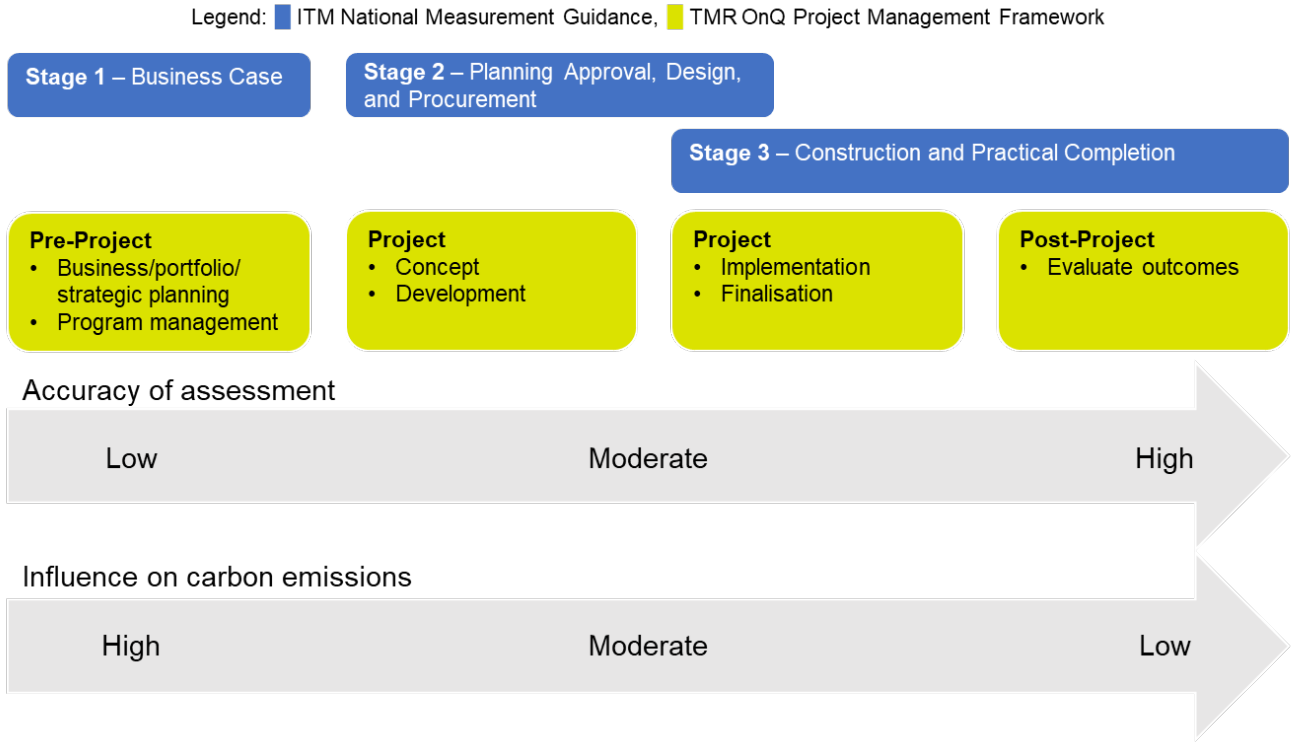
7.2 When Designers can Calculate Carbon

Designers are increasingly being asked to consider the sustainability impacts and outcomes of their designs, particularly regarding the embodied carbon emissions. They have a responsibility to not only consider the long-term impacts of performance and durability, but also the structure's embodied carbon contribution. Throughout the life of a structure (or any transport infrastructure project), there is an inverse relationship between the level of influence on carbon emissions and the accuracy of assessment, as shown in Figure 7.3. This highlights the importance of establishing benchmarks or estimates of the carbon emissions as early as possible despite the lack of accuracy.

As designers play a pivotal role in these early stages, they can significantly influence the embodied carbon of a structure. It is important to encourage designers to take an active role in understanding the impact of their design choices on not only durability and costs, but also the broader sustainability impacts including embodied carbon. Consideration must be given to the influence of design choices on the later stages of the project beyond its practical completion and operation.

This report focuses on the pre-project and project concept and development stages. The later project stages (i.e. project implementation and finalisation, and post-project) are briefly discussed to provide some context on how designs may impact the carbon emissions of the structure.

Figure 7.3: The accuracy of assessment and influence on carbon emissions throughout the life of a structure

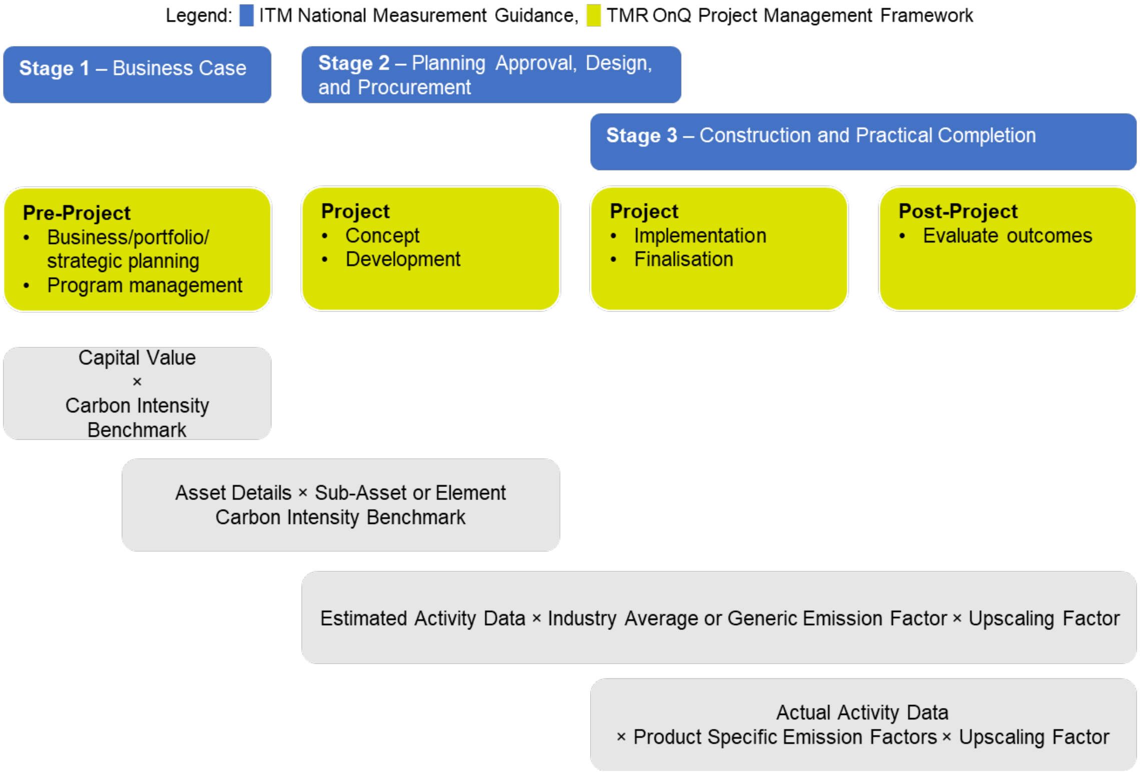


7.3 How Designers can Calculate Carbon

This section describes how designers can calculate the carbon at each stage of a project's life. Figure 7.4 outlines the suitable approaches to calculating the embodied carbon of a structure at each stage of its life. The pre-project stage lacks confirmed information and data about the structure and estimating the embodied carbon requires the use of benchmark values based on the capital value of the project. As the project progresses to concept, development and implementation, more information and data progressively becomes available that can be used to refine and improve the carbon calculations.

During the stages where designers are involved, there are three approaches available to calculate the embodied carbon. This section discusses the approaches, including the level of coverage or detail required to capture the materials and activities associated with the structure and indicates the available data sources and tools for material type and quantity and emissions factors.

Figure 7.4: How to calculate embodied carbon throughout the life of a structure



Note: For further information about the upscaling factor, see Appendix A

7.3.1 Pre-project

At the pre-project stage, the focus is on developing the business case for the structure and there is significant uncertainty around the structure's design and detailed requirements. This makes it difficult to make any accurate assessments due to the lack of confirmed project details (e.g. material selections, quantities etc). It is unlikely that approximate estimates of the material quantities will be available during the pre-project stage. At this early stage, only benchmarking can be performed using asset level costs and material spend proportions to estimate the upfront carbon (modules A1-A5). This benchmark of the upfront carbon is useful to gain an initial appreciation of the magnitude of upfront carbon emissions and use to compare initial concepts/designs during later stages.

The National Measurement Guidance[4] (ITM 2024) has provided a set of pre-project factors for road and rail bridges (Table 7.2). These recommended factors (low, mid and high) utilise the anticipated capital expenditure and the material share of the capital expenditure. The midpoint is recommended to be used as the default value for use in submissions to Infrastructure Australia, while the low and high values can be used to provide a range for a sensitivity analysis if desired (ITM 2024). The product stage factors are considerably greater than the transport and construction factors, highlighting the importance of choices in material selection and structural design on the embodied carbon.

[4] The National Measurement Guidance acknowledges there is a current lack of available asset level carbon intensity benchmarks and encourages transport agencies and industry bodies to further develop these.

Table 7.2: Pre-project emission factors based on material spend for bridges ($kgCO_2e$/$ material spend)

Bridge type	Range	Material share of capital expenditure (MS_C)	Product stage (A1 – A3)	Transport (A4)	Construction (A5)
Rail bridge	Low	23%	1.270	0.061	0.134
	Mid	31%	1.700	0.081	0.179
	High	39%	2.120	0.102	0.224
Road bridge	Low	23%	1.270	0.054	0.122
	Mid	31%	1.700	0.073	0.163
	High	39%	2.120	0.091	0.203

Source: ITM (2024).

The upfront carbon emissions can be estimated from the capital expenditure of the project and the material share and emissions factors (Table 7.2) using Equation 1.

$$Emissions = CAPEX \times MS_C \times EF_{CIB} \times \frac{1}{1,000}\ (tCO_2e) \quad (1)$$

where

$CAPEX$ = estimated capital expenditure of the structure ($)

MS_C = material share of the capital expenditure (%)

EF_{CIB} = emission factor (carbon intensity benchmark) for asset type ($kgCO_2e$/$ material spend)

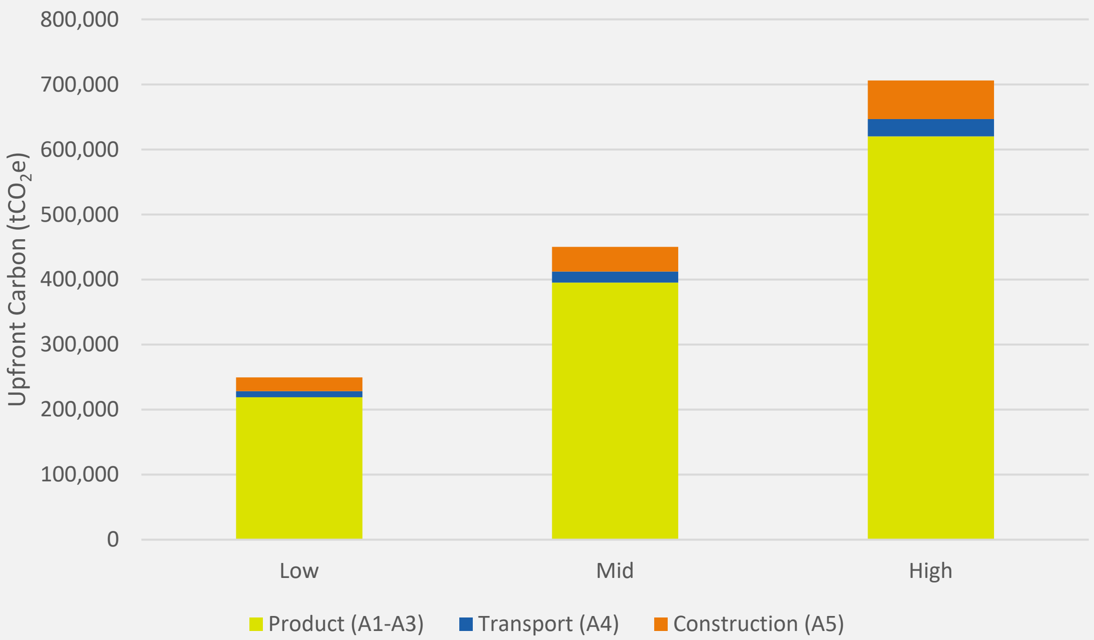
A worked example of how to use this equation and data to estimate the upfront carbon emissions for a road bridge is presented in Box 1.

BOX 1: Example calculation of upfront carbon at the pre-project stage

Consider a new road bridge that is estimated to cost $750 million. Using the mid-point estimate of the material share of the capital expenditure, the carbon associated with the product, transport and construction stages can be calculated using Equation 1 to estimate the total upfront carbon:

- Product (A1 – A3): 750,000,000 × 0.31 × 1.700 × 1/1000 = 395,250 tCO_2e
- Transport (A4): 750,000,000 × 0.31 × 0.073 × 1/1000 = 16,972.5 tCO_2e
- Construction (A5): 750,000,000 × 0.31 × 0.163 × 1/1000 = 37,897.5 tCO_2e
- **Total upfront carbon: 395,250 + 16,972.5 + 37,897.5 = 450,120 tCO_2e**

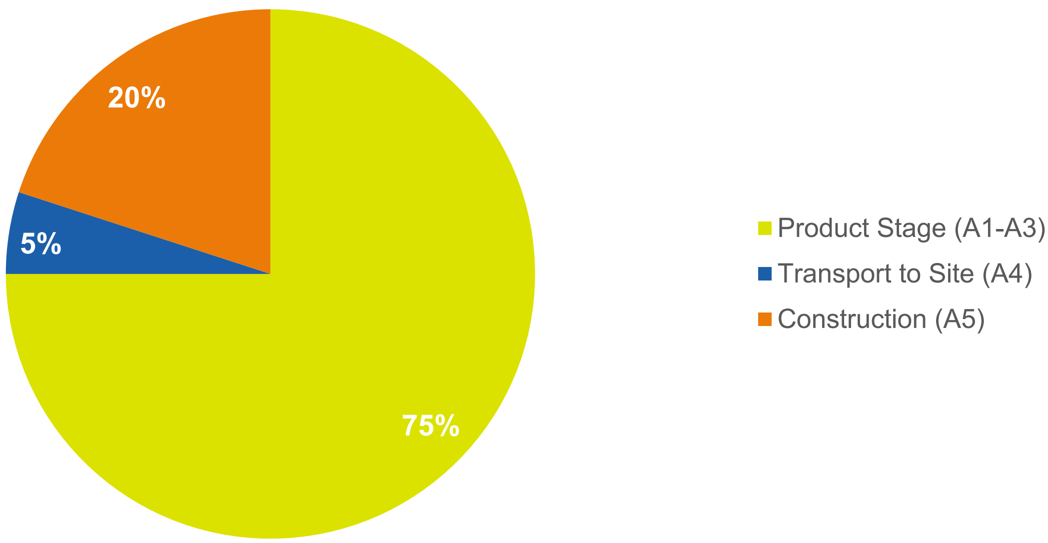
The low and high values can be used to provide a range of the upfront carbon rather a single value using the mid-point. The chart below illustrates the effect of the low, mid, and high values on the upfront carbon. For all values, the results indicated that most of the upfront carbon emissions are associated with the product stage and so the materials used in the structure play a significant role in the sustainability outcomes. This highlights the importance of the design of the structure and the role materials selection plays in reducing embodied carbon emissions.



7.3.2 Project: Concept and Development

The project concept and development stages are when designers will be developing conceptual and detailed designs of the bridges and they can have a strong level of influence on the embodied carbon emissions. A recent study by Infrastructure Australia estimated that the input materials were responsible for the vast majority of the upfront carbon (Figure 7.5). Sufficient data will not be available to comprehensively calculate the upfront or embodied carbon, but input material information can be used to estimate the carbon emissions.

Figure 7.5: Share of upfront carbon by life cycle modules for Australian infrastructure and buildings



Source: Infrastructure Australia (2024a).

The basis for estimating carbon emissions associated with materials is presented in Equation 2. To estimate the material carbon emissions, data on the quantity of materials used and an associated emission factor for the materials is required.

$$Emissions = material\ quantity \times emission\ factor\ (tCO2e) \quad (2)$$

where

$material\ quantity$	=	material quantity used in the structure (UoM)
$emission\ factor$	=	emission factor of material (tCO_2e/UoM)
UoM	=	unit of measurement (tonnes or m^3)

The life cycle module coverage of the emissions is dependent on the emission factor used. The data sources that are likely available during the project concept and development stage to estimate the carbon emissions associated with the materials are summarised in Table 7.3. These data sources are focused on estimation before actual data becomes available during the project development (i.e. construction data from material tracking registers or suppliers). The available data sources and their limitations will be discussed in the following sections by the different life cycle stages and modules.

The 2 data sources identified to be available in the future are the use of building information modelling (BIM) and sub-asset (element) level estimates. The latter would be particularly useful at the project concept stage (for estimates or benchmarks in tCO_2e/m, tCO_2e/m^2, etc. While there are none currently available, the National Measurement Guidance recommends that jurisdictions begin to develop these alongside industry associations (ITM 2024) to provide an improved approach to estimating the upfront carbon of a structure.

Table 7.3: Summary of data sources for material type and quantity for estimation

Type	Available now	Available in the future
Material type and quantity	• Initial BoQs • Contract documents and claims(1) • Digital designs(1)	• Building information modelling(2)
Emission factors	• Generic national or industry average factors • Environmental product declarations (EPDs)	• Sub-asset level estimates(3)

1. Initial review of provided data sources found them to be not useful. If material type and estimates of total quantities (t or m^3) are easily accessible from these sources, then they will be useful.
2. Unable to be reviewed in this project but expected to be useful in providing material type and quantity data.
3. No data currently exists, but the National Measurement Guidance strongly recommends that jurisdictions work to develop these datasets.

Product stage (A1 – A3)

The product stage is focused on the supply of materials for the structure, comprising the supply of raw materials (A1), the transport of these raw materials to the manufacturing site (A2), and the manufacturing of the raw materials into the product (A3). This is where designers should focus their efforts, as through their designs and materials selection, they can significantly impact the carbon emissions of the structure.

Calculating the product stage carbon emissions requires the quantity of materials used and the carbon intensity of each material. Material quantities can be obtained from BoQs, contract documents or digital designs but the data needs to be made accessible. Initial BoQs are likely to be the best source of data, with data sourced from BIM a potential future option if available. When sourcing emission factors for materials and considering their use in the design of a structure, designers should develop an understanding of the carbon intensity (tCO_2e/tonne of material) of typical structural materials and where they can replace materials with recycled or low carbon alternatives.

Emission factors for materials covering the product stage are available from various sources:

1. Product specific emission factors

Ideally, product specific emission factors should be used where available, determined from a life cycle assessment or EPD. EPDs outline the life cycle environmental impact of a company's products and are becoming increasingly common among product and material suppliers and manufacturers. In Australia, EPDs cover a range of materials relevant to structures, including concrete, steel (reinforcing and structural), and wood and timber products. EPDs are often generated by a third party and always independently reviewed and verified according to ISO 14025.

The data required to undertake an EPD include specific (or foreground) data that is sourced directly from the producer/manufacturer and generic (or background) data from life cycle inventory databases such as AusLCI. EPDs offer a partial pathway to better, more accessible data as they are built off current-practice product specific information and undergo rigorous validation testing prior to publication. EPDs however, also rely on the aging AusLCI and ecoinvent datasets and have limited coverage of infrastructure materials with high development costs and long approval timelines constraining their expansion.

EPDs for a range of building and construction products are available via the EPD Australasia (2024) website.

2. *Generic (industry/national average) emission factors*

The ALCAS provides and maintains a national, publicly accessible database to assist in undertaking life cycle assessment (ALCAS n.d.). In May 2023, ALCAS developed the AusLCI Construction Emissions database specifically for the construction sector based on the AusLCI database (and shadow database to fill gaps in available Australian data). The AusLCI database and shadow database are used extensively in several tools across Australia (e.g. IS Materials Calculator, SAT4P) and are the standards used in assessing the embodied carbon (and broader environmental impacts) for LCAs and EPDs in Australia.

The data does not have a secure and sustainable funding source to ensure timely data updates. As an interim approach, the AusLCI database is complemented by the AusLCI shadow database, which is a localised version of the international ecoinvent v2.2 database, with input flows changed to AusLCI where process data is available (e.g. electricity, transport, natural gas, materials etc.).

Despite its limitations, the AusLCI database is still considered the industry standard and is accepted as current best practice throughout the life cycle evaluation and sustainable infrastructure communities. It is recommended to be used when product-specific data is not available in the National Measurement Guidance (ITM 2024).

3. *Emission factors provided by tools*

There are several tools that can be used to estimate the carbon emissions associated with the materials of a structure. Many tools have been developed over the years that are made to be accessible by designers and non-life cycle experts. These tools often rely on a combination of industry average, product specific and proprietary data. These tools are generally used early in the design stages to estimate the carbon emissions of different designs. Some common tools include:

- NABERS Embodied Emission Tool (NABERS 2024)
- IS Materials Calculator (Infrastructure Sustainability Council 2023b)
- SAT4P for pavements (Hall et al. 2020)
- eTool by Cerclos (Cerclos 2024).

Construction stage (A4 – A5)

The construction stage covers the transport of materials to the construction site (A4) and the construction activities to build and commission the structure (A5).

The transport module is indirectly influenced by designers through their materials selection. To calculate the emissions associated with the transport of materials to site, data is needed on the quantity of materials and the distance transported. Transport also has strong links to procurement and designers can aid in encouraging sustainable procurement practices to encourage low carbon materials or transport alternatives to deliver materials to site. Designers may consider the impact of their material choices (both in quantity and type) on the transport module through the origins of the materials, and if they are sourced from local, interstate, or overseas. Where possible, arterials should be located as close as possible to the construction site (i.e. local rather than interstate or international).

The construction stage, focused on the carbon emissions associated with building and commissioning the structure, is one that is difficult for designers to directly influence and assess. Consideration could be given to, for example, how to recycle or reuse waste materials that may be available on site that can be used in or around the structure, or how the design could improve constructability (e.g. through modular design, minimising earthworks, etc.).

Estimating the construction stage carbon emissions requires knowledge of the energy usage (kWh of electricity, litres of diesel, etc.) and waste generation to landfill. Further information is provided in the National Measurement Guidance (ITM 2024), particularly Appendices 3, 4, and 9 which provide default (i.e. generic) emission factors and data for the transport and construction modules. The National Measurement Guidance provides default calculations for:

- transport distances for materials (to site and to waste) by state and mode of transport (road, rail, sea)
- construction waste generation rates by material
- end-of-life waste treatment rates (recycling, landfill and incineration) by material.

Box 2 provides a simple worked example to calculate the carbon emissions to transport materials to site using the default data provided in the National Measurement Guidance (ITM 2024).

BOX 2: Example calculation of emissions to transport materials to site

Consider a new bridge that requires 25 t of material that needs to be transported to site. To estimate the emissions associated with the transport, the following equation is used:

- Emissions = material quantity (t) × distance travelled (km) × emission factor (tCO_2e/tkm)

Default data from the National Measurement Guidance (emission factors from Appendix 3, transport distances from Appendix 9) can be used to estimate the carbon emissions to transport the cement to the site by the different modes:

- Truck (articulated): 25 × 475 × 0.00007 = 0.83 tCO_2e
- Rail (bulk transport): 25 × 1,576 × 0.00002 = 0.79 tCO_2e
- Sea (shipping): 25 × 813 × 0.00001 = 0.20 tCO_2e

Note: Several complexities influence the carbon intensity of transport, but these are outside the scope of this report.

7.3.3 Project: Implementation and Finalisation, Post-Project

The project implementation stage is concerned with the delivery of the structure, namely its construction. After this has been completed, the project finalisation stage deals with the handover, close-out and evaluation of the project. The post-project stage also involves some level of outcomes evaluation and the ongoing operation of the structure. Designers will have limited, if any, involvement during these stages of the project.

During these stages, the level of accuracy in the structure's embodied carbon increases significantly with the utilisation of actual data – the data sources available include material tracking registers, detailed BoQs, and the IS Materials Calculator. These data sources should be used to replace previous estimates and fill in gaps where data was previously not available. The increase in accurate data being available during implementation means that most major decisions have already been made and so there is little scope to have an influence on reducing embodied carbon.

It66hile66antt that the data and calculations of materials, activities, and emissions from each of the project stages are recorded and made available to designers. A repository[5] with such data for historical projects would be invaluable to designers as they work on future projects to provide benchmarking against their designs and refine initial estimates and benchmark carbon intensities at the asset or sub-asset levels.

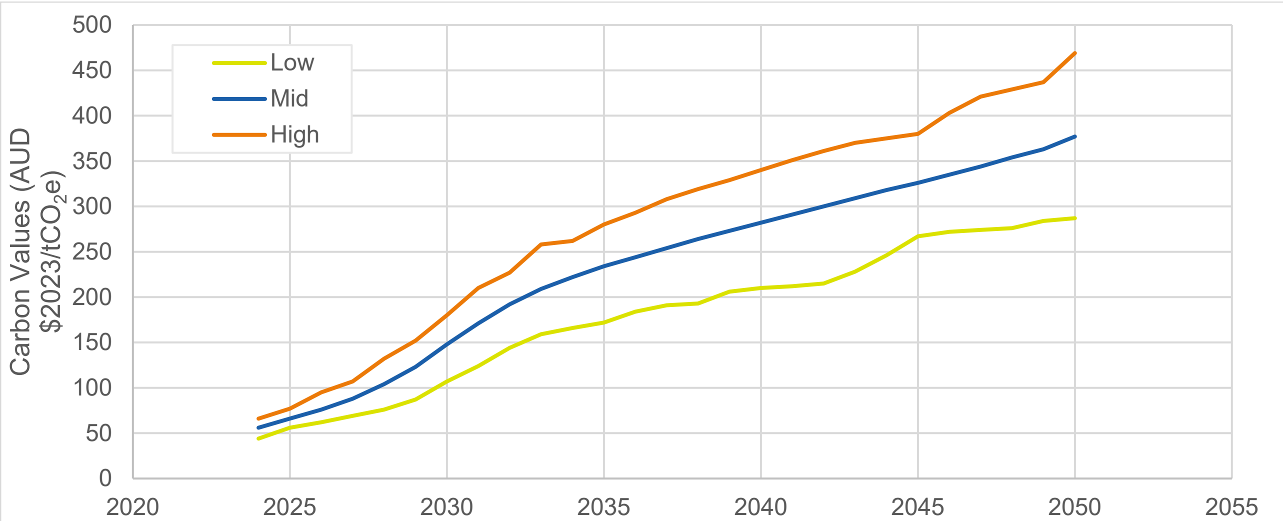
[5] Further information on this is found in the IS Ratings and National Measurement Guidance.

7.3.4 The Value of Carbon

While carbon emissions are often expressed in mass per unit of equivalent carbon, another common approach is to use a carbon value to provide a monetary value. In May 2024, IA released a guidance note on 'Valuing Emissions for Economic Analysis' (Infrastructure Australia 2024b). The values are considered to be used to measure the social impacts of carbon emissions in infrastructure proposals and are required in submissions to Infrastructure Australia from Australian, state or territory governments. The guidance note provides a set of nationally approved annual emissions values from 2024 to 2050 and outlines how they should be applied. The 3 sets of values are shown in Figure 7.6. The central value is the default to be used in any submission to IA, while the low and high values can be used for sensitivity analyses.

The increasing value of carbon emissions over time places greater importance on when materials are used and activities are undertaken, including longer term impacts on maintenance, repairs, refurbishment and replacement. The use of low carbon and recycled materials will have a greater emphasis in future years. A worked example of the impact of material selection on the valuation of carbon emissions is provided in Box 3.

Figure 7.6: Carbon emission values for infrastructure projects



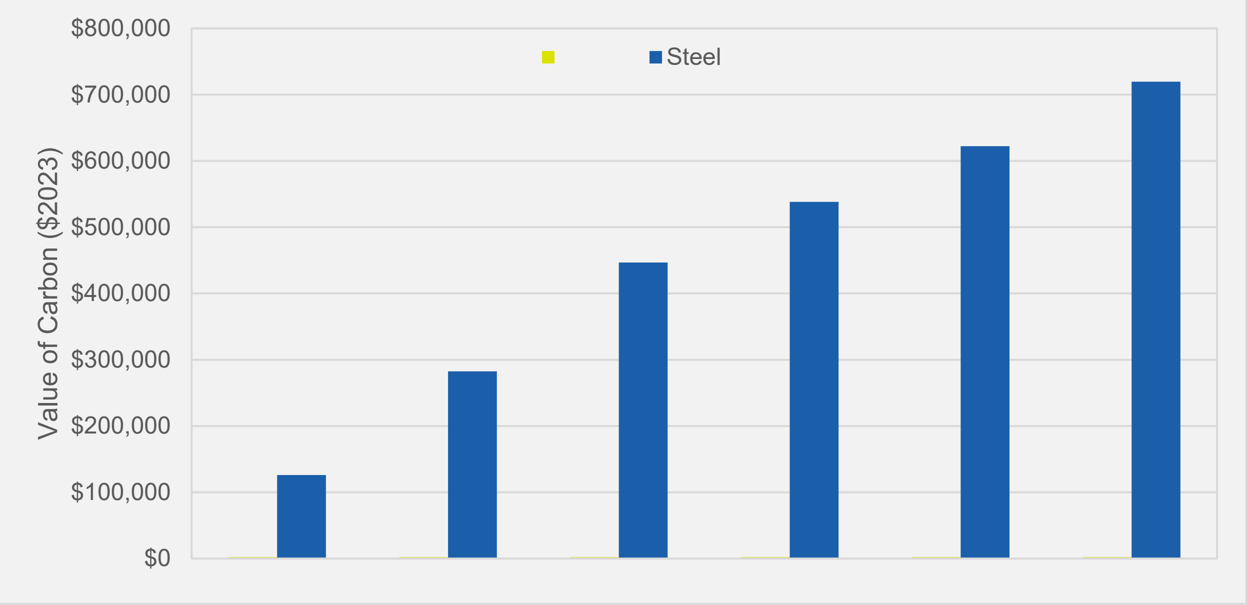
Source: Infrastructure Australia (2024a)

BOX 3: Example of the impact of valuing carbon and the role of low carbon materials

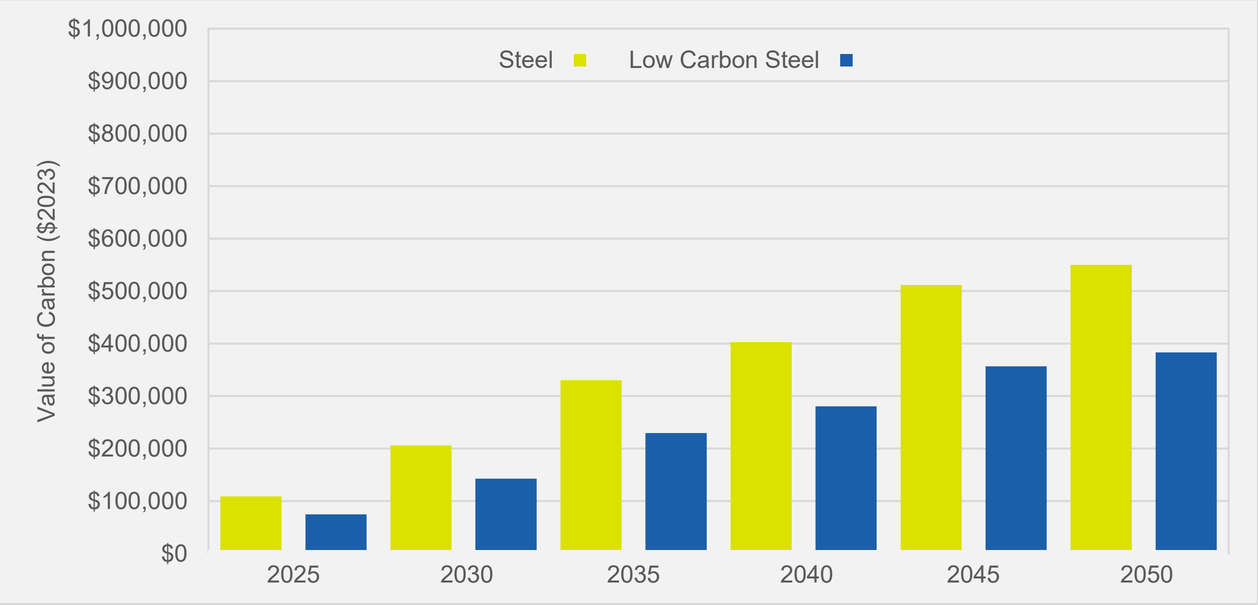
Consider a new road bridge that is estimated to utilise 1,000 tonnes of steel reinforcement. Using the steel reinforcement emission factor from SAT4P (Hall et al. 2020), and for simplicity assuming that a low-embodied-carbon steel provides a 30% reduction of emissions, the emission factors are:

- Steel = 1.909 tCO_2-e/tonne → 1,909 tCO_2-e
- Low carbon steel = 1.336 tCO_2-e/tonne → 1,336 tCO_2-e

The value of the material carbon emissions associated with the conventional and low carbon alternative if the bridge is to be constructed in various future years using the central value is shown in the chart below. The increased valuation of carbon in future years shows the benefits of careful material selection will significantly grow towards 2050, and since these values will be used in any IA assessment, it is important to consider the impact of material choice.



The low and high values can also be used to examine the sensitivity of the material choice on the value of carbon emissions in various years into the future, as shown below.



7.4 Consideration of Broader Sustainability Impacts

Broader sustainability impacts, beyond carbon emissions, consider the economic, social, cultural and environmental outcomes for a structure and the role that designers can play in achieving them. This project identified the relevant criteria to assess the broader sustainability impacts and outcomes that designers have some level of influence or control over (see Appendix B).

7.4.1 When Designers can Evaluate Broader Sustainability Impacts

ISC has developed a series of ratings schemes that assess the economic, environmental and social performance of infrastructure from design to operation of the asset (Infrastructure Sustainability Council 2024a). The complexity of the process and assessment criteria are directly linked to the capital value of the project, as shown in Table 7.4. The IS Ratings scheme is the ISC's comprehensive rating system that covers the planning, design, construction and operational phases of an infrastructure project, while the IS Essentials scheme is a simpler version recommended for use in smaller projects (Infrastructure Sustainability Council 2024a). The IS Essentials has a materiality assessment that will assist designers in identifying the most critical sustainability impacts that should be assessed. Even for smaller infrastructure projects that are under the IS Essentials threshold, the ISC encourages an assessment be undertaken.

The Design and As Built modules are where designers will be most involved and can influence the broader sustainability outcomes.

Table 7.4: Options for evaluating the broader sustainability impacts of structures by capital value

Capital value of structure	Program to evaluate impacts	ISC module coverage
< $5m	IS Essentials*	Design, As Built
$5m – $100m	IS Essentials	Design, As Built
> $100m	IS Ratings	Planning, Design, Operations, As Built

Note: * Optional for projects under $5 million.

Source: Infrastructure Sustainability Council (2024a).

7.4.2 How Designers can Consider Broader Sustainability Impacts

The focus should not solely be on the costs (i.e. the cost to construct) when designing a structure. The broader implications of designs should be considered across as many sustainability outcomes as possible. These include environmental, economic, social and governance sustainability, their interactions and dependencies, and what alternative solutions (options) can be developed.

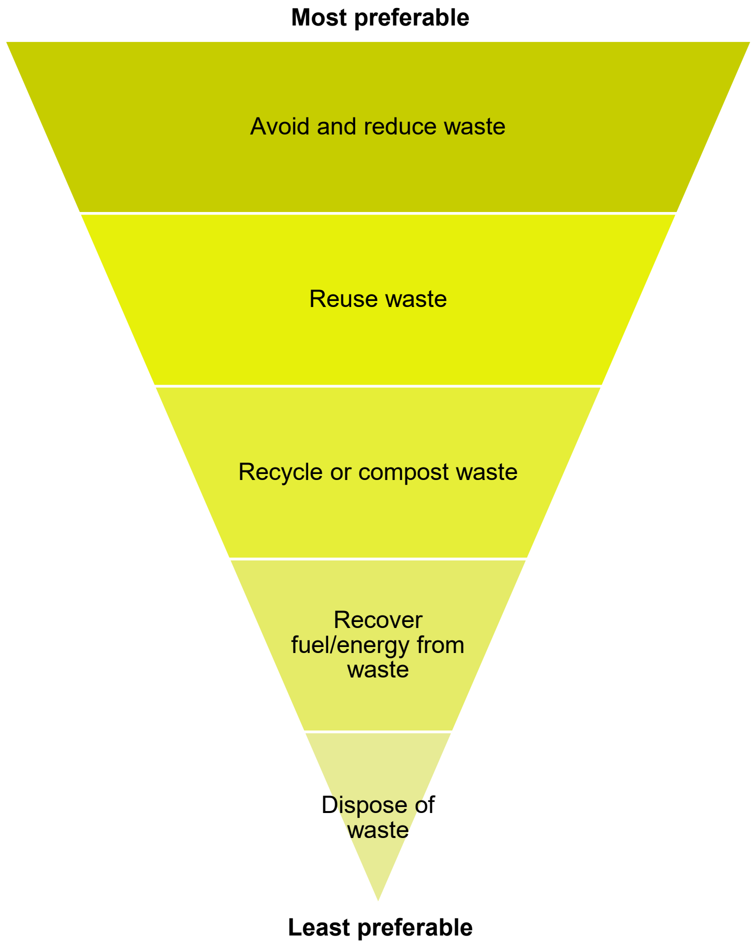
A good starting point for designers is to understand the life cycle of a structure. The sustainability and economic impacts can be evaluated through a quantitative LCA for the bridge, comprising all activities and the individual materials and components, or by benchmarking the outcomes using similar projects or materials where quantitative LCA data is not available.

A series of examples of different sustainability impacts and how designers could consider them are outlined in the following sections.

Example 1: Resource efficiency and management (Rso-1 to Rso-7)

Resource efficiency is the sustainable use of natural resources by minimising the overall consumption of materials and ensuring they are utilised to their fullest extent. While zero waste might always be out of reach, designers should strive to minimise resource use and maximise resource recovery. This requires an appreciation of the impacts of material selection on the construction of a bridge and where material inefficiencies/losses occur. The Queensland Government's (2019) *Waste Management and Resource Recovery Strategy* presents the standard resource and waste management hierarchy (Figure 7.7).

Figure 7.7: Hierarchy of waste and resource management and considerations for designers



Considerations for designers

- Minimising the total quantity of materials required.
- Prefabricate components off-site to reduce waste and improve efficiency.
- Simulate the performance of different design options to identify the most efficient and sustainable solution.
- Identify opportunities to use innovative recycled materials in the structure.
- Consider the entire life cycle of materials and design for end-of-life recovery.

- Identify opporunttiies to utilise waste in subsidiary infrastructure, or alternative infrastructure, e.g. recycled crushed concrete for road aggregates, or composted materials in landscaping.

- Identify opportunities to recover energy from waste materials, e.g. large amounts of concrete, steel and other materials can be generated during bridge demolition or leftover from construction. These materials can be recycled or used as feedstock for waste to energy technologies.

- Develop a comprehensive waste management plan that outlines waste segregation and disposal procedures.
- Provide separate storage containers for different waste streams, such as concrete, metal, wood and general waste.
- Evaluate the effectiveness of waste management practices and identify areas for improvement.

Source: Adapted from Queensland Government (2019).

One area of resource efficiency that has been gaining significant attention in recent years is the use of recycled materials to reduce embodied carbon and avoid wastage. For example, as described, SCMs such as fly ash and GGBS in concrete can generate a reduction in carbon emissions by up to 60% (Singh 2022). Furthermore, the use of geopolymers offers significant reductions in carbon emissions, with Hilton (2022) demonstrating up to an 80% decrease compared to traditional Portland cement. Additionally, using material waste generated on site (or nearby) is another option that designers should consider, including identification of contaminated materials and consideration of reuse opportunities in early works.

Consider how designs and material selections will impact on waste according to this hierarchy and identify and evaluate opportunities for alternative materials that may be available to reduce waste and carbon emissions. These should be considered in terms of the circular economy – one recent example is the

Northwestern Program Alliance's Keon Parade[6] level crossing removal in Victoria, which brought new and innovative recycled products to market and generated a range of sustainability benefits.

Example 2: Resilience (Res-1 and Res-2)

Resilience is the capability of a structure to be prepared for, respond to, and recover from threats with the minimum damage to social well-being, the economy and the environment (PIARC 2015). Resilience is becoming increasingly important due to climate change impacts on the frequency and intensity of extreme weather events. The resilience of a bridge is critical for designers, who need to ensure that structures are appropriately designed to withstand any future damaging effects.

As described, the AS 5100 bridge design standards have recently updated the requirements for bridges to meet the threats posed by natural disasters and flooding events. The choice of materials will play a significant role in the design of the bridge and how it performs under such circumstances. A thorough understanding of the new requirements are necessary to ensure they conform to the standards.

In addition, a thorough risk assessment in the design phases using available data to assess the sensitivity of a proposed bridge to the potential risks and develop appropriate mitigation strategies is invaluable.

Example 3: Environmental Impacts (Env-1 to Env-5)

Broader environmental impacts for bridges are focussed on reducing the life cycle pollutive impacts with regard to water, noise, air, vibration and light. While many of these impacts can be considered in both the construction and use phases of a bridge's life, the impacts here are focused on the use phase over which a designer can exert greater influence. To effectively reduce these impacts, utilise data on the existing conditions of the site and perform modelling to assess the potential impacts and risks, and redesign to incorporate mitigation measures as appropriate.

Example 4: Ecology (Eco-1)

The design and construction of modern bridges should aim to protect and enhance terrestrial and aquatic ecology through an evidence-based identification and management approach (ISC 2021). While designers are not solely responsible for this, they can have some direct and indirect influence over the impacts during construction, operation and maintenance. Designers should consider the following key principles:

- maximising the retention of vegetation/habitats
- maintaining biodiversity
- ensuring access and connectivity for wildlife.

Evaluation of the broader ecological impacts of designs, for example the creation of necessary temporary structures during the construction process, and how these could be minimised will improve the overall sustainability of a bridge and maintain or improve the local ecology.

See the Byford Rail Extension[7] case study for an example of positive ecological outcomes that increased canopy retention compared to the baseline.

Example 5: Stakeholder Engagement (Sta-2)

Stakeholder engagement has been highlighted by the ISC as a significant component of sustainability with its own dedicated credit. Effective stakeholder engagement with the community who live around the project and who will likely use the structure being built is recommended. While designers are usually not responsible

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[6] https://www.iscouncil.org/a-recycled-first-precinct-keon-parade-lxrp-level-crossing-removal-project-economic-outcomes/

[7] https://www.iscouncil.org/metronet-byford-rail-extensions-urban-forest-strategy-social-outcomes/

for this function, they can contribute in meaningful ways and should take an active role in stakeholder engagement to receive feedback on important aspects or outcomes of the proposed bridge and, in return, demonstrate to stakeholders where their feedback has been incorporated.

One example of positive outcomes achieved through collaborative stakeholder engagement and community consultation highlighted by the ISC is the Byford Rail Extension[8] that focused on improving both design and construction methodologies to protect significant trees and habitat, resulting in a 94% improvement in tree canopy retention.

7.4.3 Resources for Designers on Broader Sustainability Impacts

The ISC has a significant library of invaluable supporting resources that provides information and ideas about how to incorporate and achieve broader sustainability outcomes in a project. An overview of the ISC's resources is outlined below.

IS Ratings Scorecard: The IS Ratings Scorecard provides a clear list of the criteria to be assessed across the various sustainability impacts and how they are measured and achieved (Infrastructure Sustainability Council 2024a). The Scorecard and criteria are used to support the IS Essentials and IS Ratings programs. The relevant criteria for designers where they have the most influence are summarised in Appendix B.

IS Materials Calculator: The IS Materials Calculator is a spreadsheet-based tool that designers can use to calculate the life cycle impacts of materials in an infrastructure project and compare alternative designs (Infrastructure Sustainability Council 2023b).

Isupply: The ISC provides a regularly updated and maintained registry of sustainable suppliers via Isupply (Infrastructure Sustainability Council 2024a). The suppliers range from materials and components (e.g. Boral, Bluescope) to other services. These suppliers are useful to help designers and TMR find partners to meet their various sustainability targets and outcomes.

Case studies: The ISC compiles an ever-growing number of case studies to highlight how projects have achieved notable individual sustainability outcomes across economic, environmental, governance and social IS Ratings (Infrastructure Sustainability Council 2024b). These provide useful information and ideas for consideration across various aspects of sustainability.

7.5 Summary

This project aimed to equip TMR staff with practical guidance to assess and improve the sustainability of structural design decisions. By leveraging insights from Year 1 of this project, Year 2 developed methods to estimate embodied carbon and broader sustainability outcomes throughout the project life cycle.

This guidance focuses on the stages of a structure when the designers are most involved and greatly influence the sustainability outcomes, outlining methods and information requirements for different project stages, and how and when to apply material and emissions factor data for embodied carbon measurement. This guidance is aligned with and informed by the *Embodied Carbon Measurement for Infrastructure: Technical Guidance* which was approved by all states (ITM 2024).

The area in which designers can have the most impact is on the upfront carbon. Given that designers may have a limited scope for drastically changing the design of the structure and adjusting maintenance schedules, the greatest area of impact is around the materials (type and quantity) used in the structure. The materials are generally the largest component of a structure's carbon emissions, excluding the enabled emissions from the user's utilisation of the asset, and are the focus of this work. With this mind, this guidance

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[8] https://www.iscouncil.org/metronet-byford-rail-extensions-urban-forest-strategy-social-outcomes/

recommended that designers be aware of the increasing value of carbon emissions over time, which places greater importance on when materials are used and activities are undertaken, including longer term impacts on maintenance, repairs, refurbishment and replacement. The use of low carbon and recycled materials will have a greater emphasis in future years.

This report focused on the pre-project and project concept and project development stages. The later project stages (i.e. project implementation and finalisation, and post-project) are briefly discussed to provide some context on how designs may impact the life cycle carbon emissions of the structure. The guidance provided in this report identified ways in which a designer can influence the sustainability of a structure at each project stage and is summarised in Table 7.5.

The focus should not be solely on the costs (i.e. the cost to construct) when designing a structure but consider the broader implications of their designs on as many sustainability outcomes as possible. These include environmental, economic, social and governance sustainability, their interactions and dependencies, and what alternative solutions (options) can be developed. A good starting point is to understand the life cycle of a structure (from design to end of life). The sustainability and economic impacts can be evaluated through a quantitative LCA for the bridge, comprising all activities and the individual materials and components, or by benchmarking the outcomes using similar projects or materials where quantitative LCA data is not available.

To support designers, the ISC has a significant library of invaluable supporting resources that can provide designers with information and ideas about how to incorporate and achieve broader sustainability outcomes in a project.

Table 7.5: Summary of project stage estimation approaches including purpose, sources, limitations and actionable steps for designers

Project stage	Coverage	Type	Purpose/Focus	Data sources	Limitations	Actionable steps
Pre-project	Benchmarking data for upfront carbon	High level estimates	• Establish a baseline understanding of upfront carbon emissions. • Acknowledge broader sustainability impacts including environmental, social, and economic factors. • Set the stage for sustainable decision-making in later phases.	• Asset-level costs based on material spend (National Measurement Guidance)	Significant uncertainty due to lack of detailed project information	• Perform initial carbon benchmarking using available data • Apply National Measurement Guidance factors for carbon estimates • Consider the increasing value of carbon emissions over time • Begin identifying potential broader sustainability impacts
Concept and development	Detailed material quantities and associated emissions	Material specific estimates	• Make design choices that significantly reduce embodied carbon. • Integrate value of carbon to weigh long-term financial implications. • Address broader sustainability by considering environmental, social and governance factors in design. • Enhance resource efficiency and promote sustainable materials.	• BoQs • Contract documents • Digital designs • EPDs • AusLCI Database • Estimation tools (e.g. IS Materials Calculator)	May lack comprehensive data; estimates based on assumptions	• Estimate carbon emissions based on material quantities and emission factors • Select low carbon and recycled materials • Use tools such as IS Materials Calculator for detailed comparisons • Incorporate carbon values into material selection and design decisions • Use emission values from Infrastructure Australia to inform economic analysis • Assess broader sustainability impacts using ISC resources (e.g. IS Ratings Scorecard) • Optimise designs for resource efficiency and minimal environmental impact
Implementation	High accuracy data on materials used and emissions	Actual data from construction	• Validate and refine previous estimates with real data. • Understand financial implications of carbon emissions using actual values. • Learn from outcomes to improve future designs. • Support continuous improvement in sustainability practices.	• Material tracking registers • Detailed BoQs • Supplier data • Estimation tools (e.g. IS Materials Calculator)	Changes costly at this stage; limited influence on design	• Replace estimated data with actual construction data to refine calculations • Document all materials, activities and emissions • Revise carbon emissions value with updated data • Identify successes and areas for improvement in sustainability practices • Share learnings to promote sustainable practices in future projects
Post-project	Data on maintenance, repairs, refurbishment	Actual operational data	• Close the feedback loop by applying operational insights to future designs. • Understand the life cycle cost implications of carbon emissions. • Enhance future projects by learning from past performance. • Promote sustainability throughout the asset's lifespan.	• Operational data • Maintenance records • Infrastructure Australia (IA) carbon values	Designers have limited influence at this stage	• Analyse operational performance and maintenance impacts on sustainability • Calculate the total value of carbon emissions over the asset's life cycle • Incorporate feedback and lessons learned into future design guidelines • Plan for life cycle impacts, including maintenance, refurbishment and end-of-life scenarios • Evaluate the achievement of broader sustainability outcomes (environmental, social, economic)

8. Research Summary

This section provides a summary of each of the areas of research which were undertaken in the preceding sections. This includes:

- lower carbon concrete (Section 8.1)
- innovation assessment (Section 8.2)
- implementing low carbon concrete solutions (Section 8.3)
- materials usage data (Section 8.4)
- defining sustainability in design (Section 8.5)
- support for sustainable decision-making in structural design (Section 8.6).

Overarching recommendations and conclusions from the overall project are addressed in Section 8.7.

8.1 Lower Carbon Concrete

The low carbon concrete research undertaken investigated existing and emerging technologies for reducing the embodied carbon footprint of concrete, with a particular focus on Queensland. The high volume of concrete used in Queensland coupled with its significant embodied carbon impact, necessitated a close examination of potential reduction strategies. The assessment considered the technical maturity of these technologies within the state, their market readiness and the feasibility of their implementation.

The research identified 2 technologies with the potential for immediate carbon reduction in Queensland's concrete industry. Firstly, driving the utilisation of high-volume SCMs offers a significant opportunity to lower embodied carbon. By incorporating more SCMs into concrete mixes, particularly in precast applications, the reliance on traditional Portland cement, a major contributor to embodied carbon, can be substantially reduced.

Secondly, geopolymer concrete appears to be a promising technology for precast concrete production. While further investigation is required to determine its broader applicability within the construction industry, geopolymer concrete offers a viable path towards lower embodied carbon concrete.

While not yet readily available for widespread implementation, several other technologies hold promise for future carbon reduction in Queensland's concrete sector. Alternative limestone calcined clay cement binder (LC^3) represents a technically sound approach but requires further development of manufacturing capabilities within Australia and particularly within Queensland. Similarly, carbon capture and utilisation (CCU) technologies applied to clinker production offer significant potential but necessitate the development of supporting infrastructure within the relevant markets. The use of alternative fuels in both clinker production and transportation presents another promising avenue for future carbon reduction. However, similar to CCU, this technology requires market-specific development and investment in infrastructure.

Magnesium-based binders, although researched for over a century, are not yet a mature technology for replacing GP cement. Their technical maturity remains low, and concerns exist regarding their potential embodied carbon footprint due to CO_2 emissions during some manufacturing processes. Further research and development are needed before magnesium-based binders can be considered a viable solution.

Continued research and development are critical to unlock the full potential of these emerging technologies and to facilitate their broader adoption within Queensland's concrete industry. Additionally, implementing policy and market incentives can significantly accelerate the development and implementation of these solutions. By promoting innovative approaches and supporting infrastructure development, Queensland can achieve a substantial reduction in the embodied carbon footprint of its concrete sector.

8.2 Innovation Assessment

The innovation assessment section of the report provided an overview of the innovation assessment procedure which has been developed to assess innovative products and solutions with a claimed sustainability benefit.

This includes an administrative process to receive, assess and approve new materials, products and methods under the umbrella of sustainability. However, it does not develop an assessment protocol or define criteria. It only defines broad categories, rather than providing a method to develop the criteria. This information has been provided by TMR.

This section notes that the elements of a strong pathway towards assessment and adoption of innovations, particularly those with sustainability benefits, already exist within Structures documents and processes. However, they can be improved upon and expanded.

Furthermore, it notes that a clear overarching protocol would be advantageous to create shared expectations between industry and the Department. E&T published an *Engineering Innovation* document in 2014 that, as noted by TMR representatives, struggled to land on what it was trying to achieve to move past a simple flowchart to actionable guidance. A new document should be developed to articulate E&T's approach to innovation and provide clear pathways to industry.

Any new specifications should take the approach of MRTS70 and provide avenues for flexibility where known areas of research and development exist. A key actionable step would be known areas of research and development to be identified and published, and to be noted within specifications. The *Design Criteria* could provide more details about how design innovations are managed and if/how they differ from standard departures.

Lastly, the current product assessment schemes (e.g. the *Product Index for Bridges and Other Structures*) could be expanded to explicitly address innovation rather than be bounded by the Specifications. Structures' internal processes for assessment and approval can also be revised to provide stronger consistency and clearer communication and therefore hopefully reduce assessment timeframes.

8.3 Implementing Low Carbon Concrete Solutions

This area of the research culminated in the development of TMR Technical Note 59 *Low Carbon Concrete.* This technical note provides an overview of available and emerging technologies under the banner of low carbon concrete. It also discusses how embodied carbon can be measured in order to compare and assess these technologies. It is hoped this Technical Note will encourage efficient governance of these innovations.

8.4 Material Usage Data

The materials usage data assessment undertaken identified limitations in TMR's ability to estimate the embodied carbon footprint of their structures. A key challenge is the availability of data on material quantities used in construction. Existing project data is often limited, making accurate embodied carbon estimates difficult.

The assessment identified several sources of material data with varying degrees of usefulness. The IS Materials Calculator and Materials Tracking Register provide the most detailed information on materials types and quantities. However, the IS Calculator is only used for projects undergoing specific sustainability ratings, and the Materials Tracking Register is generated during construction after key design decisions are made. The BoQ can also be used, but it requires additional information to accurately estimate materials quantities. Contract documents and claims as well as digital drawings were found to be of low value for embodied carbon assessments due to their lack of specific materials data.

The assessment also highlighted limitations in the quality of embodied carbon factors used by 77hilee industry-standard databases such as AusLCI and ecoinvent are used, the underlying data may be outdated. Additionally, generic embodied carbon factors are suitable for high-level estimates but not for detailed comparisons of different materials or design options. EPDs offer some improvement but have limited coverage for infrastructure materials.

Despite these limitations, TMR can produce good quality materials data that allows for high-level embodied carbon estimates. However, these estimates should be interpreted with caution and their limitations considered when making critical decisions.

The assessment recommends 2 key improvements to enhance TMR's ability to estimate embodied carbon. These include:

- developing a centralised repository to improve data accessibility and ensure consistent access to materials data across project stages
- incentivising or mandating suppliers particularly those providing large quantities of concrete and steel, to provide detailed product information including materials composition and EPDs.

8.5 Defining Sustainability in Design

The research undertaken to define sustainability in design explored how sustainability principles can be effectively integrated into bridge design. The findings emphasise the importance of a comprehensive approach that considers the bridge's entire life cycle, from materials extraction and construction to operation, maintenance and decommissioning.

LCA emerged as the most accurate method for evaluating a bridge's environmental impact. LCAs provide a detailed picture, quantifying the environmental footprint across all stages of the bridge's existence. However, LCA data may not always be readily available. In such cases, benchmarking against successful sustainable bridge projects offers valuable insights. Comparing the proposed design to similar projects that have achieved positive environmental outcomes allows designers to assess the potential environmental footprint relative to industry standards and best practices.

A critical takeaway from this section is that achieving sustainability requires a holistic approach. Focusing solely on minimising costs, for instance, might not translate to sustainable outcomes. Careful consideration must be given to the weighting of various criteria ensuring a balance between environmental, economic and social aspects. To achieve this balance stakeholder engagement is crucial. By including a diverse range of stakeholders in the design process, the project benefits from a well-rounded perspective that considers all viewpoints. This collaborative approach is key to identifying and implementing truly sustainable solutions for the bridge, fostering adjustments throughout the development phase and ultimately leading to a more sustainable and successful outcome.

This section also highlights the designer's significant role in influencing a bridge's sustainability across its entire life cycle. Designers can indirectly influence procurement by working collaboratively with procurement professionals. This collaboration helps them understand the procurement implications of their design choices such as material selection, construction methods and maintenance practices, all of which can significantly impact the sustainability outcomes throughout the bridge's lifespan. Designers should consider the recently released Commonwealth guidance on sustainable procurement in infrastructure to better understand what requirements can be included. Additionally, designers play a direct role in ensuring the bridge's resilience. By designing bridges that can withstand potential threats such as climate change and natural hazards, they contribute to the bridge's long-term sustainability and continued service.

Material selection and sourcing are crucial aspects of sustainable bridge design. Designers can minimise material use, prioritise sourcing materials locally and consider using recycled materials or geopolymers to reduce the embodied carbon footprint and overall resource consumption. Early-stage modelling tools can be useful in assessing the environmental impact of these material choices and design decisions. Furthermore, bridge design can indirectly influence factors including water pollution, noise, air pollution and light pollution.

Designers should be mindful of these potential impacts and strive to minimise them through thoughtful design strategies.

Furthermore, the importance of minimising waste throughout the bridge's life cycle should be emphasised. This aligns with the principles of the waste hierarchy which prioritises options such as minimising material use in the first place, exploring the use of recycled materials and selecting appropriate materials that can be readily disposed of or even reused at the end of their lifespan.

Ecological considerations are another important aspect of sustainable bridge design. The design should account for wildlife habitat retention, biodiversity and wildlife connectivity. Meaningful dialogue with stakeholders including the local community is also essential. By incorporating community feedback into the design process, the project can be tailored to better serve the needs of the surrounding area. Additionally, bridge design can contribute to the local community or environment by using local resources or focusing on innovative design solutions. Finally, the report highlights the importance of considering the cultural significance of the bridge location. The design should be sensitive to the cultural heritage of the area and potentially even enhance it.

8.6 Support for Sustainable Decision Making in Structural Design

This guidance focuses on the stages of a structure when the designers are most involved and greatly influence the sustainability outcomes, outlining methods and information requirements for different project stages, and how and when to apply material and emissions factor data for embodied carbon measurement. This guidance is aligned with and informed by the *Embodied Carbon Measurement for Infrastructure: Technical Guidance* which was recently approved by all states (ITM 2024).

This project identified that the area in which designers can have the most impact is on the upfront carbon through the choice and use of materials used in the structure. The materials are generally the largest component of a structure's carbon emissions, excluding the enabled emissions from the user's utilisation of the asset. With this mind, designers will need to be aware that managing carbon emissions will become more and more important over time placing greater importance on when materials are used and activities are undertaken such as future maintenance, repairs, refurbishment and replacement. That is, locking-in future extensive (and expensive) 'carbon-spends' should be avoided.

The guidance provided in this report identified ways in which a designer can influence the sustainability of a structure at each project stage and is summarised in Table 7.5. More detail is given at pre-project and project concept and project development stages as these are where more gains are possible.

The focus should not be solely on the costs (i.e. the cost to construct) when designing a structure but consider the broader implications of their designs on as many sustainability outcomes as possible. These include environmental, economic, social and governance sustainability, their interactions and dependencies, and what alternative solutions (options) can be developed. A good starting point is to understand the life cycle of a structure (from design to end of life).

To support designers, the ISC has a significant library of invaluable supporting resources that can provide designers with information and ideas about how to incorporate and achieve broader sustainability outcomes in their own project.

8.7 Recommendations and Conclusions

This research investigation has provided several key recommendations and conclusions. These are summarised as follows:

- Opportunities for increasing the use of lower carbon concrete should be promoted by:
  - Encouraging more wide-spread use of mixes with at least 50% SCM replacement, among contractors and designers.
  - Encouraging the use of existing approved alternative concretes, such as geopolymers, among contractors and designers.
  - Fostering the development of local manufacturing capabilities for limestone calcined clay cement (LC^3) and infrastructure for carbon capture and utilisation (CCU) to unlock future carbon reduction potential.
- Enhance the adoption of sustainable innovations, by developing a clear, overarching assessment protocol with defined criteria, building upon existing Structures documents and processes, to create shared expectations with industry. Furthermore, technical specifications should be revised to include flexibility for known research and development areas, and approval schemes should be expanded to explicitly address and streamline the assessment of innovative products.
- Improve the accuracy of embodied carbon footprint estimations by establishing a centralised repository for material usage data, enhancing accessibility and consistency across project stages. Also, incentivising suppliers of high-volume materials such as concrete and steel to provide detailed product information and Environmental Product Declarations (EPDs), enabling more precise assessments.
- Effectively integrate sustainability into bridge design by incorporating quantitative benchmarking against prior projects into structural design as standard. Life Cycle Assessments (LCAs) can be used when data and resources permit. A holistic approach should be adopted, balancing environmental, economic and social factors through robust stakeholder engagement. Furthermore, designers should actively collaborate with procurement professionals to influence material selection and construction methods, prioritise material efficiency and local sourcing, and incorporate ecological and cultural considerations into their designs.

By implementing these key findings, bridge designers can make significant contributions to the development of more sustainable infrastructure. This comprehensive approach, which considers the bridge's entire life cycle and balances environmental, economic and social aspects, will lead to the creation of bridges that are not only functional and aesthetically pleasing but also leave a minimal footprint on the environment and contribute positively to the communities they serve.

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Appendix A Minimum Inclusions for Embodied Carbon

When undertaking calculations to estimate the upfront carbon or embodied carbon, robust and complete coverage of all sources of emissions is needed but it is not practical to capture every single process or activity due to time or information constraints. To ensure carbon emission assessments are complete and comparable, the National Measurement Guidance recommends that at least 80% of materials and 80% of construction activities should be covered when undertaking embodied carbon calculations for transport infrastructure projects and then performing upscaling to reach 100% coverage (see ITM (2024) for details).

The National Measurement Guidance outlines the typical minimum inclusions for road and rail bridges across the product, construction and in-use stages of a structure's life cycle (Table A.1). During the pre-project and project concept and development stages, focus is given to the modules A1-A5 and B3-B5 (which are associated with repair, replacement and refurbishment of the structure and are complementary to the product stage). The remaining modules (B1, B2 and C1-C4) make a relatively small contribution to the embodied carbon emissions and can be covered by upscaling (ITM 2024).

Designers will not be able to quantify all the items outlined in the table but should focus on the elements where they have the most influence and control, namely over the design of the structure and component or material selection.

For further details about minimum inclusions, see the National Measurement Guidance (ITM 2024).

Table A.1: Minimum inclusions for calculating the embodied carbon of rail and road bridges

Life cycle modules	Minimum inclusions for rail bridges	Minimum inclusions for road bridges
Product (A1–A3)	• Rail tracks • Sleepers and fastening system • Track slab • Ballast • Drainage • Aggregates • Major electrical equipment and cabling (including major transformers) • Electrical support structures • Service/access walkways • Temporary civil and structural works • Associated infrastructure (where relevant): major civil and structure components for stations and active transport links • Bridge structure (deck, piers, piles/footings)	• Pavement • Road base • Civil structures • Retaining walls • Drainage • Aggregates • Temporary civil and structural works • Associated infrastructure (where relevant): major civil and structure components for bus stops, interchanges and active transport links. • Bridge structure (deck, piers, piles/footings)
Transport and Construction (A4–A5)	• Electricity purchased • Fuel consumption associated with plant, equipment and site vehicles • Land use change (stored carbon and loss of future sequestration from vegetation removal) • Transport of materials to site • Waste generated during construction (on-site) • Inert waste from earthworks • Construction material wastage • Vegetation waste • Site office waste • Transport of waste to end destination	
In-use (B1–B5)	• Rail tracks replacement, sleepers, and fastening system replacement • Drainage structure replacement • Major electrical equipment and cabling replacement • Electrical support structures replacement	• Pavement rehabilitation and resurfacing • Drainage structure replacement • Aggregates replacement

Source: ITM (2024).

Appendix B IS Ratings Criteria

The IS Rating Scheme is a comprehensive rating system to evaluate the economic, environmental and social performance of infrastructure across the planning, design, construction and operational phases.

In Year 1 of this project, the criteria of the 'Design & As Built' from the IS Ratings Scorecard (version 2.1) were refined to the criteria most relevant for designers to consider in TMR's structures (Table B.1).

Table B.1: Relevant IS Ratings criteria to consider for the sustainability of TMR's structures and the

Theme	Category	Criteria (IS code)	Designer control/influence
Governance	Sustainable procurement	Supplier assessment and selection (Spr-2)	Indirect
	Resilience	Climate and natural hazard risks (Res-1)	Indirect
		Resilience planning (Res-2)	Direct
Economic	Options assessment	Options assessment and significant decisions (Ecn-1)	Direct
	Benefits	Benefits mapping (Ecn-4)	Indirect
Environmental	Energy and carbon	Energy efficiency and carbon reductions (Ene-1)	Indirect
		Renewable energy (Ene-2)	Indirect
		Offsetting (Ene-3)	Indirect
	Environmental impacts	Receiving water quality (Env-1)	Indirect
		Noise (Env-2)	Indirect
		Vibration (Env-3)	Indirect
		Air quality (Env-4)	Indirect
		Light pollution (Env-5)	Indirect
	Resource efficiency and management	Resource strategy development (Rso-1)	Direct
		Resource recovery and management (Rso-4)	Direct
		Adaptability and end of life (Rso-5)	Direct
		Material life cycle impact measurement and management (Rso-6)	Direct
		Sustainability of labelled products and supply chains (Rso-7)	Indirect
	Water	Avoiding water use (Wat-1)	Both
	Ecology	Ecological protection and enhancement (Eco-1)	Both
Social	Stakeholder engagement	Stakeholder engagement and impacts (Sta-2)	Both
	Legacy	Leaving a lasting legacy (Leg-1)	Both
	Heritage	Heritage protection and enhancement (Her-1)	Direct