Sustainability assessment of timber bridge design

An iterative study of a conceptual timber bridge design using life cycle assessment and life cycle costing

Master's thesis in the Master's Programme Structural Engineering and Building Technology

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ABSTRACT

Today, the building and infrastructure sector is a significant contributor to global greenhouse gas emissions, with bridges often designed using materials with high embodied carbon, such as steel and concrete. Timber bridges present a renewable, carbon-storing alternative that can significantly reduce environmental impact. However, the demand remains low due to negative perceptions about durability and maintenance.

This thesis aims to compare the environmental and economic performance of timber and steel components in bridge design, identifying key factors that influence sustainability and cost across the entire life cycle. Developed with Timber Bridges Specialist AB, the project follows an early-stage design process for an ongoing project using its context as a framework. The work was carried out using FEM-Design, where the bridge was structurally modeled and dimensioned, followed by iterative Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) to evaluate alternative deck and railing configurations. The study also assessed the substitution of pressure-impregnated timber with heat-treated timber to explore potential sustainability improvement.

The results show that timber components, particularly in railings, significantly lower climate impact and cost compared to steel. Efficient use of steel, such as trapezoidal corrugated sheets, can be a good alternative due to its efficient material use. Overall, timber outperforms steel both when it comes to environmental impact and cost, especially when carbon storage is considered. The findings emphasize that optimizing material selection and material efficiency for each bridge component can improve sustainability and cost-effectiveness, promoting broader adoption of timber bridges in future projects.

Key words: Timber bridge, Structural design, LCA, LCCA, FEM-Design, Sustainability

Sustainability Assessment of Timber Bridge Design
An Iterative Study of a Conceptual Timber Bridge Design Using Life Cycle Assessment and Life Cycle Costing

Examensarbete inom masterprogrammet Konstruktionsteknik och byggnadsteknologi

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SAMMANFATTNING

Broar, som innefattas inom bygg- och infrastruktursektorn, en sektor som är en stor bidragare till globala växthusgasutsläpp, utformas ofta med material som har högt inbäddat kolinnehåll, såsom stål och betong. Träbroar däremot, utgör ett förnybart och kollagrande alternativ som kan minska den totala miljöpåverkan avsevärt. Trots detta är efterfrågan på träbroar fortfarande låg, vilket främst beror på kvarstående uppfattningar om träets begränsade livslängd och omfattande underhållsbehov. Syftet med detta examensarbete är att jämföra den miljömässiga och ekonomiska prestandan hos trä- och stålelement i träbrokonstruktioner, samt att identifiera de viktigaste faktorerna som påverkar hållbarhet och kostnad under hela livscykeln. Arbetet har genomförts i samarbete med Timber Bridges Specialist AB och följer en tidig designfas för ett pågående projekt.

Brodesignen dimensionerades i programvaran FEM-Design och följdes av en iterativ designprocess, där livscykelanalyser (LCA) och livscykelkostnadsanalyser (LCCA) användes för att utvärdera alternativa utformningar av brobane- och räckesdesign i olika materialval.I slutskedet av projektet undersöktes även möjligheten att ersätta tryckimpregnerat trä med värmebehandlat trä för att identifiera potentiella hållbarhetsförbättringar. Resultaten visar att vissa delar av bron, särskilt räckena, kan minska både klimatpåverkan och kostnader avsevärt om de konstrueras i trä istället för stål. Samtidigt kan ett effektivt utnyttjande av stål exempelvis genom användning av korrugerad plåt, TRP-plåt, utgöra ett mer hållbart och kostnadseffektivt alternativ än en brobana i korslimmat trä, som istället innefattar en relativt stor materialvolym. Sammanfattningsvis presterar trä bättre än stål både avseende miljöpåverkan och kostnad, särskilt när kolinlagring beaktas. Resultaten understryker vikten av att optimera materialval och materialeffektivitet för varje brokomponent för att förbättra hållbarhet och kostnadseffektivitet. Kunskaper som hoppas främja en ökad användning av träbroar i framtida projekt.

Nyckelord: Träbro, Konstruktionsdesign, Livscykelanalys(LCA), Livscykelkostnadsanalys (LCCA), FEM-Design, Hållbarhet

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Preface

This master's thesis was carried out at Chalmers University of Technology during the spring of 2025 as part of the Master's Programme in Structural Engineering and Building Technology. The work has been both challenging and rewarding, providing us with valuable insights.

We would first and foremost like to express our sincere gratitude to our supervisor Dániel Honfi, whose commitment and expertise have been invaluable. We also wish to thank our supervisor and examiner Yutaka Goto, who continuously challenged our way of thinking and contributed to the quality of this work. Finally, we thank our friends and families for their support and patience during this journey.

Gothenburg, September 2025
Olivia Holmström
Anna Högberg

Notations

Mathematical Symbols

α_t	Coefficient of thermal expansion
$E_{0.05}$	Characteristic modulus of elasticity
$E_{0,\mathrm{mean}}$	Mean modulus of elasticity parallel to grain
$E_{90,\mathrm{mean}}$	Mean modulus of elasticity perpendicular to grain
$f_{c,0,k}$	Characteristic compressive strength parallel to grain
$f_{c,90,k}$	Characteristic compressive strength perpendicular to grain
$f_{m,k}$	Characteristic bending strength parallel to grain
$f_{t,0,k}$	Characteristic tensile strength parallel to grain
$f_{t,90,k}$	Characteristic tensile strength perpendicular to grain
f_{ub}	Ultimate tensile strength of steel
$f_{v,k}$	Characteristic shear strength parallel to grain
f_{yb}	Yield strength of steel
$G_{0.05}$	Characteristic shear modulus
G_{mean}	Mean shear modulus
ρ_k	Characteristic density
ρ_{mean}	Mean density

Abbreviations

CLT	Cross Laminated Timber
EAC	Equivalent Annual Cost
EUPAVE	European Concrete Paving Association
FEM	Finite Element Method
GWP	global warming potential
LCA	Life Cycle Assessment
LCCA	Life Cycle Costing Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land Use
MRS	Mineral Resource Scarcity
NPV	Net Present Value
RHS	Rectangular Hollow Section
RISE	Research Institures of Sweden
SIS	Swedish Standards Institute
SLS	Service Limit State
TBS	TBS Timber Bridge Specialiststs AB
TRP	Trapezoidal Profiled Sheet
ULS	Ultimate Litmit State

1 Introduction

1.1 Background

Through human history, we have always encountered unavoidable physical obstacles preventing our passing, such as rivers, gorges and swamps. To overcome these challenges, bridges were invented. What began as fallen tree trunks laid across rivers or ravines has evolved into remarkable structures (Träguiden, n.d.). Modern bridges, with their impressive spans and widths, connect anchor points across rivers and straits, enabling transportation and supporting economic and social development.

In relation to new initiatives for car-free and bicycle- and pedestrian-friendly cities and communities, the demand for pedestrian and cycle bridges will increase (Brinkhoff et al., 2020). There are socioeconomic benefits of developing access for pedestrians and cyclists, including improved accessibility, enhanced traffic safety, and reduced transportation time and distance. Bridges that expand the pedestrian infrastructure network can further contribute to these benefits by potentially lowering vehicle-related costs and emissions while promoting public health through increased physical activity (Sveriges Kommuner och Landsting, 2010).

Historically, timber and stone were the primary materials used for bridge construction. Timber was widely popular due to its accessibility and versatility, and over time, bridge construction became more systematic and technically advanced (Svenskt Trä, 2019). As durability became a greater focus, wooden piles were replaced by stone pillars to enhance the bridges' service life. In the 19th century, many timber bridges were built for both roads and railways, but with the technological revolution, they were eventually replaced by steel and concrete bridges.

In the 20th century the development of glued laminated timber renewed the use of timber in bridge constructions, and by the 1970s, new techniques for stress-laminated timber bridge decks were developed, enabling timber bridges to be used for heavy traffic (Svenskt Trä, 2019). Returning to a more extended use of timber in bridge construction offers several advantages, particularly in terms of sustainability (Hegeir et al., 2022). Timber is a renewable material that stores carbon, and its production requires significantly less energy compared to materials such as steel and concrete, leading to a smaller environmental footprint. Additionally, timber bridges are quick to construct due to their light weight, with straightforward expansion joints and good durability against road salting (Ekholm, 2013; Pousette et al., 2017). Furthermore, using timber often enables the local production of components and might offer aesthetic advantages.

However, using timber as construction material still presents some challenges. Timber is sensitive to environmental factors such as UV-radiation, moisture and biological decay (Mahnert & Hundhausen, 2017). Other challenges include sensitivity towards vehicle collision and sabotage. Additionally, another aspect that must be taken into consideration is fireproofing (Östman et al., 2017). Despite advancements in engineering timber, its load-bearing capacity is generally lower than steel or reinforced concrete, requiring larger cross-sections.

Nevertheless, these challenges can be resolved through proper treatment, detailing and maintenance and do not limit the possibility of building timber bridges. Despite that, according to the Swedish Transport Administration, only 9 of the 136 bridges constructed in 2017 were made of wood. This might originate from a generalized misperception that timber bridges have a low credibility as a safe economical, and reliable investment. Unfortunately this mistrust have been even more strengthened since two recent timber bridges collapses in Norway, the Perkolo Bridge in 2016 and Tretten Bridge in 2022. Both of these bridges shared a similar type of construction but collapsed for various structural reasons. (Jessel, 2022)

The reason this misperception exists is most likely due to fact that the expected service life of timber bridges is relatively low, either 40 or 80 years depending on protection, meanwhile other bridge constructions can be expected to last up to 120 years (Trafikverket, 2019). Consequently, timber bridges have the reputation of not being as durable as e.g. steel and concrete. This low expected service life set by the Swedish Transport Administration prevents timber bridges from being credited for their carbon storage, according to an article in SBUF by Petra Brinkhoff (2020). She states that without this claim, it is difficult to show timber bridges as climate positive, which in turn could have been an argument for choosing wood over other materials.

The set service life varies between countries and for our neighbouring countries Norway and Finland it is set to 100 years with the premise that some parts are designed to be replaced (Pousette et al., 2017). This goes without saying that there is no exact figure for how long a bridge, of any material, can last when placed in perfect environmental conditions. One important piece of knowledge to support the potential durability of timber bridges is real-life examples. The oldest timber bridge in Sweden, Lejonströmsbron, was built in 1737, (Länsstyrelsen Västerbotten, n.d.), more then 100 years before the first concrete bridge in Sweden was even constructed. The most important aspect is to ensure a proper initial design and a maintenance plan that addresses the specific challenges timber bridges present.

The amount of maintenance is the other misperception of timber bridges that also needs to be highlighted. There is a common perception that timber bridges require excessive maintenance such as repair, replacements of parts and surface treatment. Yet, the fact is that steel and concrete bridges also require heavy maintenance, especially if they are expected to stand for 120 years. The importance of maintenance therefore applies to any bridge. However, if potential risks are identified early, maintenance doesn't have to be costly or time-consuming when properly planned and executed.

This thesis will not focus on questioning the service life or the misconceptions but rather address a more emergent reason why we need to promote the industry to build more timber structures including timber bridges, which is the evolving climate crisis.

In 2017, Sweden legislated a long-term climate policy framework as a response to the increasing greenhouse gas emissions that promises to reach a net zero emissions by 2045 (Naturvårdsverket, 2025). Proved by previous studies that compares timber bridges with other bridge structures, timber bridges are the by far the most given alternative in terms of lowering the GHG-emissions and are proved to be a more sustainable alternative.

With the knowledge of what the challenges timber bridges present, in combination with a slow growing demand, this thesis wish to promote the field of sustainable timber bridge design.

This study is conducted in the context of a possible pedestrian bridge in Ekshärad, following an inquiry from Ekshärads Hembygdsförening to TBS Timber Bridge Specialist

AB, hereafter also referred to as TBS, a company specializing in timber bridges. The thesis strives to contribute to both research and industry by providing a design investigation that showcase the full life cycle of the economic and environmental impacts of a timber bridge. The thesis outline is to address hotspots in these impacts and find ways to address them. It will also include and find possible alterations that impacts the LCA and LCCA results that can be used in the field.

1.2 Aim

The thesis aims to quantitatively demonstrate the environmental and economic benefits of timber bridges. To achieve this, the following research questions will be explored.

What are the largest contributing factors that influence the environmental impacts and cost-effectiveness of a timber bridge? How can these factors be modified to achieve better results?

Would a carbon-negative assessment of timber in the LCA influence the design of the bridge?

1.3 Objectives

This thesis will demonstrate a conceptual design phase of a timber bridge, including a structural analysis that determines the estimated dimensions of the structural members.

Furthermore, this thesis will include an assessment of the environmental impact and cost efficiency of the design through LCA and LCCA. Hot spots will be detected and reduced through an iterative process of different design alterations.

These alterations will then be the conclusion of the report. The result will showcase how modifications of bridge design influence economical investments while lowering the environmental impact through better material choices and effective solutions.

Finally, the discussion will raise questions about whether the result can be useful in the industry and how it can be adopted and developed further.

1.4 Methods

To reach the objectives and fulfill the purpose of the thesis, the following approach was adopted. A literature review was conducted, along with an assessment of the specific site and its context. This followed by an iterative design process, which included a preliminary design of the bridge, structural analysis, life cycle analysis (LCA), life cycle cost analysis (LCCA), evaluation, and redesign based on the LCA and LCCA results. The process then restarted from the structural analysis phase, see Figure 1.1 for a visual representation of the process.

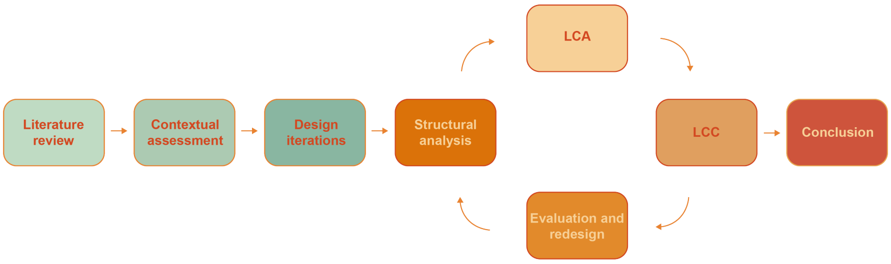


Figure 1.1. Illustration of the methodology.

Finally, a summary and analysis of the final bridge design and the findings throughout the process were presented, along with recommendations for future work and concluding remarks.

1.4.1 Literature Review

A literature review has been conducted to identify relevant research on timber bridge design, material properties, structural performance, and durability. In addition, studies on timber properties, moisture protection, deck and bridge types was included to ensure a comprehensive understanding of timber bridge design. The review focused on academic papers, industry reports, engineering standards, and guidelines for LCA and LCCA.

1.4.2 Context Analysis

The context analysis included an examination of given topographic models, with a focus on identifying geographic challenges that might influence the bridge design and construction.

Meetings with representatives from the Ekshärad Hembygdsförening took place, providing valuable insight into the historical and cultural significance of the area, as well as the community's preferences regarding the bridge design.

1.4.3 Design Iteration Process

The design iteration process can be seen in Figure 1.1, as a visual representation.

Preliminary Design Development

The preliminary design development was conducted with contextual analysis in mind and guided by insights from the literature review. Sketches and conceptual models, using Rhino 8, was developed and then compared against each other, evaluating their advantages and disadvantages in terms of structural feasibility, adaptability to the context and other relevant factors.

Structural Analysis

The structural behavior of the bridge was analyzed using the software FEM-Design, considering relevant load cases, load combinations, and the requirements for the load-bearing capacity:

Load calculations:

- Dead load (self-weight of the structure and non-structural elements)
- Traffic load (pedestrians, cyclists)

Structural performance analysis:

- Global structural integrity
- Internal and reaction forces of load effects
- Dimensioning of load-bearing structural members

Life Cycle Analysis, LCA

The environmental impact of the design was assessed through a life cycle analysis, LCA. The complete method and limitations regarding goal and scope definition, inventory analysis, impact assessment, and interpretation are stated in the LCA-chapter.

Life Cycle Cost Analysis, LCCA

Life cycle cost analysis was used to assess the economic aspect in terms of Net Present Value (NPV) and Equivalent Annual Cost (EAC). The complete method, including references to standards, data sources, and other necessary limitations, is stated in the LCCA-chapter.

Evaluation and redesign

The results from LCA and the LCCA presented an idea of which elements of the bridge stand for the largest impacts. Based on these, alternative solutions was researched and adapted to the design.

1.4.4 Conclusion and recommendations

The findings from the analyses was summarized, comparing the different design alternatives based on sustainability (LCA), and cost-effectiveness (LCCA). The evaluation highlighted key differences and trade-offs, leading to a recommendation for the most suitable design alterations.

Finally, a summary and analysis of the final bridge design and its alterations throughout the process was presented, along with recommendations for future work and concluding remarks.

1.5 Limitations

This study is limited to a preliminary dimensioning of a pedestrian timber bridge. Traffic loads beyond pedestrian and cyclist use will not be considered. Some geometric parameters are predefined, including a bridge span of 45 meters, a deck width of 2.5 meters, and a limited deck slope to ensure accessibility. The geographical placement imposes certain constraints, such as a maximum structure depth below the deck due to topography.

The study does not include an in-depth analysis of soil conditions or a detailed foundation assessment, as the focus is on the superstructure. Structural analysis will be conducted using FEM-Design (StruSoft, 2025), without physical experiments, field tests, or dynamic analyses. Connections will not be designed and analyzed in detail.

Only specific design variations will be evaluated, such as timber treatments, railings, and deck options.

The life cycle assessment (LCA) will be delimited by its system boundaries, data sources, and the exclusion of certain impact categories. Similarly, the life cycle cost assessment (LCCA) will be defined based on assumptions and decisions made regarding which elements to include. Further details on methodology and assumptions are provided in the respective sections.

2 Literature Study

2.1 Timber as a Construction Material

Timber has long been used in construction for its strength, versatility, and aesthetic appeal (Harte, 2009). Advances in technology have improved the understanding of its structural behavior, enabling safer and more efficient designs. With its high strength-to-weight ratio, ease of handling, and renewable nature, timber remains a key material in both traditional and modern applications.

The use of whole timber as a load-bearing material dates back at least to the Neolithic period (Bukauskas et al., 2019). Engineered products such as glued laminated timber (glulam) and cross-laminated timber (CLT) have expanded the possibilities for timber in structural applications, particularly in long-span construction (Mohammad et al., 2012). CLT, developed in the early 1990s in Austria and Germany, has since become widely adopted across Europe in both residential and non-residential buildings. Although timber has many advantages, it is sensitive to moisture, biological degradation, and fire, and must be properly treated and protected.

2.2 Bridge Typologies

The choice of bridge type depends on factors such as span length, clearance, height, and traffic demands (Swedish Wood, 2022). Additionally, it should be suited for the surrounding landscape and be aesthetical both for those who are traveling on it and for those observing it from a distance. Bridges can be classified according to the type of load-bearing structure, such as beam, truss, arch and cable-stayed bridges (Pousette, 2008).

2.3 Bridge Deck

2.3.1 Common Bridge Deck Solutions

Since this thesis focuses on timber bridge design, this section will exclusively present bridge decks related to and used in timber bridges.

The bridge deck, which serves as an important part of the overall structural system of the bridge, is difficult to consider in isolation from its surrounding context. However, these decks are generally composed of either slabs made of glulam panels or beams made from lumber or glulam (Pousette, 2008).

2.3.2 Slab Bridge Deck

In slab bridges, the bridge deck typically serves as the primary load-bearing element. It is transversely stiff and thereby capable of withstanding wind loads. As shown in Figure 2.1, slab bridges are usually constructed from planks or beams placed vertically, i.e., standing on their edges, and joined together with glue or nails. An alternative version to this system is cross-laminated timber (CLT) panels, see Figure 2.2 (Pousette, 2008).

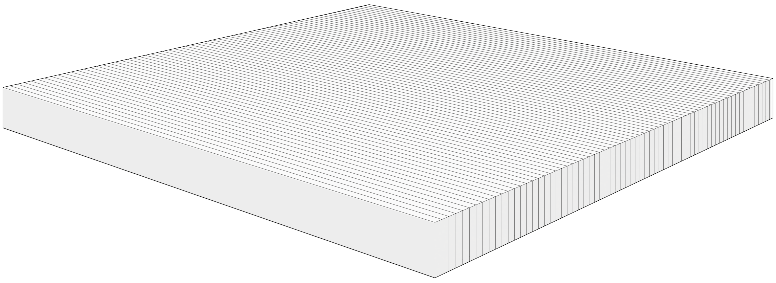


Figure 2.1. Illustration of a slab bridge plate.

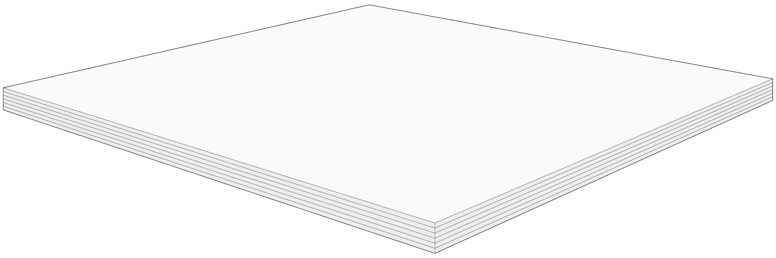


Figure 2.2. Illustration of a CLT- panel.

Throughout the development of slab bridges, the plate has been strengthened by the planks or beams have been stressed by steel bars that span across the slab. This method is called Stress-laminated timber slabs and has been developed in various shapes to optimize material efficiency while increasing stiffness and stability. Stress-laminated timber slabs are lightweight and can be applied to various bridge typologies (Pousette et al., 2017).

These bridge slabs can be categorized based on their sections where the initial transverse bridge slab, see Figure 2.3 is the most simple version is used for smaller spans.

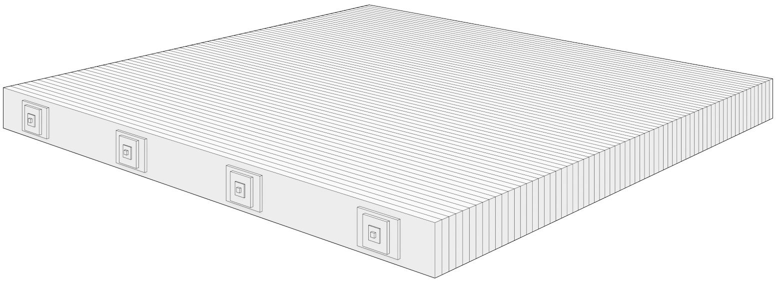


Figure 2.3. Illustration of a stress laminated timber slab.

T- beam, Figure 2.4, and Box girder bridge, Figure 2.5, are constructed to withstand larger spans in a material efficient manner. However, these bridges come with certain challenges and transfer of shear forces between web and flange needs to be carefully considered, especially when considering uneven loads distribution. The deformation of the slab may also be influenced and requires careful verification during the design and dimensioning process (Pousette, 2008).

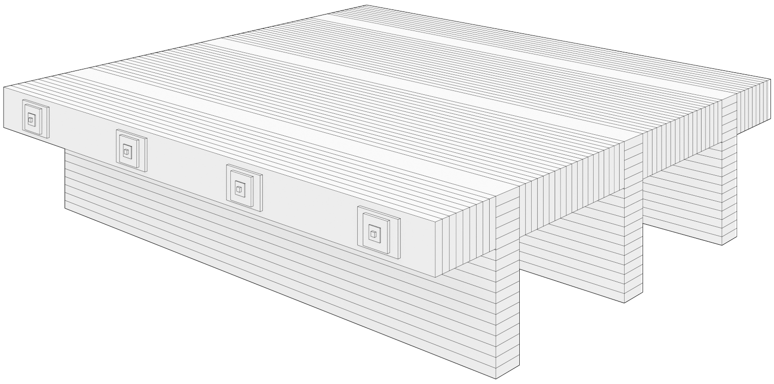


Figure 2.4. Illustration of a T-beam bridge.

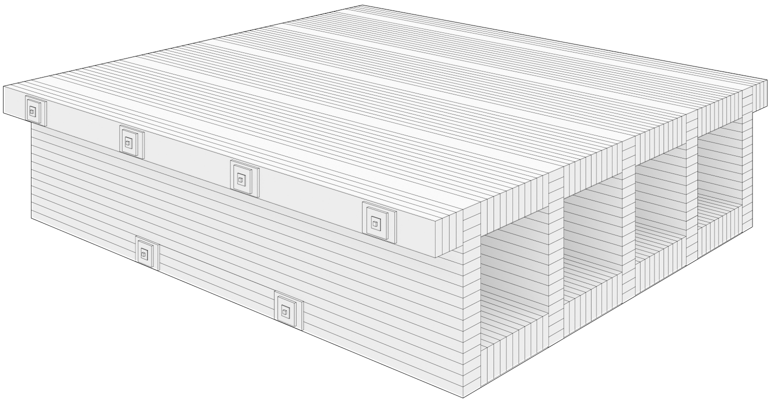


Figure 2.5. Illustration of a box girder bridge.

2.3.3 Beam Bridge Deck

Beam bridge decks are as implied constructed with beams. These, so-called main beams, are located along the bridge and can be either one or multiple beams acting together, see Figure 2.6. In Sweden it is common with multiple main beams but it depends on the span, use and width of the bridge deck itself. Between the main beams there are crossbeams. On top of the main beams there are horizontal studs or other load-transferring components. To handle transverse loads, the beams can be braced with trusses between the main beams acting together with the cross beams. The horizontal trusses can also help prevent tilting of the main beams together with the transverse beams (Pousette, 2008).

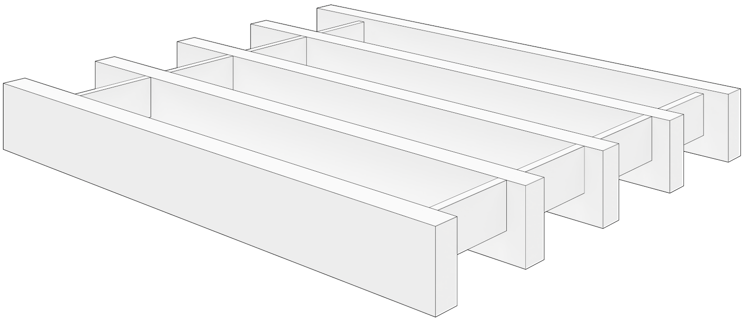


Figure 2.6. Illustration of a general beam bridge.

A specific version of beam bridges is a through bridge. Through bridges have two high main beams, and the bridge deck is suspended in-between. This concept is also seen in arch bridges.

Other versions of a beam bridge can be obtained by exchanging the horizontal studs and the timber planks with horizontal laying beams, wooden panels such as CLT-panel, see Figure 2.7, or even other more material efficient structural components such as trapezoidal steel plate, Figure 2.8. These versions can, similarly as in slab bridges, help handle the transverse loads.

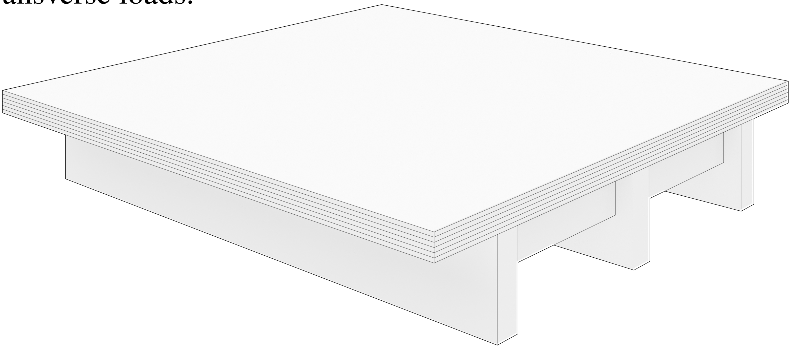


Figure 2.7. Illustration of a beam bridge with CLT-slab.

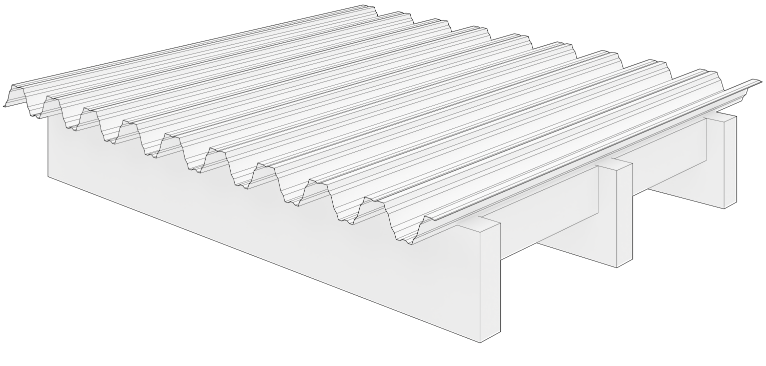


Figure 2.8. Illustration of a beam bridge with a trapezoidal plate.

2.3.4 Other Bridge Decks

Slab and beam bridges typically span large distances and are primarily constructed with glulam. However, the same structural concept can be applied to other bridge types. For shorter spans, smaller cross-sections may be used, and glulam can be replaced with planed lumber.

2.3.5 Bridge Deck Covers

The surface layer or bridge cover may differ based on the function and context of the bridge. Pedestrian bridges are usually covered with timber planks that are designed to resist weather exposure and wearing, so called wearing planks. Bridges constructed for road traffic might need asphalt paving or gravel. Beneath the cover there are one or multiple waterproofing layers that protect the loadbearing structure underneath (TräGuiden, n.d.-a) . Independent of which type of cover is used, it is important to conduct inspections that validate that no moisture penetrates the waterproofing layer. This is verified by measuring the moisture content in the bridge deck (Pousette, 2008).

To assure proper water run-off, the bridge deck is typically slightly tilted to one end, and the optimal position of the planks is in the transverse direction. However, longitudinal wearing planks are possible as long as no water gets stuck between the planks. Diagonal placement is therefore recommended since they promote a short length for the water run-off. These two versions are more optimal for bicycle bridges since it’s a calmer and less noisy alternative compared to cycling over transverse planks (Svenskt trä, 2019). Wearing planks, that are recommended at a distance of 6-8mm to avoid issues with swelling, can be replaced with tongue and groove planks since it minimizes the amount of dirt and rainwater that passes through (Svenskt trä, 2019).

The exposed edges of the bridge deck can be covered with constructive wood protection or be covered in sheet metals (TräGuiden, n.d.-a).

2.4 Timber Railing

A key element of bridge design is bridge railing. In Sweden the railings are regulated by the public authority “Swedish Transport Administration” and the requirements have increased over the last couple of years. The key aspects when constructing a bridge are functionality, aesthetics, and safety (Svenskt trä, 2019).

Depending on the function of the bridge, road bridge or pedestrian/bicycle bridge, there are different requirements. Generally, road bridges have higher requirements on the strength of the railings as they must be able to withstand collision forces from traffic accidents and other impact loads.

2.4.1 Pedestrian and Bicycle Railings

When the road bridge is designed with a pedestrian or cycle lane, it has the same requirements as the standard pedestrian/bicycle bridge. These requirements are associated with the safety of not falling off the bridge. The height of the railing of a pedestrian bridge is 1.2 and 1.4 meters for a bicycle bridge (Svenskt trä, 2019).

2.4.2 Common Railings Designs

In addition to designing based on loads from collision, self-weight, and potential load from people leaning towards the rail, railings are exposed to outdoor conditions and must withstand precipitation and wind loads (Svenskt Trä, 2019).

For pedestrian and bicycle bridges, wooden railings are permitted and are the most commonly used material (Svenskt Trä, 2019). However, steel railings are still frequently used on timber bridges, likely due to their durability and the reduced need for recurring maintenance.

In timber or steel railings constructed with pickets e.i. vertical members positioned between the top and bottom rails, the clear spacing between pickets shall not exceed 100 mm (Svenskt Trä, 2019).

2.5 Durability of Long-term Performance

2.5.1 Aging and Degradation of Timber

Over time, timber undergoes various aging and degradation processes that impact its mechanical and physical properties (Liuzzi et al., 2020). Understanding how timber deteriorates under different environmental conditions is essential for predicting its service life and ensuring durability in structural design.

The primary degradation mechanisms in timber include biological, physical, and chemical factors (Zabel & Morrell, 1992; SIS, 2013). Biological degradation is caused by fungi, mold, and insects, which require specific moisture and temperature conditions to thrive. Physical degradation includes cracking, warping, and shrinkage/swelling caused by changes in moisture content, which can result in permanent deformation. Chemical degradation, such as UV exposure and oxidation, leads to the breakdown of wood fibers, primarily affecting the wood's surface.

Moisture content is the most critical factor influencing timber degradation. When wood exceeds 20% moisture content, it becomes particularly vulnerable to biological attack (SIS, 2013a). While a constant high moisture level mainly promotes fungal growth, repeated fluctuations above and below this threshold cause additional stresses that accelerate deterioration. To manage moisture-related risks in timber structures, the European standards define two classification systems. The first, outlined in EN 1995-1-1:2004 (Eurocode 5), introduces service classes, which categorize the mechanical behavior of wood based on long-term humidity exposure. The second system, defined in SS-EN 335:2013 (SIS), establishes use classes, which assess the biological durability risk of wood according to environmental conditions and moisture levels.

2.5.2 Constructive Wood Protection

Protecting wood from moisture, decay, and biological attack through smart design and construction details is known as constructive wood protection (Pousette, 2008). This is the most important measure for ensuring the long-term durability of wood. Special attention should be given to end grain, joints, connection points, adjacent wood surfaces, and fasteners. Narrow gaps, pockets, and cavities should be avoided to prevent moisture accumulation (Trafikverket, 2024b). Proper ventilation must be ensured, and fasteners should not penetrate upward-facing surfaces.

The Swedish Transport Administration specifies different cladding requirements depending on the intended service life (Trafikverket, 2024b). For 40 years, only exposed parts such as horizontal top surfaces, open joints outside the deck's protection, the deck sides, anchorage zones, and end grain must be clad. For 80 years, almost all parts must be clad, with the underside of the deck exempted unless the bridge is located in a road or marine environment. The regulation also prescribes design details such as drip edges and spacers to secure proper ventilation. As a result, wooden cladding can be made from either treated or untreated wood (TräGuiden, 2019). Metal flashing is also a common form of cladding, particularly on horizontal surfaces where exposure to moisture is higher.

2.5.3 Chemical Treatments

Timber is frequently treated with chemical agents to enhance its durability and resistance against biological degradation and fire (Ross, 2010). Such treatments add protective substances to the wood without fundamentally altering its cell structure, although they may still influence mechanical properties and have environmental consequences. According to the Swedish Transport Administration (Trafikverket, 2024b), the need for wood preservation is determined by the intended service-life class. In general, any structural element not protected by cladding, a bridge deck, or a roof must be safeguarded against decay and wood-destroying insects.

The most common method for improving biological durability is pressure impregnation, particularly for timber components exposed to moisture and weathering. Historically, preservatives such as chromated copper arsenate (CCA) were widely used, but due to environmental restrictions in Europe, modern alternatives based on copper-organic compounds (e.g., Cu-HDO or Tanalith E) are now preferred (Ramage et al., 2017). These preservatives penetrate the wood cells and reduce permeability, thereby enhancing decay resistance without significantly changing the wood's chemical composition. Despite advances in formulation, concerns remain about the environmental impact of chemically treated timber during disposal and recycling.

The Nordic Wood Preservation Council (NTR) has established a branch standard, NTR Document No. 1:2017, based on the European standards SS-EN 351-1 and SS-EN 599 (Pousette, 2008). This standard defines the wood preservation classes NTR A, NTR AB, and NTR B for impregnated pine (TräGuiden, 2019aa). Impregnated wood treated according to NTR Document No. 1:2017 is subject to regular inspection by RISE (Research Institutes of Sweden) as part of the production certification and quality-control process, after which the material may be marked with the corresponding class.

2.5.4 Modified Wood

Modified wood is timber that has been permanently altered at the chemical or physical level of the cell wall to enhance durability and dimensional stability. These modifications are achieved through two main approaches: thermal modification and chemical modification, both of which alter the material's chemical structure at the molecular level (Ramage et al., 2017). Industrial processes have resulted in three principal categories currently available on the market: acetylated wood, furfurylated wood, and heat-treated wood. For all types of modified wood, stainless steel fasteners and connections are recommended (Svenskt Trä, 2025).

Acetylated wood is produced by treating timber with acetic anhydride, which reduces the hygroscopicity of the cell wall and thereby limits moisture uptake. There is currently no production in Sweden; the main commercial product is Accoya, which is distributed through local retailers (Swedish Wood, n.d.-a).

Furfurylated wood is created by impregnating timber with furfuryl alcohol, a bio-based chemical derived from agricultural residues, which polymerizes within the wood structure. The treatment enhances both strength and durability. Kebony is the main commercial product and has established a market presence in Norway and Belgium (Kebony, 2024).

Heat-treated wood is produced without heavy metals or synthetic preservatives. Instead, timber is gradually heated to high temperatures, which alters the chemical composition of the cell wall. The process improves decay and termite resistance, reduces the risk of cracking, and enhances dimensional stability (Thermowood, n.d.). However, several studies report that thermal modification also makes the material more brittle and reduces its ductility, which negatively affects its mechanical performance. As a result, heat-treated wood is not recommended for use in structural elements (Svenskt Trä, 2025). Reported values for technical service life also vary. For instance, an Environmental Product Declaration from Stora Enso specifies a service life of 100 years for its heat-treated products (Stora Enso, 2021), while other manufacturers report significantly shorter values.

2.5.5 Surface Treatments and Coatings

To improve aesthetics and protect the timber from moisture and UV light, appropriate surface treatments and coatings can be applied to help prevent surface cracking and maintain consistent moisture levels within the wood (Pousette, 2008).

A protective coating or sacrificial layer, such as paint, varnish, oil, or stain, is often applied to the surface of wood products to shield them from weather damage and deterioration (Ramage et al., 2017). Besides offering protection, coatings also improve the wood's visual appeal, making them ideal for exterior uses such as cladding. As a surface-level treatment rather than a deep chemical modification, coating is usually the final step in the wood finishing process. Their effectiveness depends on proper application and regular maintenance. When well-executed, surface treatments significantly extend the service life of timber elements, making them a vital component in sustainable wood construction.

2.6 Environmental aspects

2.6.1 Easy Fabrication and Assembly

One of the advantages of building bridges in timber is the possibility of easy prefabrication of either the whole bridge or parts (Pousette, 2008). Consequently, timber bridges are quick to construct, and they don't demand large cranes due to their light weight. Additionally, the prefabrications might enable easy deconstructions by a similar disassembly as when erected.

2.6.2 Reuse

In accordance with new environmental investments and regulations the Swedish Forest industries aim to have all their wooden products reusable by 2030. This is consistent with a government initiative in 2020 (Skogsindustrierna, 2025a) , which aims to develop strategies to enable the transition from a linear to a circular economy in Sweden.

When it comes to reusing timber elements or building parts, the industry still has some limitations in ensuring the quality of the new building component and that it still uphold the same condition concerning durability, viability and safety guarantees (Alsmarker, 2024).

Recycling wooden elements entails creating a material inventory, assessing the feasibility of disassembly, and classifying components according to the properties and previous use of the timber (Boverket, 2024).

For structural timber, the most crucial part is the stage, classification, since it includes the material strength class where the appropriateness of the reused part is determined. Today, the most important tool is testing material strength. Moving forward, the process might be simplified by avoiding testing and instead relying on documentation of the manufacturing process, strength class, if the wood has been treated or impregnated. It is also important to state the year when it was constructed and information about the type of structure in which the material was constructed (Boverket, 2024).

As previously mentioned, the knowledge of the strength of wood is affected by what climate and humidity it has been exposed to, and during which time period it was classified. It is not possible to directly determine the strength of recycled material without further assessment of the effect of the environment the wood has been exposed to. Studies show that it is primarily wood's elastic modulus and stiffness that are affected by a varied moisture content (Flygare & Hammar, 2024). The given service life is therefore a theoretical term that is based on a generalization covering a broad range of wood species and structural types.

To allow timber elements to be used more in a circular life cycle process, the industry must work on access to data regarding the performance of the materials. This information must include questions such as, from what environment the material has been extracted from, what is the previous and new load-bearing capacity, how has the component been managed, etc. (Svenskt trä, 2023).

Another contributing factor to the fact that wood is not reused to such a large extent is that it is not seen as economically viable. The fact that wood components are relatively cheap raw materials means that there is not much economic gain for large companies to reuse it (Brodin & Moberg, 2020).

Yet, no matter how far we get in the process, wood will ultimately have a linear life cycle process (Brodin & Moberg, 2020) that never fully closes the loop of endless reuse. However, there are ways to prolong the linear process and enhance service life of timber through the so-called cascade model. The concept is to introduce a system in which wooden elements are gradually transitioned to lower levels within a hierarchy, primarily based on their structural applicability, but also influenced by the processing level and the unit size of the product. In the first and highest row there is timber that has high structural applicability, such as glued laminated timber or timber in large dimensions of good quality. The step below includes materials with lower or no load-bearing capacity. In the penultimate stage, the recycling stages command and the wood is chipped down and can be used for fiberboards. In the last step, the wood is burned, but the energy released is used in energy recovery processes (Brodin & Moberg, 2020).

2.6.3 Carbon Storage

Carbon storage is the process where forest photosynthesis absorbs carbon dioxide from the air and transforms it into carbohydras or biomass and thereby prevent carbon dioxide from contributing to climate change. Although some carbon storage is lost during deforestation, long-lived wood products can still provide a certain amount of carbon storage. The amount might vary depending on what the products are used for (Naturvårdsverket, 2024). However, the positive effect from storing carbon is only maintained as long as the product is still in use, meaning that as soon as the products decay or get burned, the stored carbon is released back into the atmosphere (Träguiden, 2015).

The Council of the European Union has in November 2022 presented a proposal for an EU-level certification framework for carbon storage in products. This framework states that carbon storage can be used for products that meet the requirements to last for a minimum of 35 years (Council of the EU, 2024).

3 Bridge Design and Structural Investigation

This chapter presents the design development and structural analysis of the bridge. It begins with a presentation of the context and technical requirements established for the bridge, followed by the preliminary design phase, including exploration of different types of bridge and layout alternatives based on functional and site-specific requirements. The selected concept is then analyzed using finite element modeling, where the structural behavior is assessed under various load conditions. The modeling process includes definitions of geometry, materials, load cases, and boundary conditions. Based on the results of the analysis, the final bridge design is presented. The chapter concludes with reflections on the assumptions and simplifications made during the modeling process.

3.1 Technical Requirements and Site Conditions

The context of this bridge design investigation was provided by our supervisor at TBS Timber bridge Specialist AB. At the time of this thesis work, their client, Ekshärads hembygdförening, was in the early phase of planning for a new timber bridge connecting the local church with the homestead that would accommodate better accessibility over the ravine that separates the areas.

Ekshärad is a small community in northeast of Värmland, Sweden, and their hembygdsgård was established in 1923 and still comprises many old historical buildings. The site host events, e.g. Midsummer celebrations and farmers markets and is known as a local meeting point (Visit Värmland, n.d.).

The site is a 10 meters deep ravine surrounded by pine trees and lush vegetation. Today, the path consists of transverse stairs along the ravine and a steeper stair on the other side. Crossing the ravine is a footpath that will pass beneath the new bridge.

The technical requirements set for the desired bridge was a span of 45-meter spanning over the ravine from the upper ends of slopes. The area primary demanded a pedestrian bridge and was designed for that purpose. Meaning regards set for bicycle and pedestrian bridges were not strictly followed in this design. The width of the bridge deck was set to 2.5 meters by the clients, however, in this study, the width was set to 2.8 meters to apply certain margins.

The financial aspects have been clarified, and in order to proceed with the bridge construction, the cost must be kept to a minimum.

During the writing of this report, two meetings were held with the clients and TBS.

3.2 Preliminary Bridge Design

During the phase of preliminary concept development, various types of bridges were considered. Among these were a range of beam-, truss-, and arch-bridges seen in Figure 3.1.

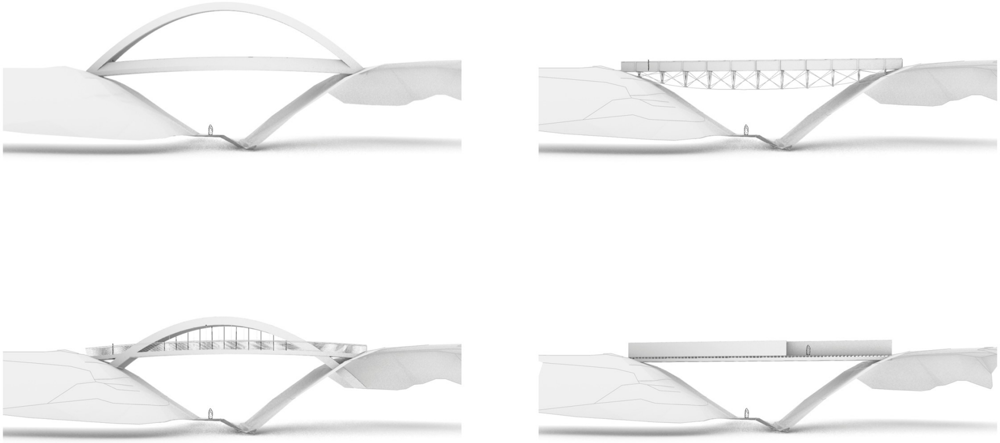


Figure 3.1. Representative of iterations from the design process.

During the two meetings with Ekshärads hembygdförening and the municipality of Hagfors, proposals for the new bridge were presented by both TBS as well as the proposals achieved from this thesis. Based on the interest of one specific bridge presented at these meetings, the bridge design for this thesis where set, see Figure 3.2. The design was inspired of the impressive Traversina footbridge constructed in Switzerland 1999 by the engineer Jürg Conzett (Conzett & Mostafavi, 2006).

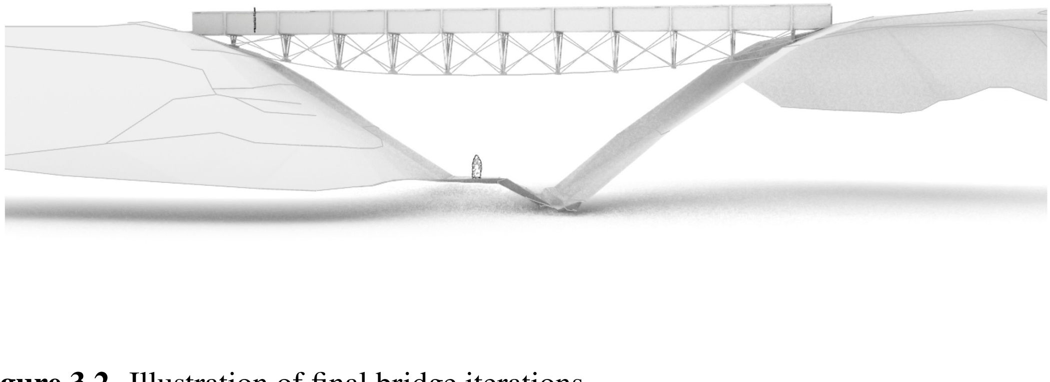


Figure 3.2. Illustration of final bridge iterations.

3.3 FEM Modeling of the Superstructure

This section presents the finite element modeling of the bridge superstructure, developed to evaluate its structural performance under relevant load conditions. The modeling procedure covers the choice of software, geometric setup, material definitions, and applied loads. Each subsection addresses a key aspect of the approach, concluding with a summary of the resulting structural analysis.

3.3.1 Modeling Approach and Software Details

The structural model was analyzed using nonlinear static analysis, as some elements are defined to carry only tensile forces, resulting in material nonlinearity. The scope of the model is the superstructure of the bridge, including the bridge deck. In the calculations, the bridge deck was modeled as CLT panels, meaning that only this option was analyzed. The implications of this limitation are discussed further in Section 3.5.The purpose of the model is to obtain reasonable dimensions of the different elements considering requirements in ULS and SLS, enabling the subsequent LCA and LCCA analyses.

The software used for modeling is FEM-Design, developed by Strusoft, version number 24.00.001, released 2025-02-06 (StruSoft, n.d.-a, n.d.-b). The modules used are 3D analysis module 3D Structure and design modules Steel Design, Timber Design and CLT Design.

FEM-Design is used by leading engineering firms such as SWECO, RAMBOLL, and WSP, which demonstrates its commercial recognition and helps strengthen confidence in the modeling results (StruSoft, n.d.-b). Another justification for using this software is the fact that all calculations are performed according to Eurocode standards, which facilitates accurate and efficient execution of the modeling process.

3.3.2 Geometric Model and Element Configuration

The span of the bridge was 45 m, with a width of 2.8 m and a rise-to-span ratio of 1:10, resulting in an inverted arch rise of 4.5 m. The compression struts were spaced at 2.65 m and oriented perpendicularly to the tangent of the arch. Bracing members were arranged diagonally between the struts, forming a cross pattern. A visualization of the geometry can be found in Figure 3.3 and Figure 3.4.

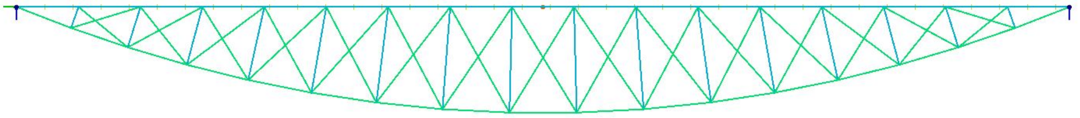


Figure 3.3. Side view of the bridge geometry.

The bracing, both in the longitudinal and transverse directions along with the bottom chord, is modeled as truss members with brittle compression behavior and a zero-compression limit force. Beam elements are used for the longitudinal and transverse beams, as well as for the compression struts, while the CLT deck is modeled using timber plate shell elements.

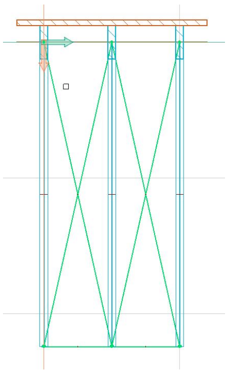


Figure 3.4. Illustration of the bridge cross-section at the central compression struts.

The longitudinal beam supports are defined as simply supported with point supports. One side of the beams is restrained in translation along the x-, y-, and z-directions, as shown in Figure 3.5, while the other side is restrained in the y- and z-directions. The connections for the beam and shell elements are assumed to be fixed, while the truss elements are assumed to have hinged connections.

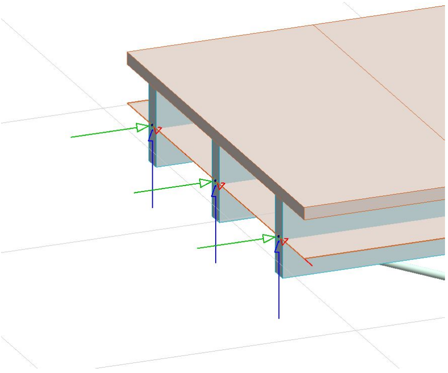


Figure 3.5. Illustration of the end supports of the longitudinal beams.

A simple mesh convergence study was conducted by testing different minimum division numbers for the mesh size in relation to the resulting translational displacements. The results showed that setting the parameter to Lowest (n = 2) was sufficient to achieve accurate results, with a deviation of less than 0.04%. All other mesh settings were kept at their default values, including refined mesh after regeneration around peak smoothing and point supports.

3.3.3 Material Properties

The material data for the timber elements, Table 3.1, correspond to the predefined properties of the respective materials in FEM-Design. For steel elements, Table 3.2, the material properties were defined based on data provided by the manufacturer. Specifically, data for the longitudinal and transverse bracing were taken from Pretec's product sheet for the PDS tie rod system (Pretec, n.d.), while the data for the tension ties is taken from the manufacturer Halfen's product sheet (Halfen GmbH, n.d.).

Table 3.1. Properties of timber elements.

	Longitudinal Beams	Compression Struts	Transverse Beams	CLT panel
Dimension [mm]	115 × 450	115 × 115	45 × 220	80 × 2800 × 45000
Material	GL30c	GL30h	C24	CLT 80 – C3s

Note. CLT 80 – C3s is a predefined material in FEM-Design by Stora Enso, composed of C24 timber.

The dimensions of the different elements are shown in the properties tables, Table 3.1 and Table 3.2.

Table 3.2. Properties of steel elements.

	Longitudinal Bracing	Transverse Bracing	Tension Tie
Diameter [mm]	20	20	48
Material	Steel 8.8	Steel 8.8	Steel S460N

The material data for steel and timber elements are presented in Tables 3.4 and 3.3, respectively. Table 3.3 summarizes the timber properties, while Table 3.4 shows the steel properties.

Table 3.3. Material data for timber elements.

		GL30c	GL30h	C24
$f_{m,0,k}$	[MPa]	30.0	30.0	24.0
$f_{m,90,k}$	[MPa]	30.0	30.0	24.0
$f_{t,0,k}$	[MPa]	19.5	24.0	14.5
$f_{t,90,k}$	[MPa]	0.5	0.5	0.4
$f_{c,0,k}$	[MPa]	24.5	30.0	21.0
$f_{c,90,k}$	[MPa]	2.5	2.5	2.5
$f_{v,k}$	[MPa]	3.5	3.5	4.0
$E_{0.05}$	[MPa]	10800	11300	7400
$E_{0,\text{mean}}$	[MPa]	13000	13600	11000
$E_{90,\text{mean}}$	[MPa]	300	300	370
G_{mean}	[MPa]	650	650	690
$G_{0.05}$	[MPa]	540	540	463
ρ_k	[kg/m^3]	390	430	350
ρ_{mean}	[kg/m^3]	430	480	420

Table 3.4. Material data for steel elements.

		Steel 8.8	Steel S420N
f_{ub}	[MPa]	800	540
f_{yb}	[MPa]	640	430
ρ	[kg/m^3]	7850	7850
E	[GPa]	210	210

3.3.4 Load Cases and Load Combinations

The used load cases is presented in Table 3.5

Table 3.5. Defined load cases and sources.

Load Case	Description	Value (kN/m^2)	Source
Permanent Load	Self-weight	1.0	Appendix B
Variable Load	Surface load	5.0	SS-EN 1991-2

The used load combinations is presented in Table 3.6.

Table 3.6. Load combinations for ULS and SLS.

Load Combination	Permanent Load Factor	Variable Load Factor
ULS (Ultimate Limit State)	1.20	1.50
SLS (Serviceability Limit State)	1.00	1.00

Both load cases are applied over the entire width and length of the bridge, as shown in Figure 3.6 and 3.7.

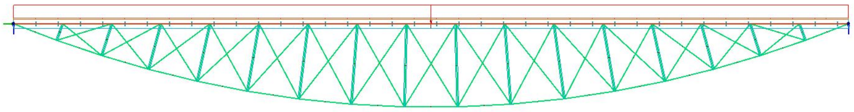


Figure 3.6. Load distribution on the bridge for variable and permanent loads.

The CLT panel is eccentric relative to the longitudinal beams, as shown in Figure 3.7, which is considered in the calculations.

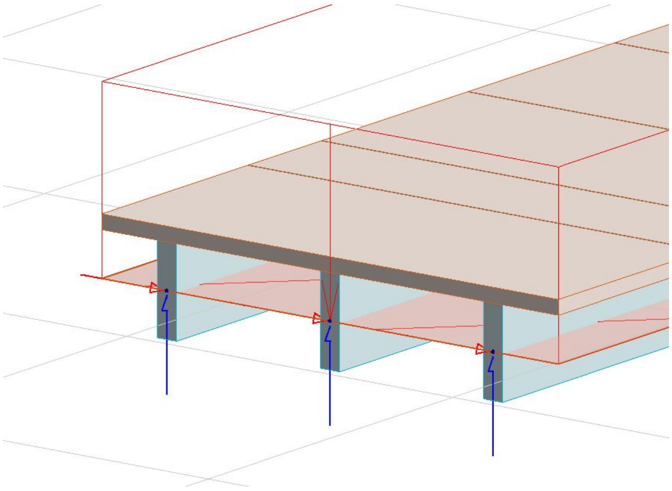


Figure 3.7. Illustration of load distribution on the bridge, showing variable and permanent loads, as well as the eccentricity of the CLT panel.

3.3.5 FEM-Design Analysis Results

Through design calculations based on relevant load combinations, the utilization of each structural element was determined. All results were below 100%, indicating that the structure meets the requirements for the Ultimate Limit State (ULS) according to Eurocode 5. No stability or dynamic analyses were performed in FEM-Design.

The normal forces for the bridge are illustrated in Figure 3.6

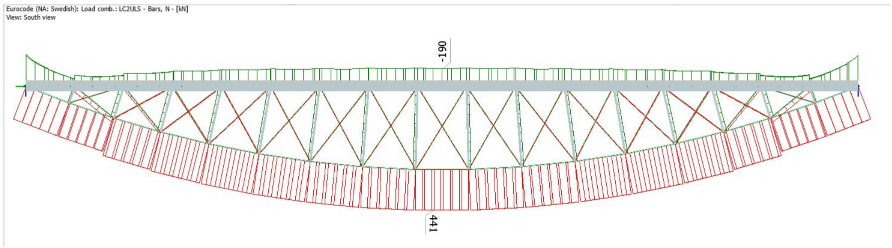


Figure 3.8. Illustration of load distribution on the bridge, showing variable and permanent loads, as well as the eccentricity of the CLT panel.

The maximum deformation of the bridge, shown in Figure 3.9, is 81mm, which is below the allowable limit of 90mm.

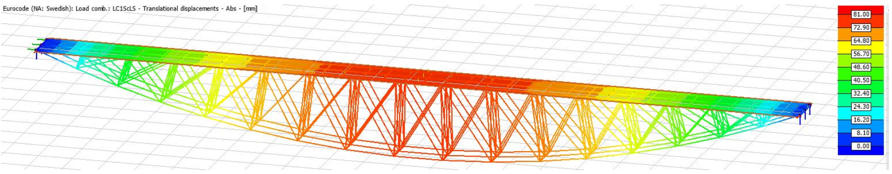


Figure 3.9. Illustration of the deformation of the bridge in SLS.

In Figure 3.10 the final superstructure is shown.

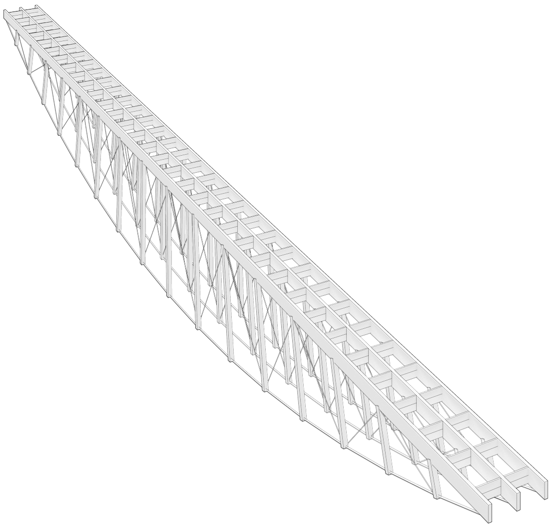


Figure 3.10. Illustration of the final superstructure, without deck and the railing.

3.4 Design of the Railing

3.4.1 Design of the Initial Railing: Steel

The initial design of the railing is steel rail posts with a center distance of 2.650 m that align with each compression strut. All components, pickets, top and horizontal rail are designed of slim steel members. Steel pickets are spaced 90 mm apart to meet safety requirements.

The dimensions of the posts are based on utilization rate in the ultimate limit state while deformation in service limit state has been compared against the vaguely stated requirements of the height from the deck, H_0, divided by 100. However, according to the Swedish Transport Administration (2019), deformations for steel railings should not be taken into account.

According to SIS-CEN/TR 16949:2016 from Swedish standards institute (2017) loads applied for the dimensioning of bridge railings are a horizontal and vertical line load of 1 kN/m each on the top of the railing together with the dead load of the post. A deadload from the steel pickets and the timber rail cap are added with is estimated load of 0.24 kN/m. Based on the mass calculated in appendix X. That gives a total load of 10.7 kN per side distributed the length of 45 meters.

The resulting dimensions are a quadratic cold Formed Rectangular Hollow Section, RHS, with the dimensions 60x60 mm and the thickness 5 mm. The material is S355J2 which is a commonly used structural steel with a minimum yield strength of 355 MPa. The area is, according to the FEM software, 1036 m^2 and the utilization rate is 78% with a deformation of max 32 mm outwards.

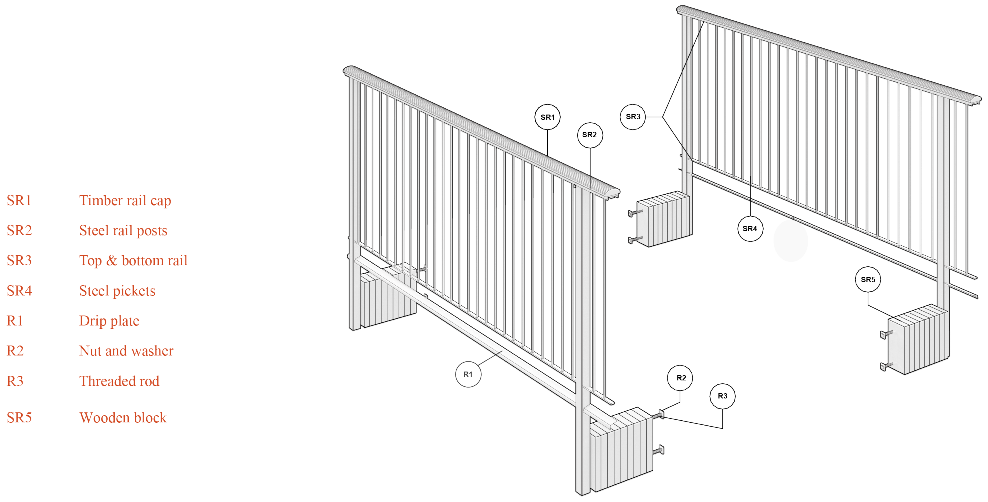


Figure 3.11. Illustration of the design of the initial railing.

3.4.2 Design of the Alternative Railing: Timber

The alternative railing is a timber railing design. This alternative differentiates both material and connections. In this version the timber rail post is connected by one threaded rod at the top and then a bottom chord at the end. This bottom chord runs transversely beneath the longitudinal beams of the bridge deck and is restrained against lateral movement by timber blocks located on the outward facing surface of the beams. The rail post is a combination of two posts in pressure treated lumber of 45x120 mm with similar loads as the railing of 1kN/m in the horizontal direction and 1kN/m in vertical direction together with the deadload of the railing pickets and top and bottom rail. The dead load 17 railing pickets of 22x70 mm equals 0.115 kN/m.

The resulting dimensions are two 45x120 mm C24 is utilized at 98% which is too high, yet for this conceptual design phase, it's assumed reasonable. The deformation is 20 mm outward.

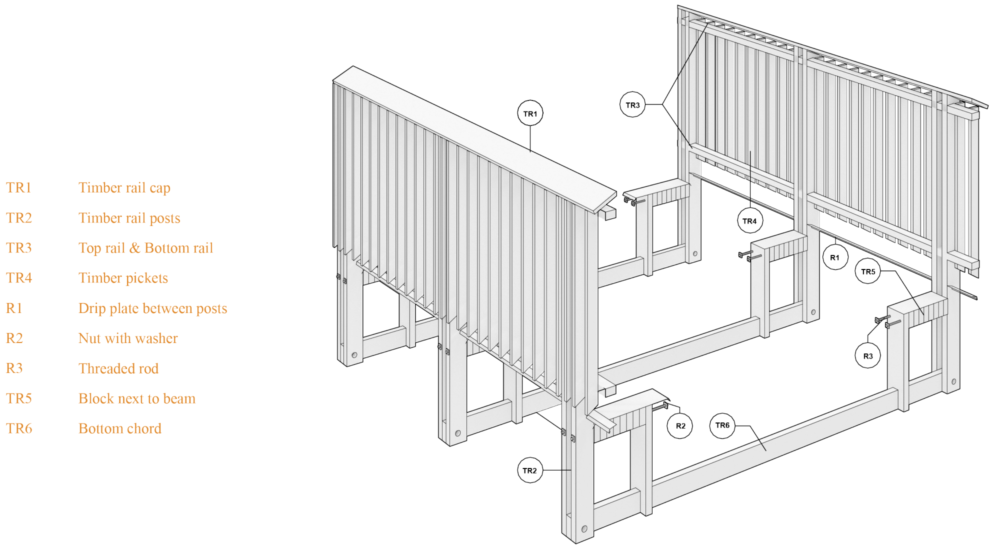
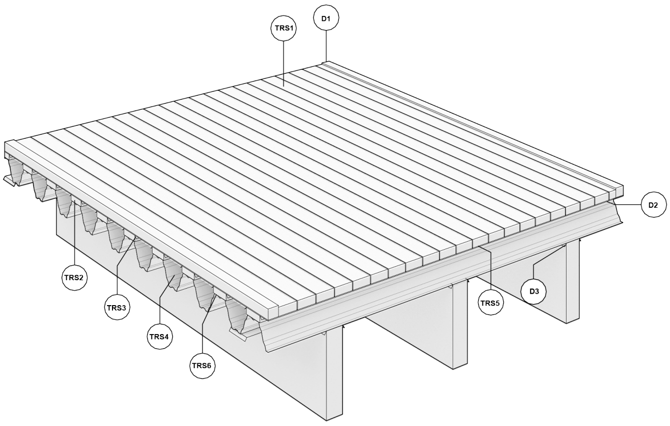


Figure 3.12. Illustration of the design of the alternative railing.

3.4.3 Design of the Initial Deck: TRP-Plate

Since the superstructure defines the baseline of the bridge deck, in this case, a general beam bridge, the key design decisions primarily concern the type of transverse load-bearing system for the deck and the choice of cover. The cover of the bridge will be the same in both the initial design and the alternative, that is wearing planks in a suitable direction.

For the initial design, the load-bearing system will be a TRP-plate since it's a recently used system set by our supervisors at TBS. The dimensioning of the deck has primarily been set by evaluating load and span tables for the different standard dimensions. From the tables the assumption concluded that height <100mm is too low (Gyproc, 2023) and that TR130 can take higher loads than the relatively small spans between the beams in this design, however since there is no standard cross-section in-between TRP130 has been assumed (Ruukki, n.d.). The thickness of the TRP modelled to 1mm. By conducting a more detailed analysis of the loads, the thickness could potentially be reduced, significantly decreasing the amount of steel required.

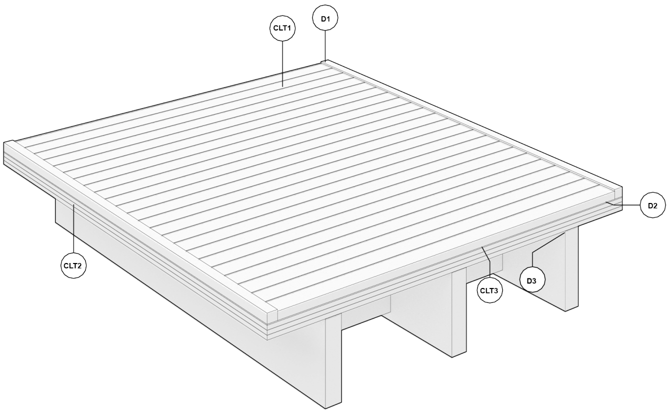


TRP1	Deck planks
D1	Edge-plank
D2	EPDM- rubber
TRP2	Screw stud
TRP3	Underlayment
TRP4	Trapezoidal corrugated sheet
TRP5	Screws (planks)
TRP6	Screws (TRP)
D3	Underlayment
D4	Angle bracket
D5	Bracket screws

Figure 3.13. Illustration of the design of the initial deck.

3.4.4 Design of the Alternative Deck: CLT-Slab

According to tables of maximal allowed spans provided by the local timber manufacturer Martinsson (2022), an 80 mm CLT slab, originally designed for roof construction, can span up to 3.8 meters in climate class 2. This is based on a load of 5.5 kN/m^2 and a deformation limit of L/200. Similarly, an 80 mm CLT slab, designed as a floor slab, can span up to 2.8 meters in climate class 1. This is based on a load of 5.0 kN/m^2 and a deformation limit of L/267. Hence, an 80 mm, three layered CLT-slab should be able to handle the span between the longitudinal beams and is the approved CLT slab option for this alternative deck design.



CLT1	Deck planks
D1	Edge-plank
D2	EPDM- rubber
CLT2	CLT-plate
CLT3	Screws
D3	Underlayment
D4	Angle bracket
D5	Bracket screws

Figure 3.14. Illustration of the design of the alternative deck.

3.5 Assumptions and Limitations in the FEM Modeling of the Superstructure

Regarding the vertical pedestrian load effect stated in SS-EN 1991-2, only a uniformly distributed load is taken into account in the preliminary design. A concentrated load is not included in the calculations, and a load representing service vehicles is ignored (SIS, 2010). Another assumption regarding loads is that, according to Eurocode 1 (EN 1991-2), the bridge was assessed using imposed load category C, appropriate for areas with moderate pedestrian traffic (European Committee for Standardization, 2003). This is regarded to be a reasonable assumption due to the bridge location in Ekshärad and the limited width of 2.8 meters.

The deformation criterion has been assumed as < L/500, which is stricter than the actual requirement in Eurocode 5 (SS-EN 1995-2:2004; (Swedish Standards Institute, 2004)). This choice is motivated by the fact that timber bridges, due to their lower self-weight, are more susceptible to vibrations and resonance, making stiffness a more critical parameter. Furthermore, since wind loads have not been considered and no dynamic analyses have been carried out, adopting a more restrictive deformation limit helps strengthen the reliability of the preliminary structural assessment. The assumption is therefore considered both justified and reasonable.

The model only considers the CLT and not the TRP; however, it is assumed that the effects somewhat balance out, since the CLT likely contributes more to the structure's load-bearing capacity, deformation, and stiffness, while also having a higher self-weight. Although the behaviors cannot be assumed to be entirely equivalent, modeling has been carried out based on these assumptions.

4 Life Cycle Assessment

This chapter calculates the environmental loads of the initial bridge design, following the LCA methodology. This methodology is based on the latest version of ISO-14040 standard that includes four phases, goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (ISO, 2006). Based on the interpretation of the results, alterations of the bridge design are presented in an additional phase, and an additional calculation of the environmental loads of these alterations is presented following the same methodology.

The goal and scope definition comprises, as the name insinuates, the goal of the study and the definition of what aspects are included in the system boundaries.

Life cycle inventory, LCI, comprises gathering data that will determine the environmental emission included in the selected system boundaries. The data is organized in tables for better overview and workflow of the compilation and quantification of inputs and outputs (ISO, 2006).

Life cycle impact assessment, LCIA, comprises an analytic review of the potential environmental impacts based on their amplitude and significance for each defined product system in the study.

Life cycle interpretation comprises the findings of the inventory and their impacts in order to make qualified conclusions and discussions of the result (ISO, 2006).

4.1 Goal and Scope Definition

The intended application of this study is to identify and modify components of a timber bridge design to understand how such modifications influence the environmental impact.In response to the relatively low number of timber bridges constructed today, the study intends to give municipalities and potential bridge owners more incitement to invest in timber bridges. The intended audience are the research field and fellow students. Other intended audiences for this study are bridge designers and contractors interested in exploring cost versus sustainable solutions and the interaction in-between.

The functional unit for this study is ‘a 45 m bridge with a technical service life of 100 years’ to represent future services of timber bridges. The modified bridge versions are evaluated against the initial version. The comparison of modifications is assumed to be applicable for material choices for future bridge designs. However, the focus is to present data and assumptions and thereby proposing a framework that future LCA studies can incorporate.

4.1.1 System Boundaries

The study follows the modules included in Life Cycle Modules in SS-EN 15978, see Figure 4.1, which is a standard of the Swedish National Board of Housing, Building and Planning (Boverket, 2024) for LCA in the construction sector that addresses entire construction processes.

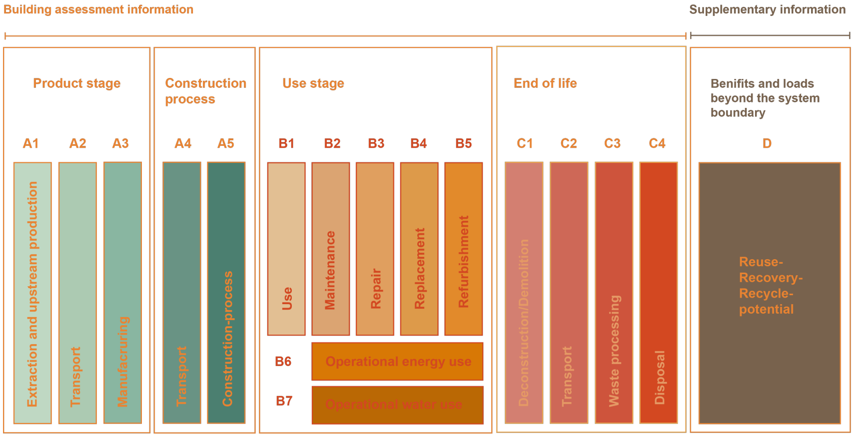


Figure 4.1. Illustration of system boundaries including life cycle stages (A–D) and their modules as defined in SS-EN 15978:2011.

The study follows a cradle-to-cradle approach, as the life cycle assessment encompasses everything from raw material extraction, replacements during its service life, to final waste management and potential repurposing in other systems. The modules and stages included in this study are shown in Figure 4.2.

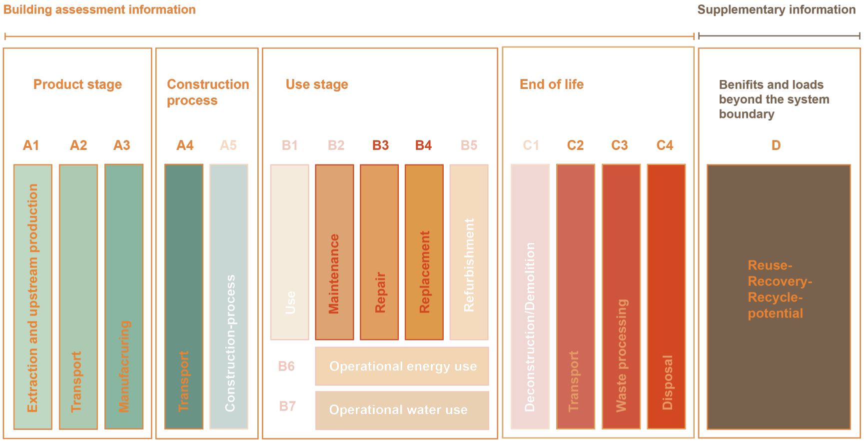


Figure 4.2. Illustration of system boundaries with highlighted modules included in the present study, based on life cycle stages (A–D) as defined in SS-EN 15978:2011.

The study includes A1-A3 either through assumptions based on findings in EPDS or through research-based assumptions. A4, transportation to site, is included and estimated from manufacture to the specific site.

A5 is excluded due to the difficulties of estimations. Furthermore, the amount would have assumed the same value for all alternatives and would therefore not have a decisive impact on the results.

Prefabrications have been assumed to be a good alternative for this type of lightweight structure and should have been a part of A4 and A5 if it had been modeled. However, this potential additional transportation has been estimated equally across all alternatives and is therefore disregarded.

For a bridge design, B1 is difficult to estimate, and its impacts are assumed to fall under other B subcategories. To address uncertainties, safety margins are incorporated into the design, while potential harm to the bridge is assumed to be included in B2-B4.

B2-B4, maintenance, repair and replacement are included. However, B3 and B4 are merged, and replacements of specific parts are simplified for entire bridge components according to a certain interval. B3 is therefore counted to some extent as included in those clusters, but the study does not take into account the aspect that the part is repaired instead of replaced. Instead, it is accounted for by a slight increase in the replacement range.

B5 is excluded since it is assumed that the bridge doesn not need refurbishment for other aspects than replacements of worn or expired parts. B6 (operational energy) and B7 (operational water use) are excluded. B6 could have been incorporated for lighting and maintenance, but [it is assumed the same for all alternatives.

C1, deconstruction, is not included for simplification.

C2-C4, transportation from site, waste processing and disposal are included. The distance for module C2 is estimated based on the nearest waste treatment facility for each material. Waste processing dominates over disposal since the study has limited the amount of landfill in accordance with Swedish standards.

D is represented in all its possibilities, that is through reuse, recovery and recycling potential.

The type of LCA is Attributional LCA, since it is based on present information. Yet, some assumptions of future developments are still included. The allocation method is set to physical allocation.

Geography of the study is Sweden and Ekshärad more specifically. The study uses a time horizon of 100 years similar to bridge service life. However, benefits gained from module D, potentially occurring beyond the 100-year timeframe, are still accounted for and seen as a subtraction of the results.

The study includes a sensitivity analysis in the shape of data range to test the best and worst-case scenario (Nickel, 2025). This includes the range of replacements and maintenance of certain parts. The study presents a minimum and maximum interval of these processes and assume that the reality is somewhere in between.

The software used for the life cycle assessment is OpenLCA 2.4.1 and the database used is Ecoinvent 3.8 (GreenDelta, 2021) .

4.2 Life Cycle Inventory (LCI) Analysis

In the following text the bridge is subdivided into three components, bridge deck, bridge railing and the superstructure. Bridge elements refer to every specific part inside each component.

General Assumptions made in A1-A3

Listed in Appendix B are detailed inventory tables for each component, including all assumed elements. The tables have complementary tables for calculation of expected area, volumes, mass etc used for inputs in OpenLCA. In both for bridge deck and bridge railing components the dimensional properties and measured quantities were manually calculated. For the superstructure these values were retrieved from the FEM-software. Here the density for each material was withdrawn from the software and thereby differs from the density that was estimated for the other bridge elements.

For timber members, volumes were the primary quantity defined in the LCA-software. Untreated timber products from Ecoinvent version 3.8 database were selected for lumber, pressure treated lumber and glulam. The pressure treated lumber was coupled with a dataset of wood preservation to represent the chemicals in the pressure treatment process. The treatment was added based on the surface area of the treated lumber.

For steel members mass was the primary quantity defined in the LCA-software. The steel products were distinguished between steel part and steel plates and different dataset was selected. All steel members were assumed to be hot-dip galvanized. To estimate the amount of zinc these processes encounter, the surface area of all steel products was calculated and added as zinc coating in the software.

For EPDM used in both in initial and alternative deck, the representation in OpenLCA was a water-resistant rubber. For the EPDM mass was the primary quantity.

The underlayment YEP2500 is a strong polyester base with SBS bitumen cover that is water resistant. The underlayment was modelled as mass. (TECCA, n.d.)

Specific dataset is documented in the appendix along with all other materials included in the study.

General Assumptions Made in A4, B2-B3 and C2

Direct transport from manufacturer was assumed and returns were not taken into account. As previously stated, no distance was added for the prefabrication site. The tables found in the Appendix B showcase an estimation of site for manufacturing for each element and the distance form this site to Ekshärad. The report "The Future Heavy Truck Fleet: A Situational Analysis" by Axelsson and Nolinder (2024) shows that according to Table 5, the high scenario predicts 100% zero-emission heavy trucks by 2040. Using a conservative estimate over the 100-year service life of the bridge, it was therefore assumed that electric heavy trucks will constitute 50% in stages A4, B2-B4, and 100% in stages C2.

General assumptions made in B2-B4

The same goes for exposed timber parts that will need maintenance by oiling the surface area. The included areas are dependent on the reachability of the surfaces.

B2, maintenance, was added for all exposed timber members as they require additional treatment to prevent moisture-related issues and to protect against drying and cracking.

Recommendations, set by producers, concerning the frequency varies from annually to every four years (Alcro Färg, n.d.). However, in practice the treatment of this kind occurs more seldom and in is thereby assumed to occur every 5-10 years (Honfi, 2025). In openLCA this was modelled as a dataset of an alkyd resin and the amount is calculated based in surface area of the lumber. The surface area was dependent on the reachability of the surfaces, meaning that, for example, the bottom surfaces of planks were excluded.

For B2 -B4, the number of maintenance and replacement processes was assumed and presented in tables per bridge component or member in Appendix B. For B4, which to some extent includes B3, it was assumed that the entire bridge component was replaced at once including all elements. This assumption does not correspond to a real scenario but was implemented for simplifications. The table below showcase assumptions for the number of replacements per bridge component (Honfi, 2025). The shortest time span for each component is the indication for max number of replacements and the highest time span will indicate the minimum of replacements. In openLCA, two scenarios were modelled, one including maximum of maintenance and replacements and one including the minimum.

Table 4.1. Estimated time span between repairs or replacement for different construction parts (Honfi, 2025).

Construction part	**Repair and replacement interval [min–max years]**
Wearing planks	15–20
Bridge deck with TRP-plate	40–60
Bridge deck with CLT slab	30–50
Steel railing	40–45
Timber railing	20–30
Glue laminated timber beams; protected with cladding	80–120
Constructive wood protection for beams; pressure treated	20–30
Bracing system	80–120
Oil treatment	5–10

General assumptions made in C2-C4 and D

In the end-of-life module, all the bridge members of the same material were combined for each bridge component. How much of each material and which type of "end of life" they enter were assumed based on research into current situations and estimations of future developments.

Stage D has both positive and negative impacts. The positive includes the reused parts, energy from energy recovery, and new recycled material. The negative impacts include energy for recycling and recovery processes. In energy recovery this was subtracted immediately to the gained energy and thereby not modeled. The positive impacts were modelled as “avoided product” to the environmental impacts when modelling the product system. The negative impacts were subtracted directly from the positive impacts within module D.

Steel Parts

Steel products are currently recycled to a significant extent, and provided that the process will be developed further, steel is considered fully recyclable. (Jernkontoret, 2019). However, the study predicts that some elements can be reused instead, and the ratio is set at 20/80 between reuse and recycling of both steel and zinc.

Today 93% of the zinc from hot-dip galvanized steel can be recycled (nordicgalvanizers, n.d) and the study assumes that the technological developments will make it possible to recycle 100% of the zinc in the future. As simplification we assumed that 2% of the total steel weight is zinc. The process of separating the zinc is made in an electric arc furnace (Avfall Sverige, n.d.) and one can be found in Oxelösund, 330 km from Ekshärad.

Electric arc furnace slag and dust was not added, yet electricity for the furnace was added around 300 – 550 kWh/ton (Industrial Efficiency Technology & Measures, 2013). Another reference states that energy consumption of electric arc furnaces is around 600-800 kWh/ton and when using recycled material or "scrap" processes savings around 75-150 kWh/ton can be made (Jernkontorets Energihandbok, n.d.). This study estimated that energy added for recycling galvanized steel products is assumed to be around 450kWh/ton.

Timber Parts

The chosen percentages for timber waste and, possibilities for beyond life scenarios, were based on current conditions and projections of how these may evolve over the next 100 years. Given the growing interest of reuse potential in glulam and other building parts, (Svenskt trä, 2024) and by following the cascade model, glulam can be reused for lower structural applications. Presumably it could be used with greater dimensions compared to a new component and thereby be less material efficient. Glulam could also be assumed to replace lumber. For this LCA it was assumed for that 40% of the glulam becomes lumber and 40% remains as glulam, whereas the remaining 20% is assumed as the potential increase of dimensions for structural applications.

Due to the growing interest in circularity, it was estimated that 100% of the untreated lumber will be recycled to particle board and other wood-based products, the current rate is around 50% (Skogsindustrierna, 2025).

Pressure treatment is known as hazardous waste (Hagfors kommun, n.d.). However, with new more strict regulations, chemicals such as creosote, arsenic and chromium have now been replaced with copper-based agents (Avfall Sverige, 2024). By assuming this development, pressure treated timber were estimated to be 80% energy recovery and 20% waste. The closest station for energy recovery is "Kils avfallsförbränningsanläggning" and it is located 90 km from Ekshärad.

Energy gained for energy recovery for timber was assumed to be the same as stored energy, which according to Träguiden (2015) is 4,5 kWh/kg dry wood or 2000 kWh/m3. Energy used for the processes was assumed to be subtracted to this sum. Around 11% will be pure electricity and 89% will go to district heating (Avfall Sverige, 2024).

Waste Treatment - Other Parts

Sweden is a country with a low percentage of waste sent to landfill and prioritizes energy recovery to the greatest extent possible (Avfall Sverige, 2025). Therefore, when choosing the dataset for each waste treatment, it was important to make sure the data refers to municipal waste incinerators and not landfill. For simplification, it was assumed that both hazardous waste and waste referred to as “other parts” have no energy recovery since the parts are relatively low in mass and do not impact the total result as much as e.g. the glue laminated products. To compensate for the loss in energy recovery, the ratio of recovered energy calculated was set high.

General simplifications were made, e.g. that all steel products are gathered to steel, low alloyed, and mass of timber treatment/preservation was disregarded.

4.3 Life Cycle Impact Assessment (LCIA)

The primary calculation methods inside OpenLCA were “ReCiPe 2016 Midpoint (H)” (Huijbregts et al., 2016). This method was evaluated by comparing the CO_2 equivalents from ReCiPe with CML-Baseline and IPCC 2013 GWP 100a to justify the credibility of the results. The impact categories that are included in this study and can be found in ReCiPe 2016 Midpoint (H) are illustrated in Figure 5.3.

Figure 4.3. Illustration of the impact categories: Global Warming Potential, Mineral Resource Scarcity, and Land Use, with corresponding units.

The choice of impact categories was set to give a broad perspective of the impacts and thereby include negative impacts from both steel and timber products. Mineral resource scarcity was expected to contribute to negative results from steel, and land use was expected to be affected by the amount of timber extraction.

4.4 Life cycle Interpretation of the Results - Initial Design

To investigate the total environmental impact of the bridge, a comparison between various calculation methods was made. This was done for two reasons. The first reason was to enhance comparability with future studies, allowing the results to be aligned with similar calculations. The second reason was to find the margins of error that can be included in each method. The three methods that were compared are ReCiPe 2016 Midpoint (H), compared to CML-Baseline and IPCC 2013 GWP 100a. To ensure consistent units for comparison, this analysis included only one impact category, i.e., kg CO_2 emissions.

The results in Figure 4.4 show similar values for all three cases in terms of kg CO_2 equivalents. ReCiPe has a result that is slightly higher than the others. Since ReCiPe 2016 Midpoint (H) includes all relevant impact categories, Global warming potential, mineral resource scarcity, and land use, it is chosen as the calculation method going further.

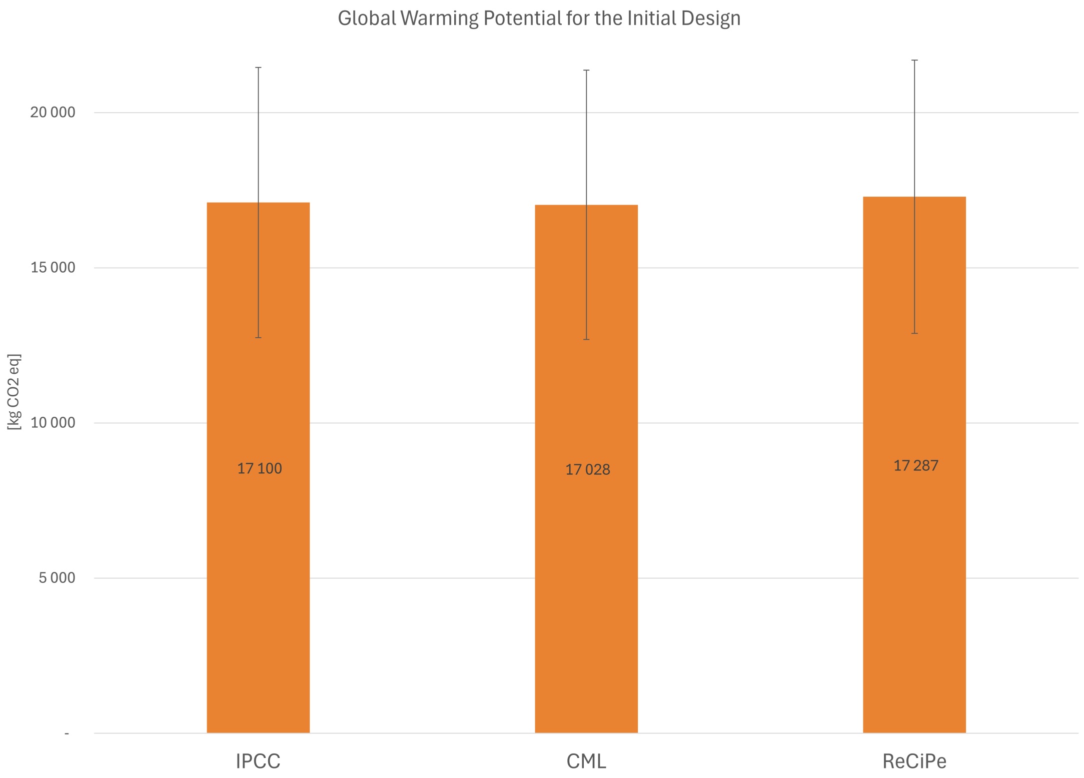


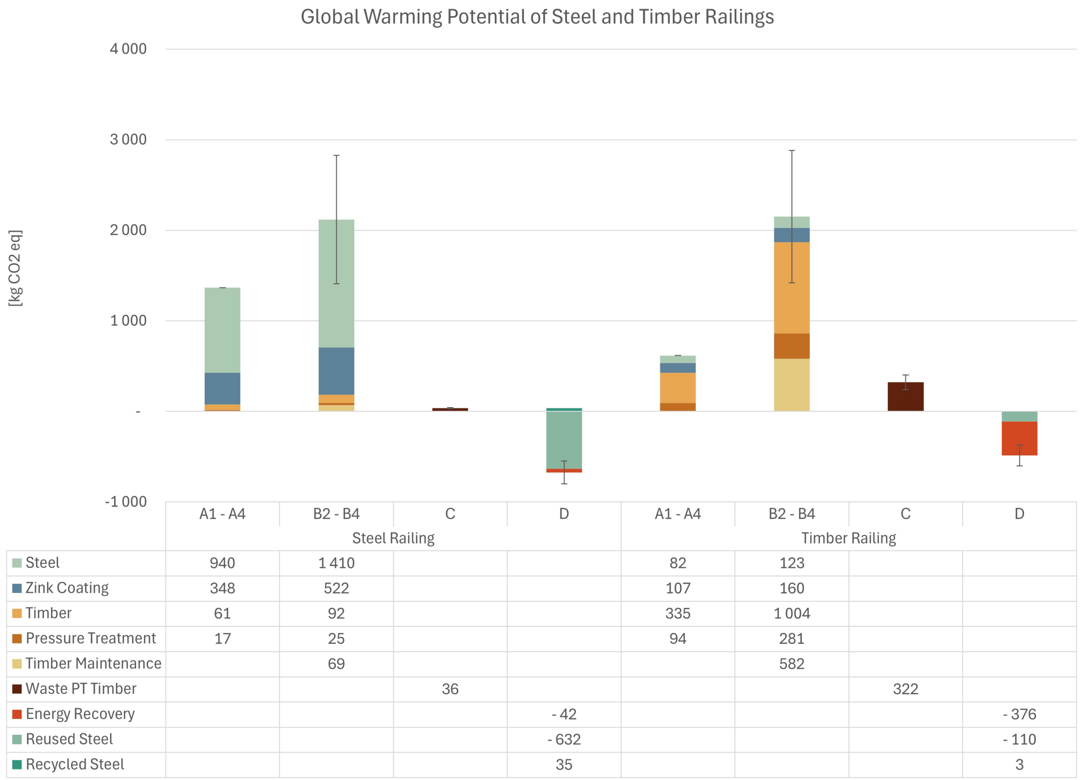
Figure 4.4. Results for global warming potential of the initial bridge using the calculation methods IPCC, CML, and ReCiPe.

4.5 Life Cycle Interpretation of the Results – Comparative Assertion, Phase 1

Based on the result of the initial bridge, an iterative design process resulted in alternative designs for each bridge component, i.e., the railing, the deck, and the superstructure. Based on the results, the study included a variation for the whole bridge where the pressure treated lumber was exchanged for a more sustainable option. More detailed information on this is provided in Phase 2. The environmental claim is that the alternative results have a better environmental performance than the initial bridge design. This part will investigate and discuss whether this is true. Hence, are the alterations more sustainable options than the initial design?

The graphs shown below are simplifications of the results at their mean value. Each element was merged with elements of some or similar material for easy communication of the results. Important aspects not shown but obtained from the OpenLCA are mentioned along with each paragraph. In each bar, a black line demonstrates the sensitivity analysis and showcasing where the bar would have been in terms of maximum and minimum sets of replacements.

Initial and Alternative Bridge Railing Design – Steel and Timber



	Steel Railing				Timber Railing			
	A1 - A4	B2 - B4	C	D	A1 - A4	B2 - B4	C	D
Steel	940	1 410			82	123		
Zink Coating	348	522			107	160		
Timber	61	92			335	1 004		
Pressure Treatment	17	25			94	281		
Timber Maintenance		69				582		
Waste PT Timber			36				322	
Energy Recovery				- 42				- 376
Reused Steel				- 632				- 110
Recycled Steel				35				3

Figure 4.5. Results for global warming potential of steel and timber railings.

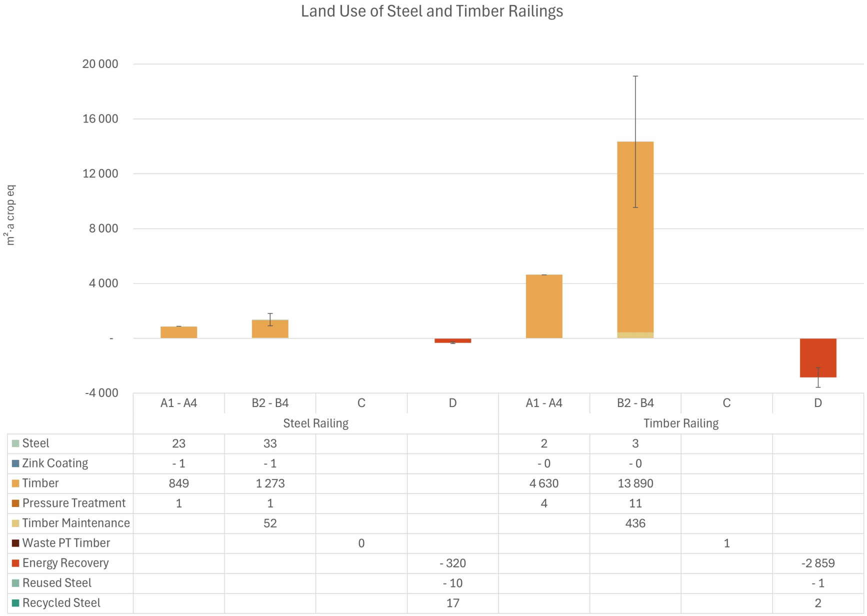
The global warming potentials from the initial railing design, Figure 4.5 show that, as expected, the amount of steel dominated the climate impact whilst the timber parts has a relative small impact despite the fact that the timber constitutes almost a quarter of the mass.

The waste is minimal since a large portion of the steel can be recycled and reused. The CO_2 emissions are 3520 kg CO_2 equivalents with a possible subtraction of 640 kg CO_2 equivalents from module D.

For the timber railing, global warming potentials from timber adds up to 3010 kg CO_2 equivalents with a possible subtraction of 490 CO_2. In this case, steel constitutes about 5% of the total mass yet still has a visible impact on the results.

Nevertheless, this leaves a relatively small difference in impact of only 360 kg CO_2 equivalents in favor av the timber railing. It is important to note that the railings in the alternative case were designed slightly differently concerning the spacing of the posts. The number of posts was therefore doubled, resulting in not only a less material-efficient design in terms of timber but also an increased number of threaded rods. A more optimized design could have avoided this matter and reduced the amount of steel in the alternative design. Another important note is that around 30% of the CO_2 emissions in the timber section stems from the pressure treatment of the lumber.

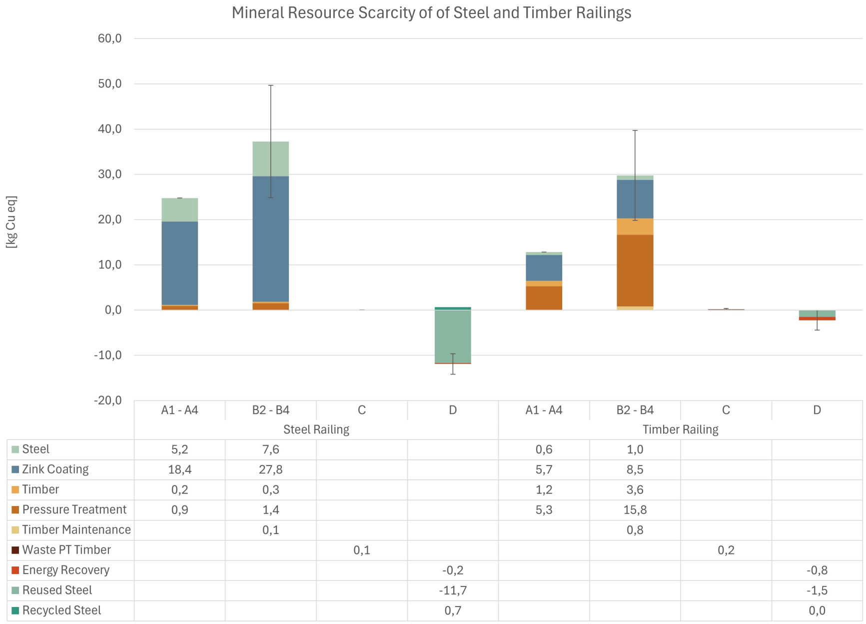
When it comes to land use, Figure 4.6, the timber industry is nearly exclusively the primary contributor to higher results. As expected, steel railing is the better alternative from this perspective. Positive impacts gained from module D are relatively small, and module C is as seen not even a factor for this impact category.



	Steel Railing				Timber Railing			
	A1 - A4	B2 - B4	C	D	A1 - A4	B2 - B4	C	D
Steel	23	33			2	3		
Zink Coating	- 1	- 1			- 0	- 0		
Timber	849	1 273			4 630	13 890		
Pressure Treatment	1	1			4	11		
Timber Maintenance		52				436		
Waste PT Timber			0				1	
Energy Recovery				- 320				-2 859
Reused Steel				- 10				- 1
Recycled Steel				17				2

Figure 4.6. Results for land use of steel and timber railings.

In the case of mineral resource scarcity, Figure 4.7, steel and zinc have a large effect on the use of non-renewable resources. When excluding module D, the steel railing has almost 50% more mineral depletion than the timber alternative. By looking at the indicators in the timber railing, it is clear that material depletion almost exclusively comes from pressure treatment of the lumber. As a renewable material, timber does not contribute substantially to the depletion, except for the depletion associated with the electricity used in its production processes.



	Steel Railing				Timber Railing			
	A1 - A4	B2 - B4	C	D	A1 - A4	B2 - B4	C	D
Steel	5,2	7,6			0,6	1,0		
Zink Coating	18,4	27,8			5,7	8,5		
Timber	0,2	0,3			1,2	3,6		
Pressure Treatment	0,9	1,4			5,3	15,8		
Timber Maintenance		0,1				0,8		
Waste PT Timber			0,1				0,2	
Energy Recovery				-0,2				-0,8
Reused Steel				-11,7				-1,5
Recycled Steel				0,7				0,0

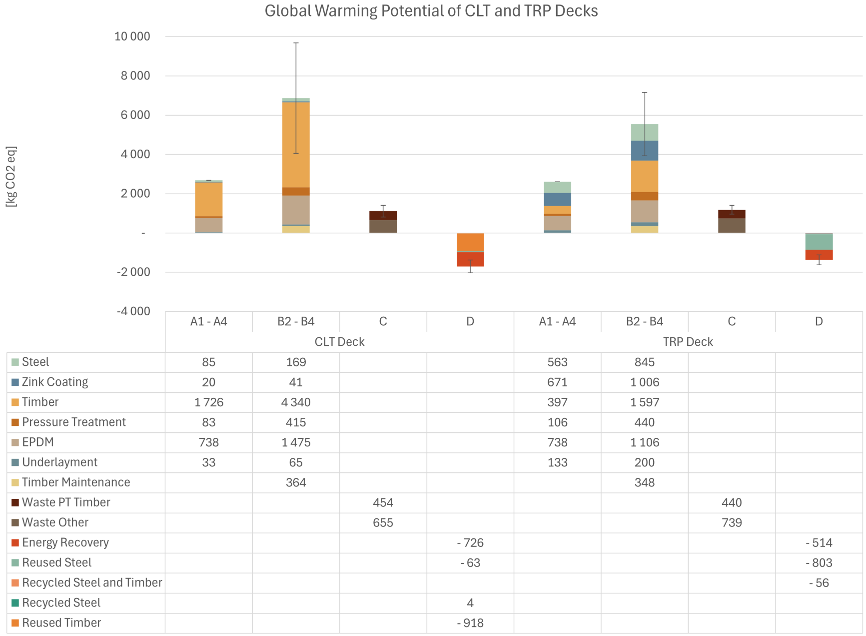
Figure 4.7. Results for mineral resource scarcity of steel and timber railings.

When comparing the two, the result shows that timber railing is the best alternative to avoid unnecessary mineral extraction. It is also clear that without sustainable forestry there are certain issues using timber as well. The amount of global warming potentials originating from the processes of producing pressure treated lumber is also a bit alarming. The mass of these products is relatively small compared to timber. Maintenance is also a factor that shows a clear contribution to emissions shown as "treatment" in the bars.

When looking at the three impacts categories, it might give an impression of an equally negative impact, which is not the case. There are studies that investigate methods of weighing the results of various impact categories, making them more comparable to a common unit. However, in this study the focus will be to compare impact categories against impact categories between components with the same function and utility, as for this case bridge railing compared to another bridge railing. The need for weighing the impacts categories is thereby excluded from this study.

Initial and Alternative Bridge Deck Design- TRP and CLT-slab

When comparing the global warming potentials gained from the two deck variations, TRP and CLT slab, the results show that their impact is a bit different than for the railing, see Figure 4.8.



	CLT Deck				TRP Deck			
	A1 - A4	B2 - B4	C	D	A1 - A4	B2 - B4	C	D
Steel	85	169			563	845		
Zink Coating	20	41			671	1 006		
Timber	1 726	4 340			397	1 597		
Pressure Treatment	83	415			106	440		
EPDM	738	1 475			738	1 106		
Underlayment	33	65			133	200		
Timber Maintenance		364				348		
Waste PT Timber			454				440	
Waste Other			655				739	
Energy Recovery				- 726				- 514
Reused Steel				- 63				- 803
Recycled Steel and Timber								- 56
Recycled Steel				4				
Reused Timber				- 918				

Figure 4.8. Results for global warming potentials of TRP and CLT decks.

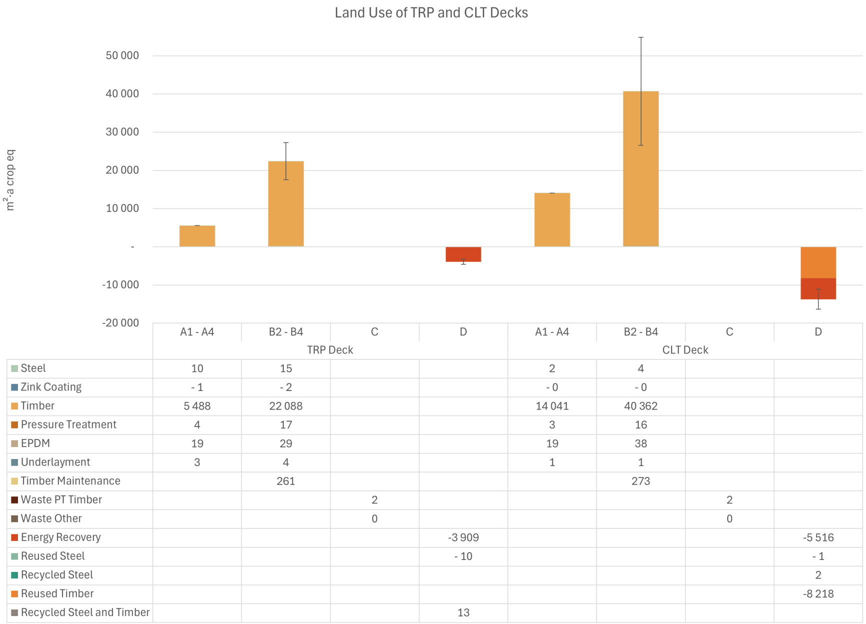
The impact from TRP in module A-C is around 9330 kg CO_2 equivalents, and with the subtraction from D, of 1370 kg, the result is 7950 kg CO_2 equivalents. For the CLT-slab, the initial contribution from module A-C is 10 660 kg CO_2 equivalents, and by subtracting D, which is relatively high due to the amount of reuse and recycling potential set for future waste treatment, the resulting emission is 8960 kg CO2 equivalents. The impact from the initial design is therefore more than 11% less than the alternative design.

When looking more closely into the alternative design, the masses are distributed as follows: 93% timber, 2% steel and 5% EPDM and underlayment. Despite the high rate of timber, only 67% of the emissions gained in A1-A3 stem from timber production.

Upon closer examination, 54% of 93% of timber is obtained by the cross laminated plate. Yet alone it stands for 1411 of the total 2684 kg CO_2 equivalents in the initial production phase, which is more than 52% of the impacts compared to the lumber that has almost equivalent mass but only 15% of the total impacts.

As seen in the sensitivity analysis, the result from CLT fluctuates more than the result from TRP, meaning that the rate of expected replacements has a great impact on the result and differs between the two from the mean value shown above. If timber could be proven to be more durable, as it is in many cases during well-designed conditions, this result might have ended up different.

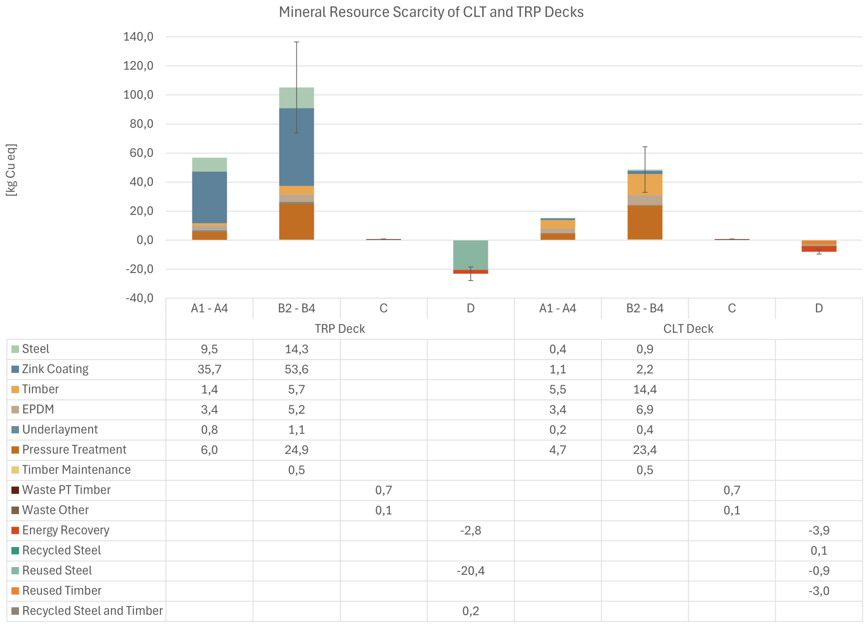
As expected, the square meter of land use, Figure 4.9, is significantly more affected by the CLT alternative rather than the trapezoidal plate. As the results the indicates without module D the trapezoidal plate has almost half the impact as for the CLT-slab. However, when including module D the CLT gets reduced by 25% whilst the trapezoidal plate only gets a reduction of 14%.



	TRP Deck				CLT Deck			
	A1 - A4	B2 - B4	C	D	A1 - A4	B2 - B4	C	D
Steel	10	15			2	4		
Zink Coating	- 1	- 2			- 0	- 0		
Timber	5 488	22 088			14 041	40 362		
Pressure Treatment	4	17			3	16		
EPDM	19	29			19	38		
Underlayment	3	4			1	1		
Timber Maintenance		261				273		
Waste PT Timber			2				2	
Waste Other			0				0	
Energy Recovery				-3 909				-5 516
Reused Steel				- 10				- 1
Recycled Steel								2
Reused Timber								-8 218
Recycled Steel and Timber				13				

Figure 4.9. Results for land use of TRP and CLT decks.

For mineral scarcity, Figure 4.10, on the other hand, the CLT has 60% less impact than the trapezoidal plate. The results were expected in coherence with previous conclusions. However, for the alternative version 74% of the impacts actually stem from timber. When looking at the trapezoidal plate , a similar amount is found for timber which indicates that it originates from the shared elements, i.e. the deck planks. A more detailed analysis reveals that 39% of pressure treated lumber in the alternative design accounts for 50% of all mineral resource scarcity. Upon even closer examination, 82% of these impacts from the lumber originate directly from the timber treatment process itself, meaning that by excluding this, the alternative design would have scored way better.



	A1 - A4	B2 - B4	C	D	A1 - A4	B2 - B4	C	D
	TRP Deck				CLT Deck			
■ Steel	9,5	14,3			0,4	0,9		
■ Zink Coating	35,7	53,6			1,1	2,2		
■ Timber	1,4	5,7			5,5	14,4		
■ EPDM	3,4	5,2			3,4	6,9		
■ Underlayment	0,8	1,1			0,2	0,4		
■ Pressure Treatment	6,0	24,9			4,7	23,4		
■ Timber Maintenance		0,5				0,5		
■ Waste PT Timber			0,7				0,7	
■ Waste Other			0,1				0,1	
■ Energy Recovery				-2,8				-3,9
■ Recycled Steel								0,1
■ Reused Steel				-20,4				-0,9
■ Reused Timber								-3,0
■ Recycled Steel and Timber				0,2				

Figure 4.10. Results for mineral resource scarcity of TRP and CLT decks.

As the result above indicates, the initial design with the trapezoidal plate is a better alternative in terms of global warming impacts and land use. However, for mineral resources, corrugated sheeting has a greater impact. Since both include an equal amount of pressure treated lumber, the result would be equally enhanced if an alternative treatment replaced the pressure treated lumber.

Ideas for further modification would be to change the CLT for another timber solution, preferably beams with perhaps a greater height than the CLT to handle to load with a center-to-center distance that might have been more material efficient than the CLT. It might even work with lumber due to the relatively short spans between the longitudinal beams in this design.

Since the modification primarily revolved around improved material efficiency in steel members, the results of this comparison are not surprising nor reveal any subjects for further discussion. The design can be modified even further to assure the best and most material efficient solutions.

4.6 Life Cycle Inventory - Heat treatment

Based on conclusions made in the previous phase of the study, it is evident that the study could benefit from having a last iterative design phase, that includes an alternative wood treatment. To simplify the process, the treatment is added to the best performing alternatives, in terms of global warming potential stated above. This means that the initial design for the deck is merged with the alternative design of the railing. As for the superstructure, only the initial design was modeled in the software and therefore is used to maintain consistency in the comparison.

General Assumptions for Transportation for Stage A-D for Heat Treatment

The exact amount of energy used in the heating processes have not been found, however EPD:s of heat-treated product shows a relatively large impact in the production phase compared to untreated timber, showcasing that the process entails additional impacts. Data obtained from one manufacturer of heat-treated timber demonstrates that the temperature should reach 100 degrees during the first 5 hours and then up to around 130 degrees for 13 hours (Thermowood, n.d). For the last 9 hours of heating the temperature goes up to 212 degrees and remains at that temperature for 3 additional hours. After more than 24 hours of heating, the timber products are cooled down for 9 hours. The heating process occurs in an oxygen-free environment, and the study assumes that the ovens for the heat treatment can handle around 20 m^3 timber products per heating process. The illustraded process can be seen in Figure 4.11.

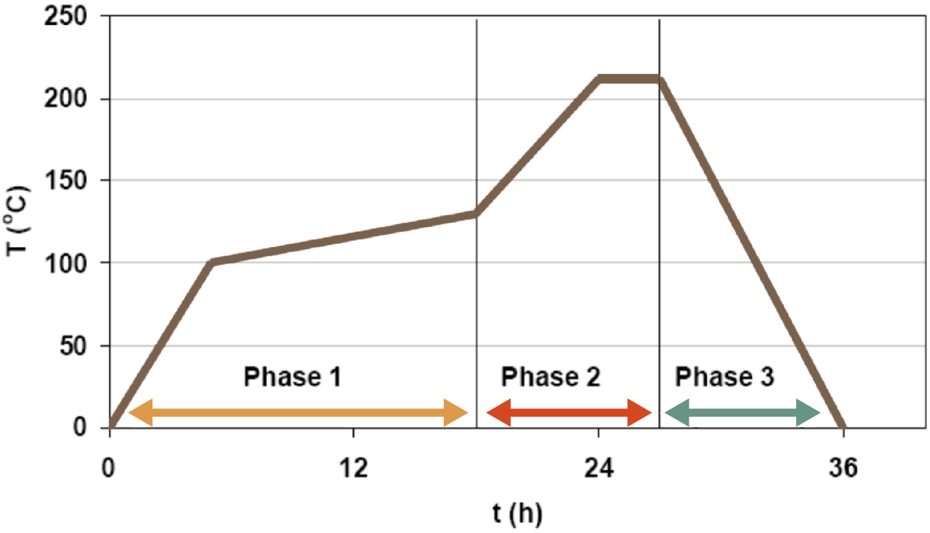


Figure 4.11. Process of heat treatment. Retrieved from heatwood.se

Total Energy Consumption

Based on calculations found in appendix B the total energy used per cubic meter is 350 kWh/m3 for heating the timber. However, based on comparisons with other EPDs, such as one published by the manufacturer Moelven (Moelven, 2025), the impacts reported for stages A1–A3 are significantly higher than the values presented here, Table 4.2. To compensate for additional processes involved, the study uses a value 800 kWh/ m^3.

Table 4.2. Process data for heat treatment with total energy

Temperature	Hours	Process	Energy Total
[°C]	[h]	-	[kWh/m^3]
0–100	5	Heating	800
100–130	13	Heating	
130–212	9	Heating	
212–0	9	Cooling	

General Assumptions for the Design

To compensate for the loss in strength during the heat treatment, the load-bearing parts have been redesigned with some complementary steel. This adjustment solely involves the railing and its timber posts. All other parts are identical to the previous designs.

For all other member, are assumed the same dimensions although the available heat-treated timber products might be more limited compared to pressure treated. This aspect has been disregarded for simplification.

Replacements, Maintenance and Potential Recycling

As stated in the literature study the technical service life of heat-treated timber varies between manufacturers. To give a reliable result, independent of manufacturer, the study set an average between these sources giving a general reduction in number of replacements as for the pressure treated timber.

According to one manufacturer the heat-treated lumber does not require maintenance to withhold its durability. However, surface treatment is needed to keep the original appearance of the wood. (Lunawood, n.d.). The treatment begins with a double application of oil to the wood, followed by additional applications as needed. Since the need is primarily aesthetic, heat-treated lumber is assumed to require half as many oil treatments as pressure-impregnated wood.

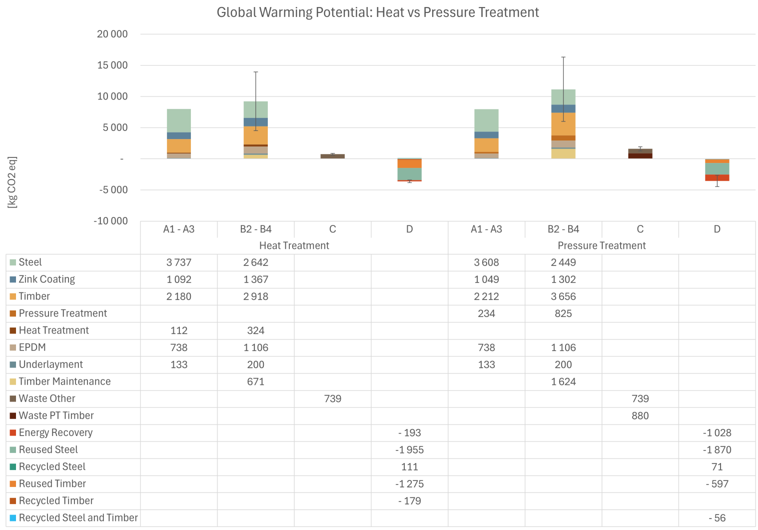
The potential for recycling lumber improves when pressure treatment is replaced with heat treatment. As for untreated lumber, thermally modified wood can be used for particleboar. However, research shows that the qualities for these particleboards are a bit different when using wood chips from heat treated wood. The result is a particleboard that offers improved water resistance but reduced mechanical strength (Iždinský et al., 2021).

The assumed replacements, and maintenance are also given a max and a minimum rate that will be modelled for a sensitivity analysis equally to the previous designs. These values along with assumptions for recycle potentials are shown in Table 9.34.

4.6.1 Life Cycle Interpretation of the Results - Comparative Assertion-Phase 2

When interpretating the result of the heat-treated timber, it is evident that to be able to state that heat- treatment to be a more sustainable option certain requirements needs to be assured, Figure 4.12.

When isolating the result from the production phase of the railing, the heat-treatment is 15% more impactful than the pressure treated lumber in terms of global warming potentials. When looking at the total the amount of the full bridge the results show a more similar impact from both pressure treated lumber and heat-treated lumber. This might solely indicates that the added impacts are gained by the exchange for steel reinforcement rather than the heat treatment. However, when comparing the results from this study and backtracking the initial phases from EPD:s set for heat treated products, the energy used for the heat treatment would probably be significantly more impactful than what these results shows.

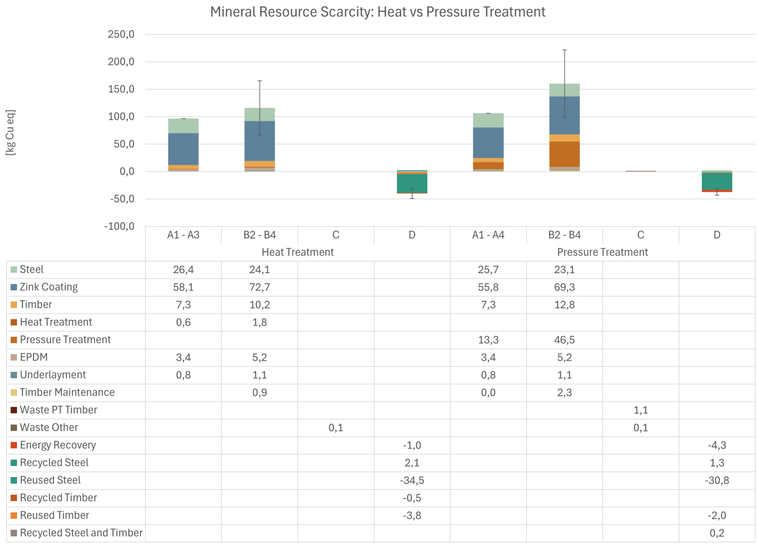


	A1 - A3	B2 - B4	C	D	A1 - A3	B2 - B4	C	D
	Heat Treatment				Pressure Treatment			
■ Steel	3 737	2 642			3 608	2 449		
■ Zink Coating	1 092	1 367			1 049	1 302		
■ Timber	2 180	2 918			2 212	3 656		
■ Pressure Treatment					234	825		
■ Heat Treatment	112	324						
■ EPDM	738	1 106			738	1 106		
■ Underlayment	133	200			133	200		
■ Timber Maintenance		671				1 624		
■ Waste Other			739				739	
■ Waste PT Timber							880	
■ Energy Recovery				- 193				-1 028
■ Reused Steel				-1 955				-1 870
■ Recycled Steel				111				71
■ Reused Timber				-1 275				- 597
■ Recycled Timber				- 179				
■ Recycled Steel and Timber								- 56

Figure 4.12. Results for global warming potential of heat-treated vs. pressure-treated timber for complete bridges, including TRP deck, timber railing, and superstructure.

The largest differences are, as seen in the graph, the impacts from amount of timber in module B2-B4, impacts form the additional pressure treatment process vs heat treatment och the reduction from recycled timber in the heat treatment alternate. The results are inevitably relatively similar.

When looking at the mineral resource depletion, Figure 4.13, and isolating the treated timber in e.i. the deck the result show significant improvements when using heat treatment. Isolated the heat treatment gives a 76% reduction of the kg Cu compared to the pressure treatment and as a total the kg Cu with 20%. This result would also increase slightly if the energy used for heating were to rise, as long as the energy remains fossil-free, the increase is unlikely to be significant enough to produce a noticeable difference.



	A1 - A3	B2 - B4	C	D	A1 - A4	B2 - B4	C	D
	Heat Treatment				Pressure Treatment			
■ Steel	26,4	24,1			25,7	23,1		
■ Zink Coating	58,1	72,7			55,8	69,3		
■ Timber	7,3	10,2			7,3	12,8		
■ Heat Treatment	0,6	1,8						
■ Pressure Treatment					13,3	46,5		
■ EPDM	3,4	5,2			3,4	5,2		
■ Underlayment	0,8	1,1			0,8	1,1		
■ Timber Maintenance		0,9			0,0	2,3		
■ Waste PT Timber							1,1	
■ Waste Other			0,1				0,1	
■ Energy Recovery				-1,0				-4,3
■ Recycled Steel				2,1				1,3
■ Reused Steel				-34,5				-30,8
■ Recycled Timber				-0,5				
■ Reused Timber				-3,8				-2,0
■ Recycled Steel and Timber								0,2

Figure 4.13. Results for mineral resource scarcity of heat-treated vs. pressure-treated timber for complete bridges, including TRP deck, timber railing, and superstructure.

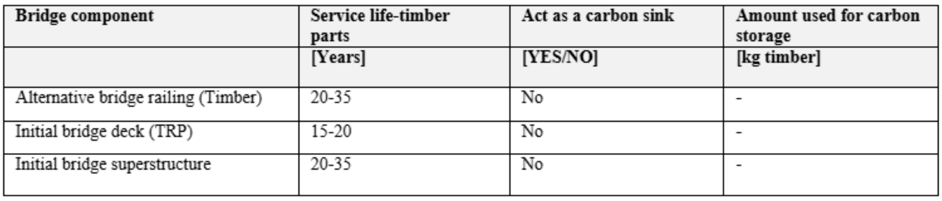
As stated in the literature study an advantage gained by using heat treatment is the fact that it is a natural process without chemicals or heavy metals giving it a better and more natural prospect beyond the service life compared to pressure treatment. Pressure treatment that contains copper and conservatives are not suitable to decay in natural environment as for heat treatment. Heat treated timber has therefore stronger incitement to be considered as a carbon sink.

In conclusion, Module D has some reliability issues due to the number of assumptions. In addition, the information is difficult to apply in comparative studies because Module D is usually not widely available in the industry. As an alternative to module D, carbon storage has been calculated for the comparison between pressure treated and the heat-treated lumber.

4.6.2 Comparative Assertion - Phase 3 - Use Carbon Storage

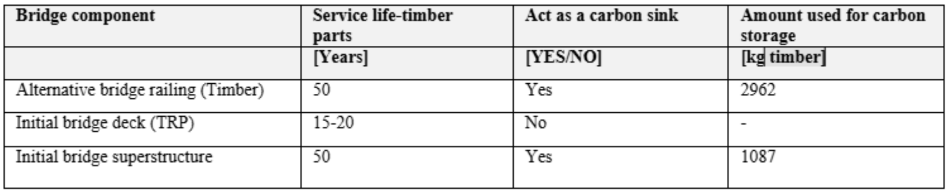
According to the EU certification framework and the goal of ensuring that long-term storage is counted over 35 years. To address this requirement, the study only consider products with a 35+ service life, as carbon sinks.

From Swedish wood's product catalog state that structural timber, untreated with the product standard SS-EN 14081-1, store 773 kg CO_2 per cubic meter. Given a density of 420 kg/m^3, this corresponds to 1.84 kg CO_2 per kg of timber (Svenskt träs produktkatalog, 2025).



Bridge component	Service life-timber parts	Act as a carbon sink	Amount used for carbon storage
	[Years]	[YES/NO]	[kg timber]
Alternative bridge railing (Timber)	20-35	No	-
Initial bridge deck (TRP)	15-20	No	-
Initial bridge superstructure	20-35	No	-

Figure 4.14. Amount of pressure treatment lumber accounted for carbon storage.



Bridge component	Service life-timber parts	Act as a carbon sink	Amount used for carbon storage
	[Years]	[YES/NO]	[kg timber]
Alternative bridge railing (Timber)	50	Yes	2962
Initial bridge deck (TRP)	15-20	No	-
Initial bridge superstructure	50	Yes	1087

Figure 4.15. Amount of heat-treatment lumber accounted for carbon storage.

As seen in the tables above only some of the heat-treated parts were considered as carbon sinks according to these assumptions. The results gathered from this shows as expected that only the heat-treated alternative gets a reduction of its global warming potentials. With this reduction it's clear, see Figure 4.16, that the heat-treated results are better in terms of sustainability when calculating both with module D and with carbon storage.

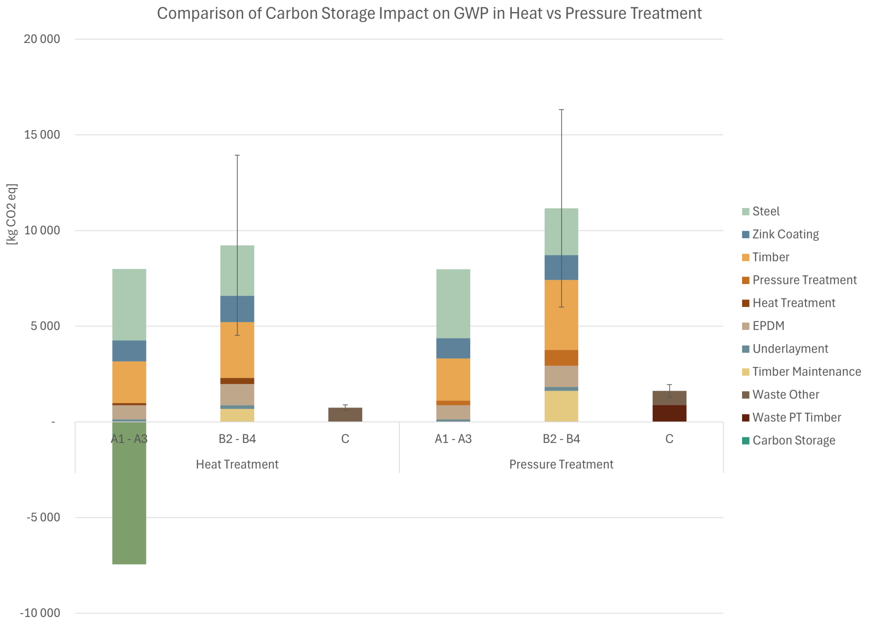


Figure 4.16. Comparison of carbon storage impact on global warming potential (GWP) between heat and pressure treatments. Data includes the superstructure, timber railing, and TRP deck components.

5 Life Cycle Cost Analysis

5.1 Methodology

The life cycle cost analysis in this thesis is based on two key economic metrics: Net Present Value (NPV) and Equivalent Annual Cost (EAC) (EUPAVE, 2018). NPV is used to calculate the total cost of the structure over its entire lifespan, discounted to present value. EAC converts this value into an equivalent yearly cost, allowing for easy comparison between design alternatives. A real discount rate (r) of 3.5% has been applied, following recommendations from Trafikverket (ASEK group, Trafikverket [ASEK], 2024). The analysis period (n) will be 100 years.

Net Present Value (NPV) and Equivalent Annual Cost (EAC) are calculated as follows:

$$\text{NPV} = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \tag{5.1}$$

$$\text{EAC} = \frac{\text{NPV} \cdot r}{1-(1+r)^{-n}} \tag{5.2}$$

Where:

C_t = Cost at year t
r = Discount rate
n = Analysis period (years)
t = Year ($t = 0$ is initial investment)

5.2 System Boundary and Assumptions

The system boundary of the LCCA is based on that of the LCA. The LCCA includes modules A1–A4 and B2–B4, as illustrated in Figure 5.1. Unlike the LCA, stages C and D are not included in the LCCA.

Material costs are accounted for in modules A1–A3, while transportation is accounted for in A4. Modules B2–B4 cover the material costs arising during the service life of the bridge, including replacements, repairs, and maintenance, treated as material exchanges based on the defined assumptions. Labour costs and other costs related to construction, maintenance, or replacement work are not included. Complete data on costs, assumptions, and sources are provided in Appendix B–D.

As in the LCA, transport was assumed to be carried out by a EURO 6 lorry (16–32 tons) with an average load of 11 tons (Lastbilstrafik 2022). Electric trucks consume 1.1 kWh/km (Volvo Trucks, 2023), which corresponds to 0.1 kWh/ton-km. At an electricity price of 3 SEK/kWh (Dagens Infrastruktur, 2025), this results in a transport cost of 0.3 SEK/ton-km. Diesel trucks, on the other hand, consume 0.28 liters/km, and with a diesel price of 18 SEK/liter (Rabe, 2024), this equals 5.04 SEK/km or 0.46 SEK/ton-km (Volvo Trucks, 2023). Assuming a 50/50 mix of electric and diesel transport, the average transport cost was estimated at 0.38 SEK/ton-km.

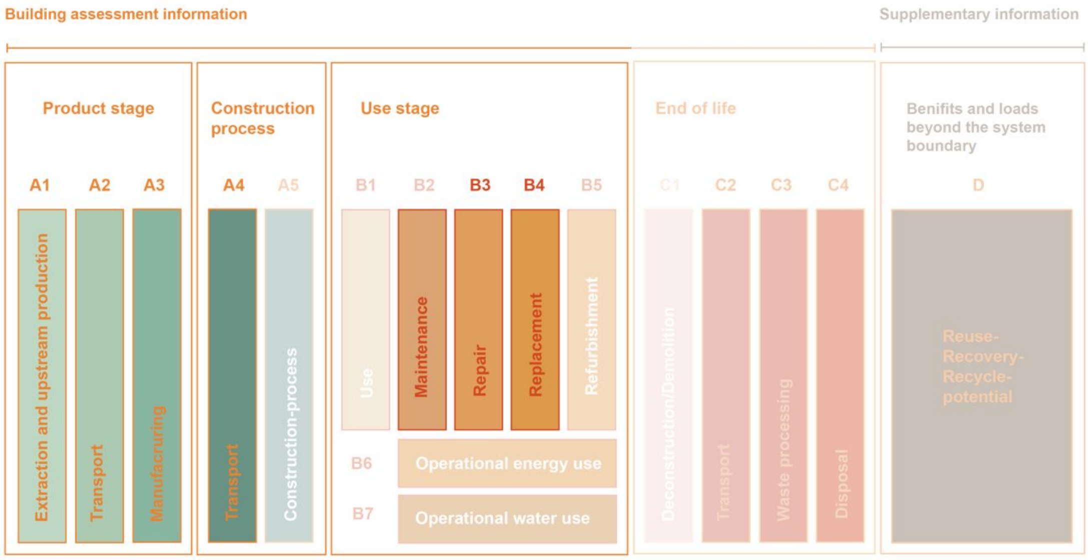


Figure 5.1. Illustration of the life cycle stages according to SS-EN 15978:2011, showing the system boundary applied in the LCCA. Light-shaded stages ,C and D, were included in the LCA but excluded from the LCCA.

The assumptions regarding replacements, repairs, and maintenance, which form the basis for the sensitivity analysis, are provided in Appendix B. This sensitivity analysis explains the range of results shown as error bars, reflecting how variations in these assumptions impact the outcomes.

Due to the linear correlation between the NPV and EAC results, any reference to cost without specifying absolute values applies equally to both measures, making comparisons consistent and valid. When absolute cost values are given, the method used, either NPV or EAC, will be clearly specified.

5.3 Results and Discussion

This section presents the results of the Life Cycle Costing (LCC) analysis performed on the various bridge components. The focus is on evaluating their Net Present Value (NPV) and Equivalent Annual Cost (EAC) to determine cost-effectiveness. The different components are then combined into four distinct bridge combinations, which are analyzed accordingly. In addition, the graphs break down the costs into initial and maintenance categories, illustrating their individual contributions.

Figure 5.2 illustrates the NPV and EAC for each of the components. As expected, the superstructure has the highest cost, with the investment cost ranging between 84% and 98%. The timber railing has the lowest cost by a significant margin compared to the steel railing. Regarding the deck components, the costs are similar, with a slight advantage for the TRP deck. However, due to the sensitivity analysis, maintenance plays an important role in determining which variant is the most cost-effective, since the error bars for the decks overlap in the diagram.

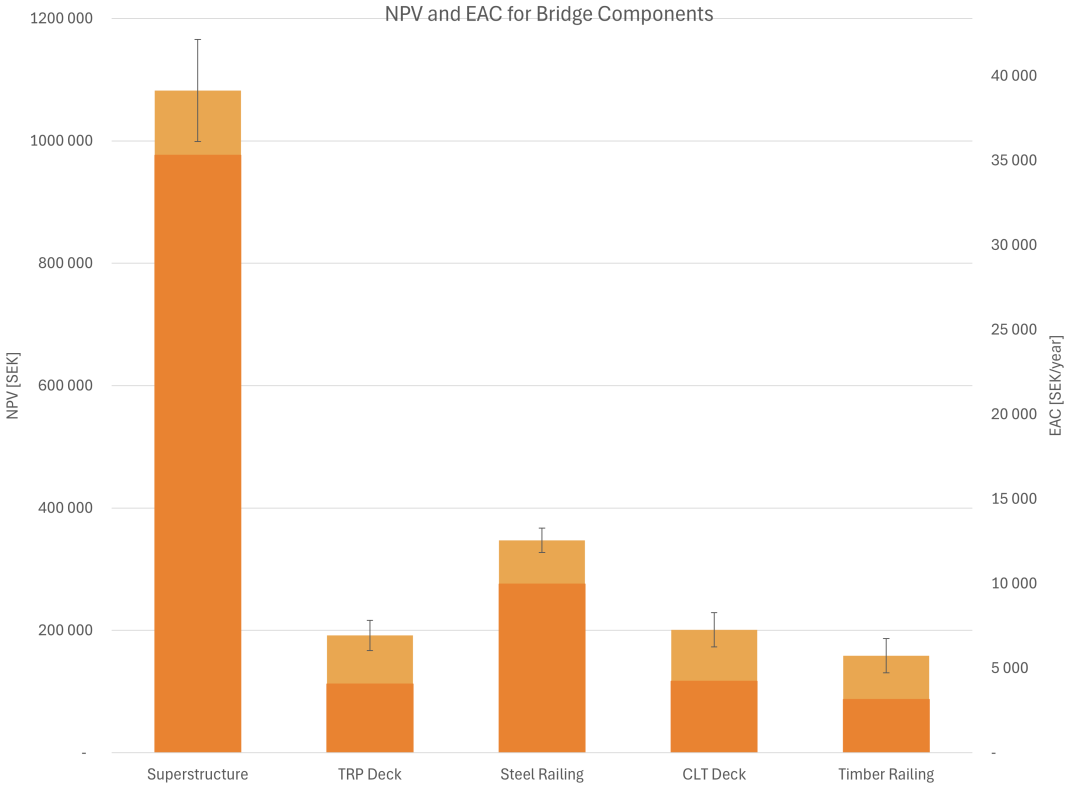


Figure 5.2. Net Present Value (NPV, left y-axis) and Equivalent Annual Cost (EAC, right y-axis) for the different bridge components.

When combining the different components into four complete bridges, the total cost of each bridge can be seen, making it easier to identify the most cost-effective combination, as shown in Figure 5.3. Each bar represents the superstructure together with one deck and railing variant.

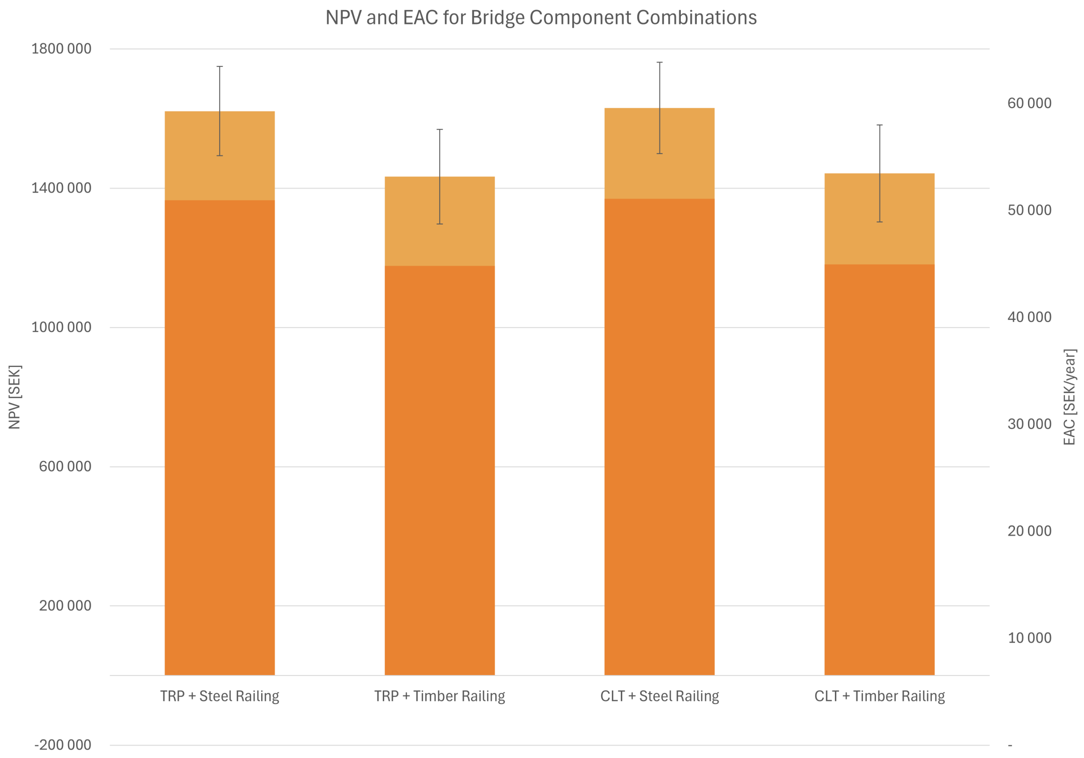


Figure 5.3. NPV and EAC for different bridge component combinations.

Both bridge options containing the timber railing are noticeably cheaper than the others on average, due to the significant cost difference between the two railing types. Since the TRP deck is also less expensive than the CLT deck, the variant with timber railing and TRP deck, represented by bar 2 in the diagram, is the cheapest combination. However, it is worth noting that all the error bars overlap, which means that the bridge's maintenance and other detailed design choices may ultimately determine which combination is the most cost effective in practice.

An LCCA of the heat-treated alternative was not conducted, as in the LCA. If this alternative were to be evaluated further, stainless steel fasteners might also be relevant to examine, as they are sometimes suggested to work well with heat-treated timber. Although heat-treated timber may have higher initial costs due to the processing required and its limited use, its overall cost-effectiveness could still depend on factors such as durability and maintenance. Further studies would therefore be valuable, including an assessment of how stainless steel fasteners might influence the performance and costs of such designs.

6 Weighted and Combined LCA and LCCA Results

This chapter presents a combined performance score, integrating results from both LCA and LCCA, to compare different bridge combinations. The score is based on min–max normalized LCA and LCCA indicators, weighted using two different methods.

6.1 Method and Assumptions

To enable comparison between different combinations of the bridge components, a combined performance score was developed. All LCA indicators, including global warming potential (GWP) , mineral resource scarcity (MRS), and land use (LU), together with the net present value from the LCCA, were min max normalized according to equation (6.1) based on the mean value results. In this normalization, a score of 1 represents the lowest impact or cost, and 0 the highest.

$$\text{Score} = 1 - \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} \tag{6.1}$$

where

- x is the current value,
- x_{min} is the minimum value in the dataset,
- x_{max} is the maximum value in the dataset,
- Score is the normalized value, where 1 means best (lowest original value) and 0 means worst (highest original value).

The normalized results were then grouped into two aggregated categories: an Environmental Score and an Economic Score, calculated for each bridge design. Subsequently, two different weighting approaches were applied: CO_2-focused and equal weighting. The CO_2-focused weighting was considered reasonable since CO_2 emissions are commonly used as a key indicator in environmental assessments, and because factors such as mineral resource scarcity and land use are generally less critical in the given context. Table 6.1 presents the internal weighting of the environmental indicators for each case.

Table 6.1. Weights assigned to environmental impact indicators under CO_2-focused and equal weighting approaches.

	GWP	MRS	LU
CO_2-focused	0,70	0,20	0,10
Equal Weighting	0.33	0.33	0.33

Note. GWP = Global Warming Potential, LU = Land Use, MRS = Mineral Resource Scarcity.

These environmental scores were then combined with the economic score to calculate the total performance for each bridge design, as shown in Table 6.2.

Table 6.2. Weights assigned to the Environmental and Economic Scores under the CO_2-focused and Equal Weighting approaches.

	Environmental Score	**Economical Score**
CO_2-focused	0,8	0,2
Equal Weighting	0,5	0,5

Note. GWP = Global Warming Potential, LU = Land Use, MRS = Mineral Resource Scarcity.

A sensitivity analysis was conducted by systematically varying the weightings of environmental and economic indicators (step size 0.01), calculated using Matlab, to examine how different assumptions affect the selection of the preferred bridge design. This approach helps verify that the predefined weighting schemes do not produce uniquely favorable outcomes with low likelihood, placing the main results into a broader context.

6.2 Results and Discussion

The normalized environmental and economic scores for each bridge combination are summarized in Table 6.3. These scores range from 0 (highest impact or cost) to 1 (lowest impact or cost).

Table 6.3. Normalized performance scores for different bridge combinations across environmental and economic indicators. Scores are not weighted. The “Sum (no weighting)” row shows the direct sum of the normalized scores and is therefore not itself normalized.

Indicator	TRP + Steel Railing	TRP + Timber Railing	CLT + Steel Railing	CLT + Timber Railing
NPV	0.05	1.00	0.00	0.95
GWP	0.79	1.00	0.00	0.21
LU	1.00	0.52	0.48	0.00
MRS	0.00	0.14	0.86	1.00
Sum (no weighting)	**1.83**	**2.65**	**1.35**	**2.17**

Note. GWP = Global Warming Potential, LU = Land Use, MRS = Mineral Resource Scarcity.

The environmental and economic performance of the bridge combinations was evaluated under two weighting strategies, as illustrated in Figure 6.1.

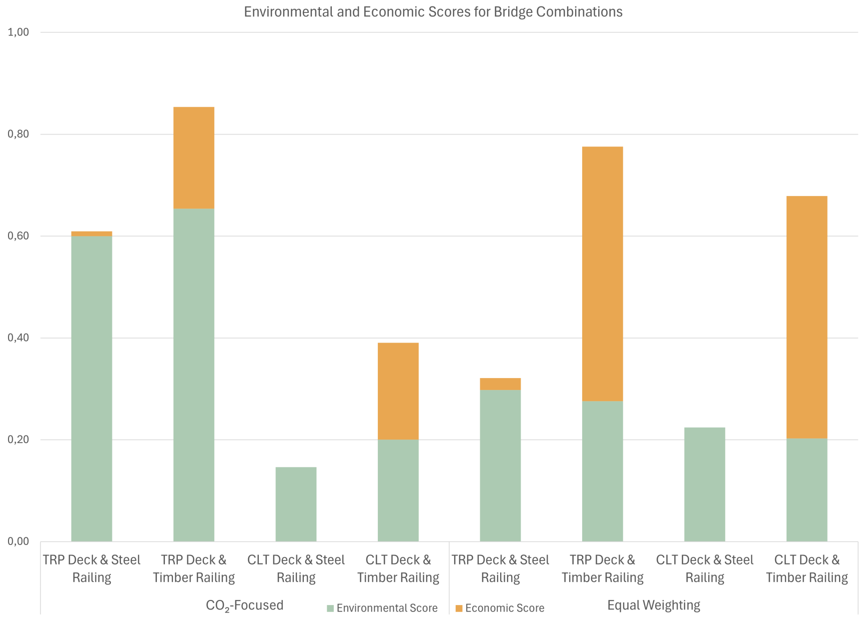


Figure 6.1. Environmental and economic performance scores for bridge combinations, evaluated under two weighting strategies: CO_2-focused and equal weighting. Higher scores indicate better relative performance.

Under both the CO_2-focused and equal weighting scenarios, the TRP Deck and Timber Railing combination achieves the highest overall scores, driven by a strong environmental score from the TRP deck and a comparatively high economic score from the timber railing. This results in the highest combined total among all bridge options. In contrast, the CLT Deck and Steel Railing consistently receives the lowest scores in both environmental and economic categories, leading to the lowest overall ranking. Timber railing combinations generally have higher economic scores than their steel railing counterparts across both deck types, especially under equal weighting where economic factors are emphasized. These findings highlight how the balance between environmental and economic weightings affects the preferred bridge combination, underlining the importance of weighting choices in the selection process.

Regarding the sensitivity analysis, Table 6.4 presents the percentage of weighting combinations for which each bridge type yields the highest total score. The TRP Deck and Timber Railing performs best overall, emerging as the top alternative in 68% of all evaluated scenarios. This confirms that the results shown in Figure 6.1 are consistent with the broader findings of the sensitivity analysis.

Table 6.4. Percentage of winning scores for each bridge combination with different weightings (step size 0.01) in the sensitivity analysis.

Bridge Type	**Winning Percentage [%]**
TRP Deck & Steel Railing	7
TRP Deck & Timber Railing	68
CLT Deck & Steel Railing	1
CLT Deck & Timber Railing	24

As shown in Table 6.4, the most favorable bridge configuration combines the timber railing with the trapezoidal plate. A visualization below, Figure 6.2, illustrates how the bridge could appear within its intended context. In this design configuration, the chosen deck and railing alternative is paired with the superstructure with outward-inclined compression struts, based on the assumption that this design would contribute to a more stable global structural system.

Figure 6.2. Perspective from the bridge entrance.

7 Discussion

The number of decisions made throughout the research process may have influenced the outcomes of this study. The following discussion addresses the margins of error in the given assumptions and explores potential implications of the results.

7.1 The structural investigation

As previously stated during the design of the deck and the load-bearing components, both the CLT plate and the trapezoidal plate have been well over the dimensions required to obtain their load-bearing capacity. With more precise calculations of how much these elements contribute to the overall stiffness of the bridge, the thickness of both elements could potentially be reduced. For the CLT this would have been a reduction of foremost global warming potential and land use as well as the material price. However, according to the results, the impact on mineral resource scarcity would be minimal. For the trapezoidal plate, the difference across all impact categories would be substantial, as the use of a 1 mm thick plate results in a 43% higher impact compared to a 0.7 mm plate, due to the increased cross-sectional area (1520 mm^2 vs. 1060 mm^2)

The steel and timber elements, in the railing, were designed with different centre-to-centre distances to account for their respective material strength properties while maintaining practical cross-sectional dimensions. The design was conducted in coherence with aesthetically principles to complement the characteristics of each specific material. The dimensions of the steel components were primarily determined by structural requirements and available prefabricated and financially viable designs. Whereas the timber railing incorporated redundance of some elements, such as pickets for primarily aesthetic purposes. These design choices may have influenced the results. However, they do reflect realistic design considerations that probably would have been applied in practical applications.

To optimize the superstructure of the bridge where in the end neglected due to the amount of inflicting and conflicting structural investigations that haven't yet been examined. The study only included static investigation, and the dynamic impacts are too important to complete disregarding, meaning that the design is still in a conceptual state. The decision was made to not make a too thorough LCA on elements of the superstructure due to the significant uncertainties affecting the reliability of the results.

7.2 Assumptions made in life cycle inventory, A-C

The study estimated replacement rates based on the experience of our supervisors at TBS. For simplicity, the entire deck was assumed to be replaced according to the service life of either the CLT plate or the trapezoidal plate. Consequently, some materials, such as the EPDM rubber and the underlayment, were replaced as frequently as the structural components to ensure their durability was not compromised. This approach resulted in different numbers of replacements for the same materials across the alternatives

The contribution from these products is therefore higher for the CLT, that has more frequent anticipated replacements, then for the trapezoidal plate. As previously discussed, the technical service life of the CLT is estimated to be 30-50 years, although ongoing research suggests that its lifespan may be significantly longer. Consequently, if this extended service life would be confirmed, the CLT alternative would demonstrate better material efficiency, both in terms of timber usage and associated materials. If, the CLT then would be a better alternative then the trapeziodal plate, goes uncertain. Yet, given the relatively small difference within the error margins when considering the minimum number of replacements, the results still suggest that the CLT and trapezoidal plate would exhibit similar impacts on global warming potential, even when assuming an extended service life for the CLT.

When modelling a life cycle assessment many assumptions have to be made. These assumptions include a certain degree of error depending on e.g. access to specific datasets for local production or waste management, assumptions made for transportation distances and methods and so on. Another scenario arises when no exact dataset is available for a material, requiring it to be modeled manually. In this report it has been addressed by combining available datasets with assumptions regarding the quantity of each material. It has been done for the pressure treated lumber and the heat treatment as well as for the general treatment of lumber in the maintenance phase. The EPDM rubber and the underlayment have been assigned dataset the almost resemble the products, however, cannot be complete accurately for a specific manufacturer. Margins of errors is therefore expected from these products and as stated in each section. With regard to the life cycle assessment of the heat treatment process, available sources indicating energy consumption have been limited. When compared with Environmental Product Declarations provided by manufacturers, it becomes evident that the energy input used in this study may have been underestimated. This could have indicated a more favourable outcome than what reflects reality. In addition, all manufacturer state completely different service life for their products which immediately introduce a certain degree of uncertainty.

7.3 Assumptions made in life cycle inventory, D

Module D entails future assumptions and is therefore subject to an even greater margin of error. The results should be interpreted with this uncertainty in mind.

The study might also have been generous when modelling future management of end-of-life products. The timber had e relative low level of pure waste and a generous reuse potential for glulam. The assumptions followed the cascade model, meaning the timber products were assumed to take on new uses with lower structural requirements after their initial service life. The outdoor conditions that might impact the reuse and recyclability, was on the other hand, not considered when making these assumptions.

For the steel the report has assumed full recyclability and reuse and no waste which might have been generous as well when considering the outdoor conditions, that might influence the steel durability in terms of rust. Studies made by SGU shows that the extraction of iron and zinc still has a large proportion of newly produced goods (SGU, 2022). Naturally, this is also influenced by how much demand there is and if it outweighs the current supply of recycled steel.

Given the more natural characteristics of heat treatment compared to pressure treatment, it was assumed that the entire material could be directed to recycling The study relied on studies showing the possibilities of recycling, yet no exact references indicate how widespread it is currently on the Swedish market.

When including module D in a life cycle assessment, it might be both less credible and harder to use when compared to other studies. Not only due to the viability from the many assumptions but also due to the lack of material in the field to compare with. To avoid this matter, this study focused on comparing within itself. However, it still encountered certain challenges in this regarding these uncertainties. By completely excluding Module D and accounting for carbon storage in the viable timber currently used in the bridge, a more fair and easy interpretation of the results were made.

8 Conclusion

This thesis has provided insights that may serve as a foundation for the field and offer inspiration for future research.

The study demonstrated the importance of the right material in the right position but also gives a nuanced view of e.i. how it is affected by several factors, in form of subcategories within the material and how it is received over time.

As expected, the study supports the indications that trapezoidal plate is being material efficient and thereby often a good alternative whilst alternatives with solid steel as for the RHS is usually not a better alternative, despite the longer expected service life.

When other factors, such as carbon storage, are included, the environmental reasoning for choosing steel changes significantly. Along with the life cycle costing the study further demonstrates that it might not even be the most financially beneficial alternative. By investigating various alternatives, it is apparent that each design is dependent on its material. The exact amount and which present and future challenges and opportunities that they might meet varies and determine the full perspective.

As for the answer to the examined research question the largest contributing factors that influence the environmental impacts and cost-effectiveness of a timber bridge is found in the main load-bearing system and the deck. Therefore, optimizing these components should be considered the primary focus. However, although the railing accounts for less than half the impact of the other two components, its less demanding requirements make it more amenable to modification and should thereby not be overlooked.

How these components or elements can be modified to achieve better results is through material efficiency, which benefits both environmental impacts and costs. The most notable result in the LCCA was the significant cost difference between timber and steel railings. Although the steel railing showed slightly lower variance in the error bars, which can be considered reasonable due to its lower maintenance needs, this did not compensate for its considerably higher initial investment cost.

When aggregating all bridge components into the different bridge combinations, maintenance costs appear to determine which combination is the most cost-effective. However, if the investment costs, meaning the amount of material, were reduced, there could be cases where one bridge combination clearly has the lowest cost regardless of maintenance requirements.

Regarding whether a carbon-negative assessment of timber in the LCA would influence the bridge design, the answer is both yes and no. Since carbon storage is calculated over the full lifespan of a tree, the carbon-negative effect is nearly twice as high mass as for the mass of timber used. Therefore, it could be suggested to add more timber and go against material efficiency to be more carbon negative. Encouraging the use of more material than necessary may also have broader implications, potentially contributing to unsustainable forestry practices or occupying land that could otherwise support uses more beneficial to biodiversity.

9 References

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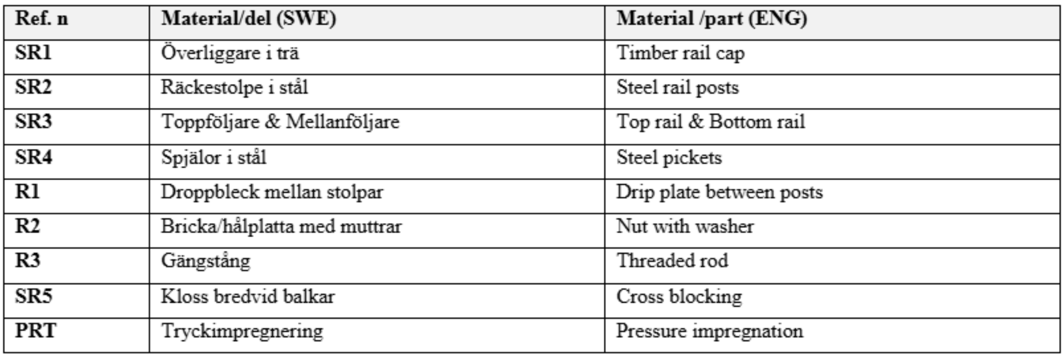
Appendix A- Vocabulary

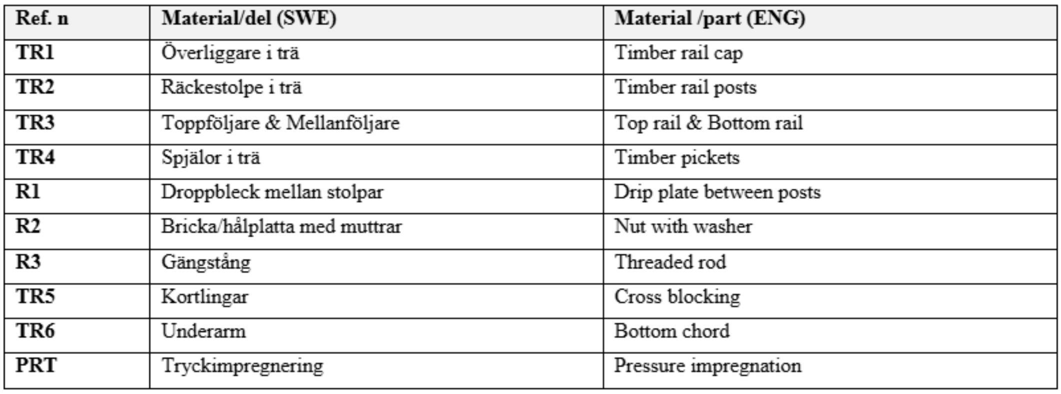
Table 9.1. Steel railing



Ref. n	Material/del (SWE)	Material /part (ENG)
SR1	Överliggare i trä	Timber rail cap
SR2	Räckestolpe i stål	Steel rail posts
SR3	Toppföljare & Mellanföljare	Top rail & Bottom rail
SR4	Spjälor i stål	Steel pickets
R1	Droppbleck mellan stolpar	Drip plate between posts
R2	Bricka/hålplatta med muttrar	Nut with washer
R3	Gängstång	Threaded rod
SR5	Kloss bredvid balkar	Cross blocking
PRT	Tryckimpregnering	Pressure impregnation

Note. SRX= Steel railing+ numbering, RX= Shared railing+ numbering

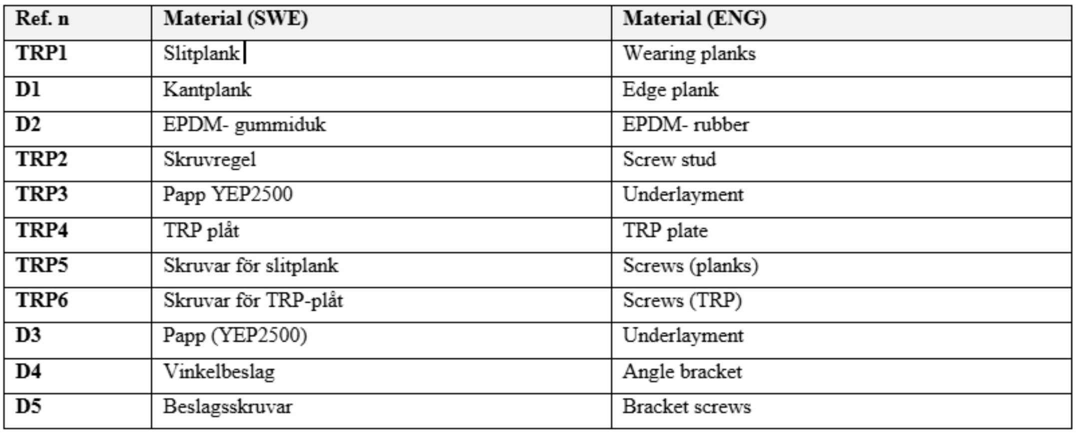
Table 9.2. Timber railing



Ref. n	Material/del (SWE)	Material /part (ENG)
TR1	Överliggare i trä	Timber rail cap
TR2	Räckestolpe i trä	Timber rail posts
TR3	Toppföljare & Mellanföljare	Top rail & Bottom rail
TR4	Spjälor i trä	Timber pickets
R1	Droppbleck mellan stolpar	Drip plate between posts
R2	Bricka/hålplatta med muttrar	Nut with washer
R3	Gängstång	Threaded rod
TR5	Kortlingar	Cross blocking
TR6	Underarm	Bottom chord
PRT	Tryckimpregnering	Pressure impregnation

Note. TRX=Timber railing + numbering, RX= Shared railing+ numbering

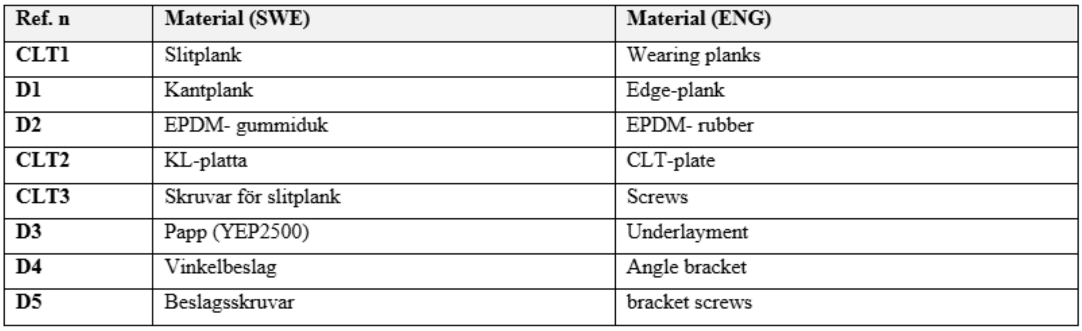
Table 9.3. Deck with trapezoidal plate



Ref. n	Material (SWE)	Material (ENG)
TRP1	Slitplank	Wearing planks
D1	Kantplank	Edge plank
D2	EPDM- gummiduk	EPDM- rubber
TRP2	Skruvregel	Screw stud
TRP3	Papp YEP2500	Underlayment
TRP4	TRP plåt	TRP plate
TRP5	Skruvar för slitplank	Screws (planks)
TRP6	Skruvar för TRP-plåt	Screws (TRP)
D3	Papp (YEP2500)	Underlayment
D4	Vinkelbeslag	Angle bracket
D5	Beslagsskruvar	Bracket screws

Note. TRPX=TRP-plate+ numbering, DX= Shared deck components + numbering

Table 9.4. Deck with cross-laminated plate



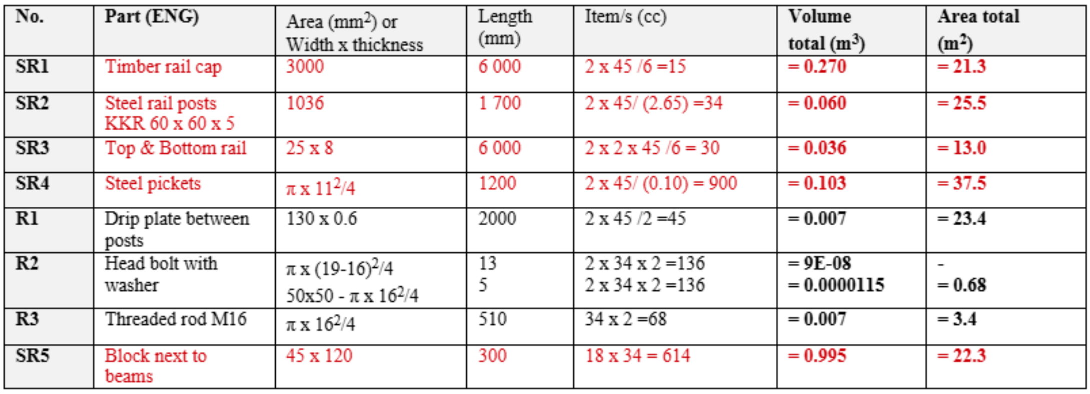
Ref. n	Material (SWE)	Material (ENG)
CLT1	Slitplank	Wearing planks
D1	Kantplank	Edge-plank
D2	EPDM- gummiduk	EPDM- rubber
CLT2	KL-platta	CLT-plate
CLT3	Skruvar för slitplank	Screws
D3	Papp (YEP2500)	Underlayment
D4	Vinkelbeslag	Angle bracket
D5	Beslagsskruvar	bracket screws

*Note.*KLX=TKL-plate + numbering, DX= Shared deck components + numbering

Appendix B- Inventory and Tables

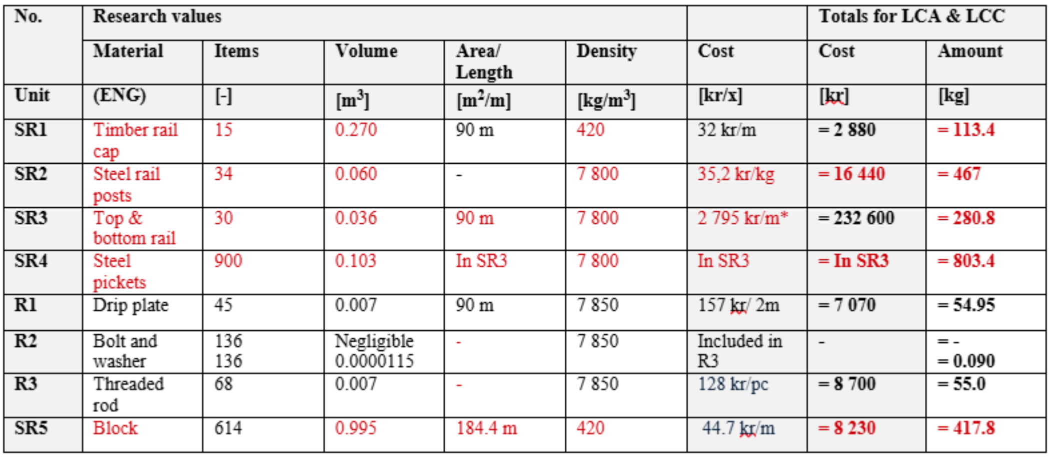
Bridge Railing - Initial Design (Steel)

Table 9.5. Initial bridge volumes: steel railing



No.	Part (ENG)	Area (mm^2) or Width x thickness	Length (mm)	Item/s (cc)	Volume total (m^3)	Area total (m^2)
SR1	Timber rail cap	3000	6 000	2 x 45 /6 =15	= 0.270	= 21.3
SR2	Steel rail posts KKR 60 x 60 x 5	1036	1 700	2 x 45/ (2.65) =34	= 0.060	= 25.5
SR3	Top & Bottom rail	25 x 8	6 000	2 x 2 x 45 /6 = 30	= 0.036	= 13.0
SR4	Steel pickets	π x 11^2/4	1200	2 x 45/ (0.10) = 900	= 0.103	= 37.5
R1	Drip plate between posts	130 x 0.6	2000	2 x 45 /2 =45	= 0.007	= 23.4
R2	Head bolt with washer	π x (19-16)^2/4 50x50 - π x 16^2/4	13 5	2 x 34 x 2 =136 2 x 34 x 2 =136	= 9E-08 = 0.0000115	- = 0.68
R3	Threaded rod M16	π x 16^2/4	510	34 x 2 =68	= 0.007	= 3.4
SR5	Block next to beams	45 x 120	300	18 x 34 = 614	= 0.995	= 22.3

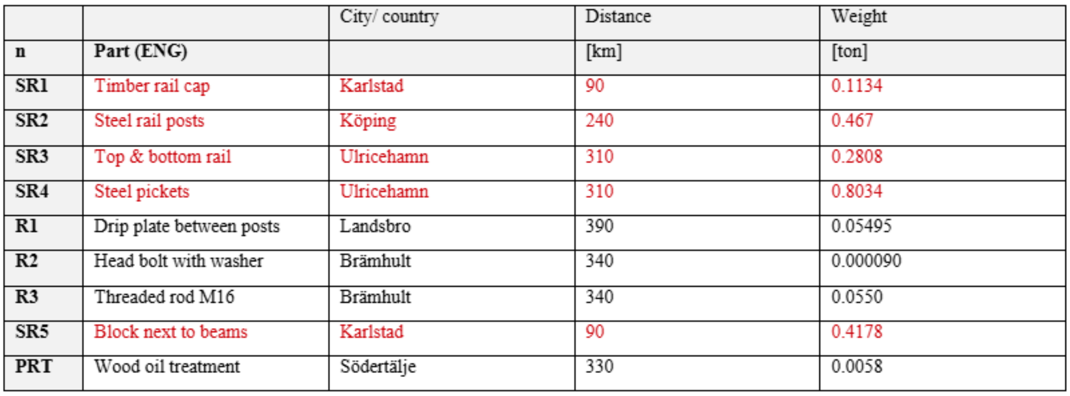
Table 9.6. Inventory initial bridge: steel railing



No.	Research values						Totals for LCA & LCC	
	Material	Items	Volume	Area/ Length	Density	Cost	Cost	Amount
Unit	(ENG)	[-]	[m^3]	[m^2/m]	[kg/m^3]	[kr/x]	[kr]	[kg]
SR1	Timber rail cap	15	0.270	90 m	420	32 kr/m	= 2 880	= 113.4
SR2	Steel rail posts	34	0.060	-	7 800	35,2 kr/kg	= 16 440	= 467
SR3	Top & bottom rail	30	0.036	90 m	7 800	2 795 kr/m*	= 232 600	= 280.8
SR4	Steel pickets	900	0.103	In SR3	7 800	In SR3	= In SR3	= 803.4
R1	Drip plate	45	0.007	90 m	7 850	157 kr/ 2m	= 7 070	= 54.95
R2	Bolt and washer	136 136	Negligible 0.0000115	-	7 850	Included in R3	-	= - = 0.090
R3	Threaded rod	68	0.007	-	7 850	128 kr/pc	= 8 700	= 55.0
SR5	Block	614	0.995	184.4 m	420	44.7 kr/m	= 8 230	= 417.8

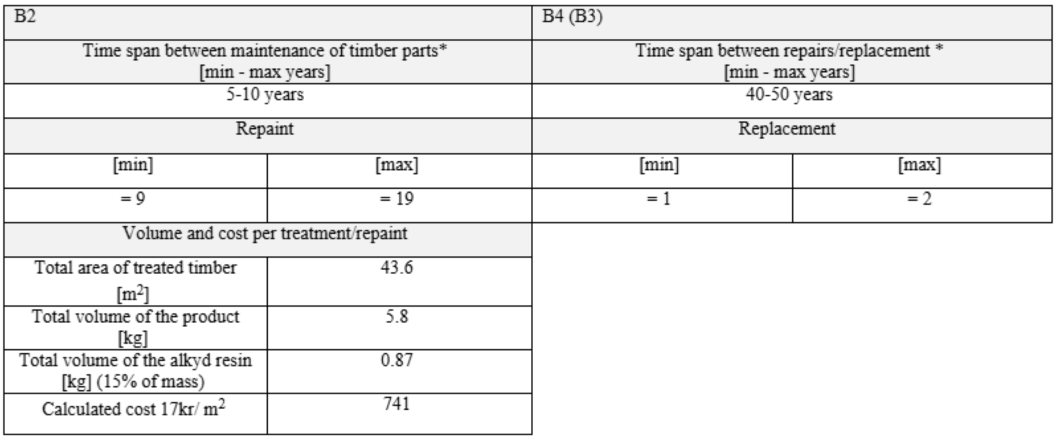
Note: the column "area total" comprises various kinds of areas depending on the material and what the area is needed for. In steel products it means all the volumes complete surface area since we need it as an input for the hot-dip galvanization in OpenLCA. The same goes for exposed timber parts that will need maintenance by oiling the surface area. The included areas are depended on the reachability of the surfaces. For the layered products such as underlayment and EPDM as well as the TRP the area is the out-layer surface since this is the unit that determines the cost for these products.

Table 9.7. Bridge railing transport for stage A4, B2 and B4



		City/ country	Distance	Weight
n	**Part (ENG)**		[km]	[ton]
SR1	Timber rail cap	Karlstad	90	0.1134
SR2	Steel rail posts	Köping	240	0.467
SR3	Top & bottom rail	Ulricehamn	310	0.2808
SR4	Steel pickets	Ulricehamn	310	0.8034
R1	Drip plate between posts	Landsbro	390	0.05495
R2	Head bolt with washer	Brämhult	340	0.000090
R3	Threaded rod M16	Brämhult	340	0.0550
SR5	Block next to beams	Karlstad	90	0.4178
PRT	Wood oil treatment	Södertälje	330	0.0058

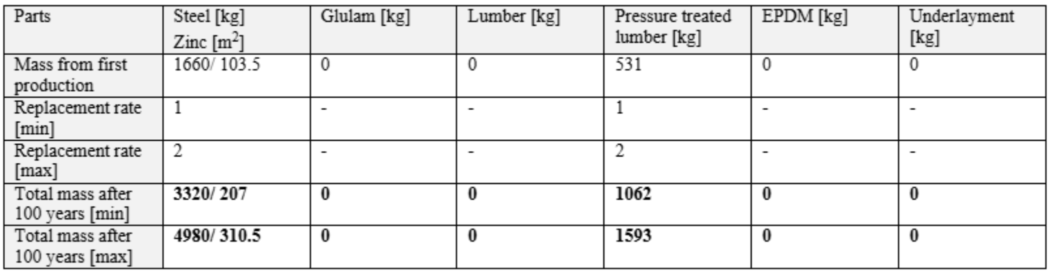
Table 9.8. Steel railing end of life



B2		B4 (B3)	
Time span between maintenance of timber parts* [min - max years]		Time span between repairs/replacement * [min - max years]	
5-10 years		40-50 years	
Repaint		Replacement	
[min]	[max]	[min]	[max]
= 9	= 19	= 1	= 2
Volume and cost per treatment/repaint			
Total area of treated timber $[m^2]$	43.6		
Total volume of the product [kg]	5.8		
Total volume of the alkyd resin [kg] (15% of mass)	0.87		
Calculated cost 17kr/ m^2	741		

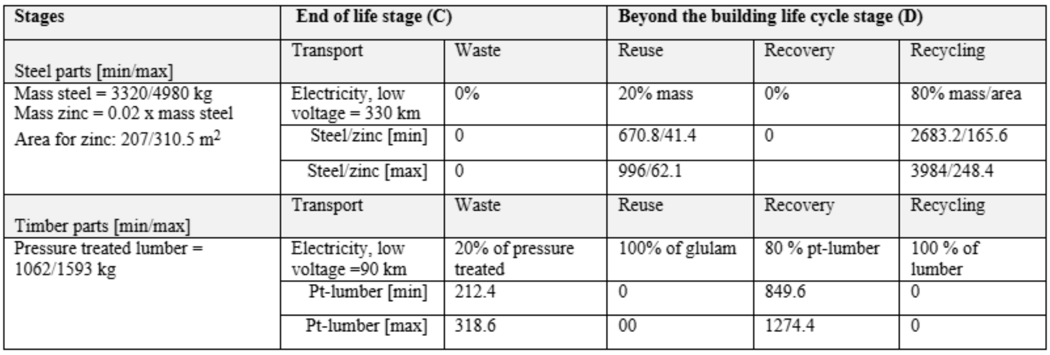
*Note.**Time span between repairs/replacement retrieved by consultation with TBS

Table 9.9. Mass over 100 years



Parts	Steel [kg] Zinc $[m^2]$	Glulam [kg]	Lumber [kg]	Pressure treated lumber [kg]	EPDM [kg]	Underlayment [kg]
Mass from first production	1660/ 103.5	0	0	531	0	0
Replacement rate [min]	1	-	-	1	-	-
Replacement rate [max]	2	-	-	2	-	-
Total mass after 100 years [min]	**3320/ 207**	**0**	**0**	**1062**	**0**	**0**
Total mass after 100 years [max]	**4980/ 310.5**	**0**	**0**	**1593**	**0**	**0**

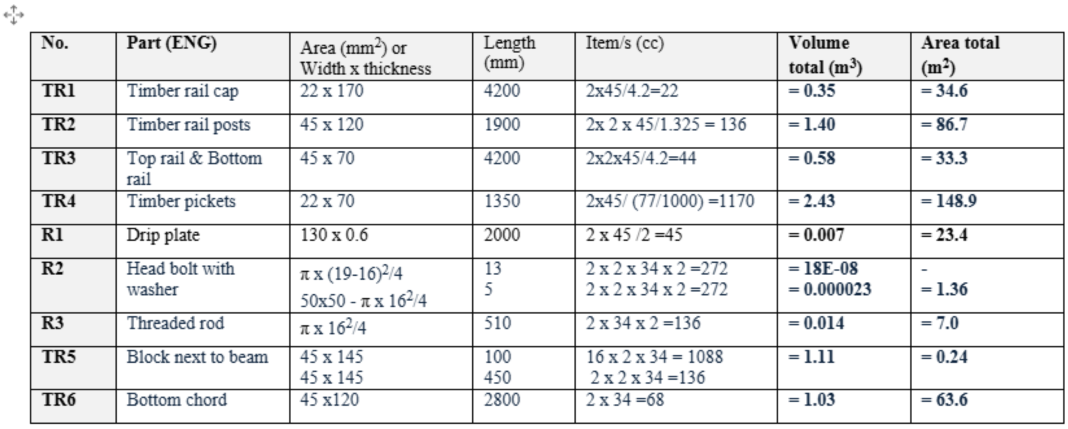
Table 9.10. Bridge railing end of life and beyond



Stages	End of life stage (C)		Beyond the building life cycle stage (D)		
Steel parts [min/max]	Transport	Waste	Reuse	Recovery	Recycling
Mass steel = 3320/4980 kg Mass zinc = 0.02 x mass steel Area for zinc: 207/310.5 m^2	Electricity, low voltage = 330 km	0%	20% mass	0%	80% mass/area
	Steel/zinc [min]	0	670.8/41.4	0	2683.2/165.6
	Steel/zinc [max]	0	996/62.1		3984/248.4
Timber parts [min/max]	Transport	Waste	Reuse	Recovery	Recycling
Pressure treated lumber = 1062/1593 kg	Electricity, low voltage =90 km	20% of pressure treated	100% of glulam	80 % pt-lumber	100 % of lumber
	Pt-lumber [min]	212.4	0	849.6	0
	Pt-lumber [max]	318.6	00	1274.4	0

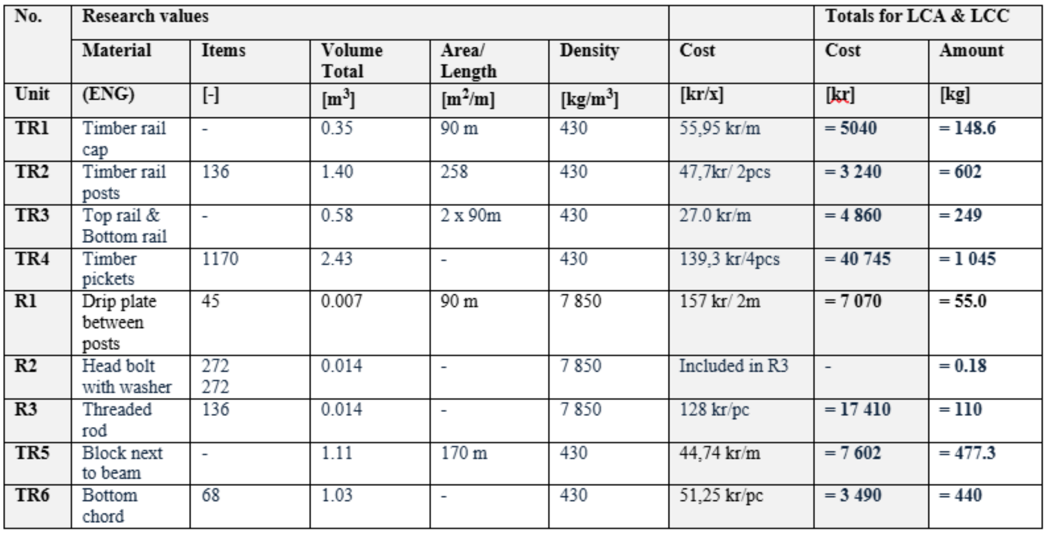
Bridge Railing - Alternative Design (Timber)

Table 9.11. Alternative bridge volumes: timber railing



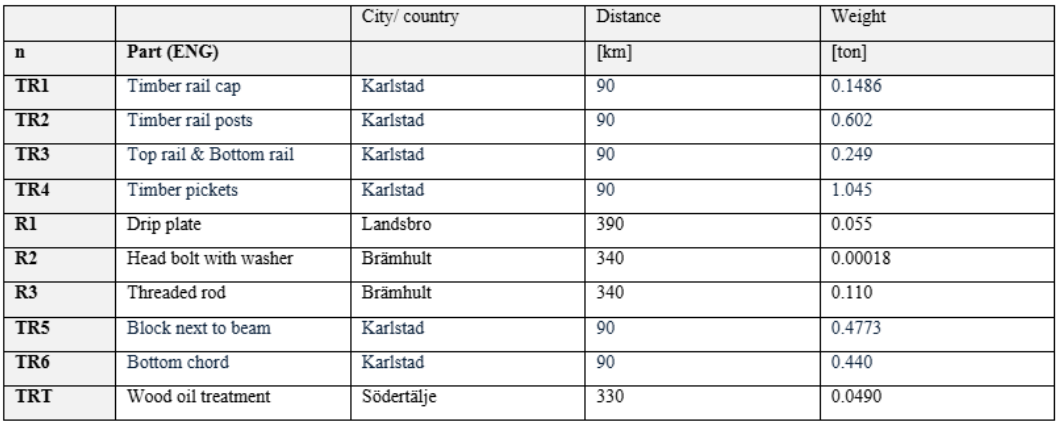
No.	Part (ENG)	Area (mm^2) or Width x thickness	Length (mm)	Item/s (cc)	Volume total (m^3)	Area total (m^2)
TR1	Timber rail cap	22 x 170	4200	2x45/4.2=22	**= 0.35**	**= 34.6**
TR2	Timber rail posts	45 x 120	1900	2x 2 x 45/1.325 = 136	**= 1.40**	**= 86.7**
TR3	Top rail & Bottom rail	45 x 70	4200	2x2x45/4.2=44	**= 0.58**	**= 33.3**
TR4	Timber pickets	22 x 70	1350	2x45/ (77/1000) =1170	**= 2.43**	**= 148.9**
R1	Drip plate	130 x 0.6	2000	2 x 45 /2 =45	**= 0.007**	**= 23.4**
R2	Head bolt with washer	π x (19-16)^2/4 50x50 - π x 16^2/4	13 5	2 x 2 x 34 x 2 =272 2 x 2 x 34 x 2 =272	**= 18E-08** **= 0.000023**	- **= 1.36**
R3	Threaded rod	π x 16^2/4	510	2 x 34 x 2 =136	**= 0.014**	**= 7.0**
TR5	Block next to beam	45 x 145 45 x 145	100 450	16 x 2 x 34 = 1088 2 x 2 x 34 =136	**= 1.11**	**= 0.24**
TR6	Bottom chord	45 x120	2800	2 x 34 =68	**= 1.03**	**= 63.6**

Table 9.12. Inventory alternative bridge: timber railing



No.	**Research values**						**Totals for LCA & LCC**	
	Material	**Items**	**Volume Total**	**Area/ Length**	**Density**	**Cost**	**Cost**	**Amount**
Unit	**(ENG)**	**[-]**	**[m^3]**	**[m^2/m]**	**[kg/m^3]**	**[kr/x]**	**[kr]**	**[kg]**
TR1	Timber rail cap	-	0.35	90 m	430	55,95 kr/m	**= 5040**	**= 148.6**
TR2	Timber rail posts	136	1.40	258	430	47,7kr/ 2pcs	**= 3 240**	**= 602**
TR3	Top rail & Bottom rail	-	0.58	2 x 90m	430	27.0 kr/m	**= 4 860**	**= 249**
TR4	Timber pickets	1170	2.43	-	430	139,3 kr/4pcs	**= 40 745**	**= 1 045**
R1	Drip plate between posts	45	0.007	90 m	7 850	157 kr/ 2m	**= 7 070**	**= 55.0**
R2	Head bolt with washer	272 272	0.014	-	7 850	Included in R3	-	**= 0.18**
R3	Threaded rod	136	0.014	-	7 850	128 kr/pc	**= 17 410**	**= 110**
TR5	Block next to beam	-	1.11	170 m	430	44,74 kr/m	**= 7 602**	**= 477.3**
TR6	Bottom chord	68	1.03	-	430	51,25 kr/pc	**= 3 490**	**= 440**

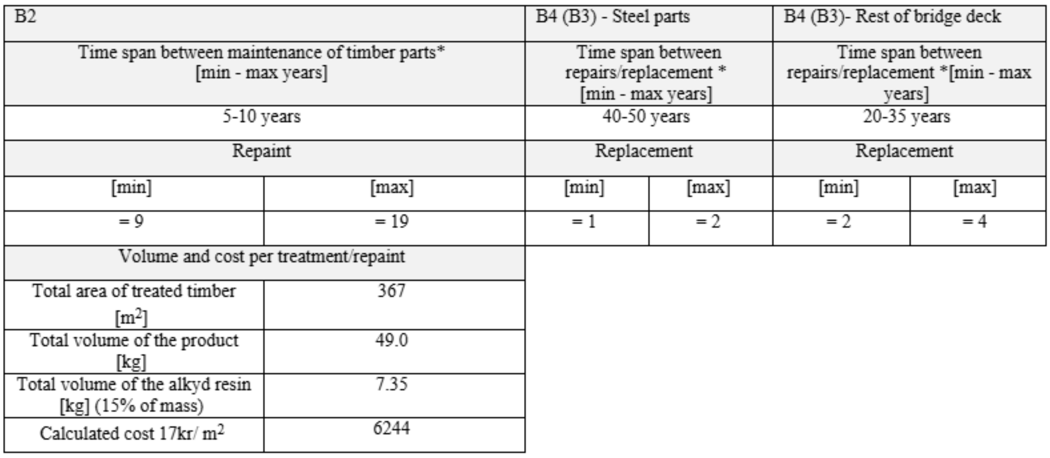
Table 9.13. Bridge railing transport for stage A4, B2 and B4



		City/ country	Distance	Weight
n	**Part (ENG)**		[km]	[ton]
TR1	Timber rail cap	Karlstad	90	0.1486
TR2	Timber rail posts	Karlstad	90	0.602
TR3	Top rail & Bottom rail	Karlstad	90	0.249
TR4	Timber pickets	Karlstad	90	1.045
R1	Drip plate	Landsbro	390	0.055
R2	Head bolt with washer	Brämhult	340	0.00018
R3	Threaded rod	Brämhult	340	0.110
TR5	Block next to beam	Karlstad	90	0.4773
TR6	Bottom chord	Karlstad	90	0.440
TRT	Wood oil treatment	Södertälje	330	0.0490

For B2 and B4, the number of maintenance and replacement processes is assumed and presented in tables per bridge section. For B2, the volume, the area covered by the product and the cost per square meter are calculated. For B4, which to some extent includes B3, we assume that the entire bridge section is replaced at one time including all parts. This assumption does not correspond to a real scenario but is necessary for simplifications.

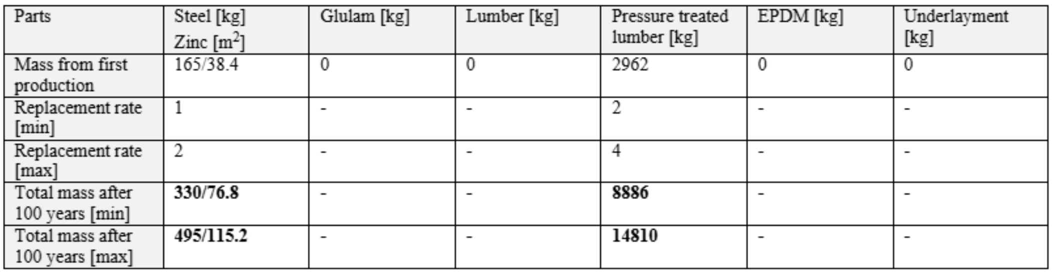
Table 9.14. Timber bridge railing end of life



<table>
<tr><td colspan="2">B2</td><td colspan="2">B4 (B3) - Steel parts</td><td colspan="2">B4 (B3)- Rest of bridge deck</td></tr>
<tr><td colspan="2">Time span between maintenance of timber parts* [min - max years]</td><td colspan="2">Time span between repairs/replacement * [min - max years]</td><td colspan="2">Time span between repairs/replacement *[min - max years]</td></tr>
<tr><td colspan="2">5-10 years</td><td colspan="2">40-50 years</td><td colspan="2">20-35 years</td></tr>
<tr><td colspan="2">Repaint</td><td colspan="2">Replacement</td><td colspan="2">Replacement</td></tr>
<tr><td>[min]</td><td>[max]</td><td>[min]</td><td>[max]</td><td>[min]</td><td>[max]</td></tr>
<tr><td>= 9</td><td>= 19</td><td>= 1</td><td>= 2</td><td>= 2</td><td>= 4</td></tr>
<tr><td colspan="2">Volume and cost per treatment/repaint</td><td colspan="4"></td></tr>
<tr><td>Total area of treated timber [m^2]</td><td>367</td><td colspan="4"></td></tr>
<tr><td>Total volume of the product [kg]</td><td>49.0</td><td colspan="4"></td></tr>
<tr><td>Total volume of the alkyd resin [kg] (15% of mass)</td><td>7.35</td><td colspan="4"></td></tr>
<tr><td>Calculated cost 17kr/ m^2</td><td>6244</td><td colspan="4"></td></tr>
</table>

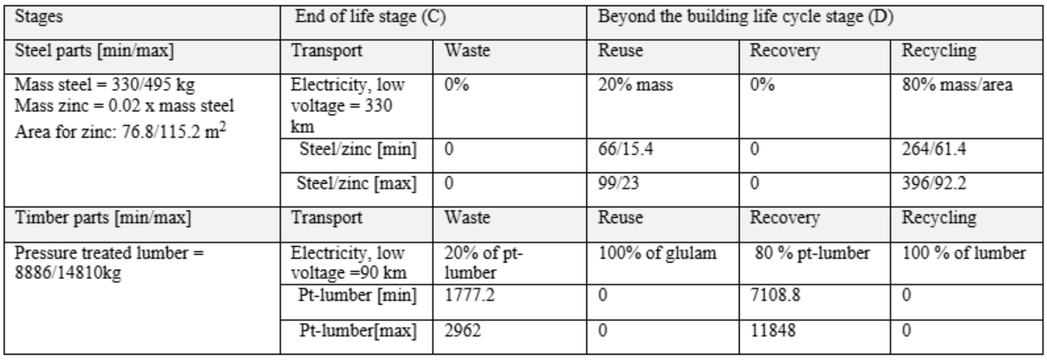
*Time span between repairs/replacement retrieved by consultation with TBS. The steel parts are assumed to replace half the time as the timber as it is for the initial railing.

Table 9.15. Mass over 100 years



Parts	Steel [kg] Zinc [m^2]	Glulam [kg]	Lumber [kg]	Pressure treated lumber [kg]	EPDM [kg]	Underlayment [kg]
Mass from first production	165/38.4	0	0	2962	0	0
Replacement rate [min]	1	-	-	2	-	-
Replacement rate [max]	2	-	-	4	-	-
Total mass after 100 years [min]	**330/76.8**	-	-	**8886**	-	-
Total mass after 100 years [max]	**495/115.2**	-	-	**14810**	-	-

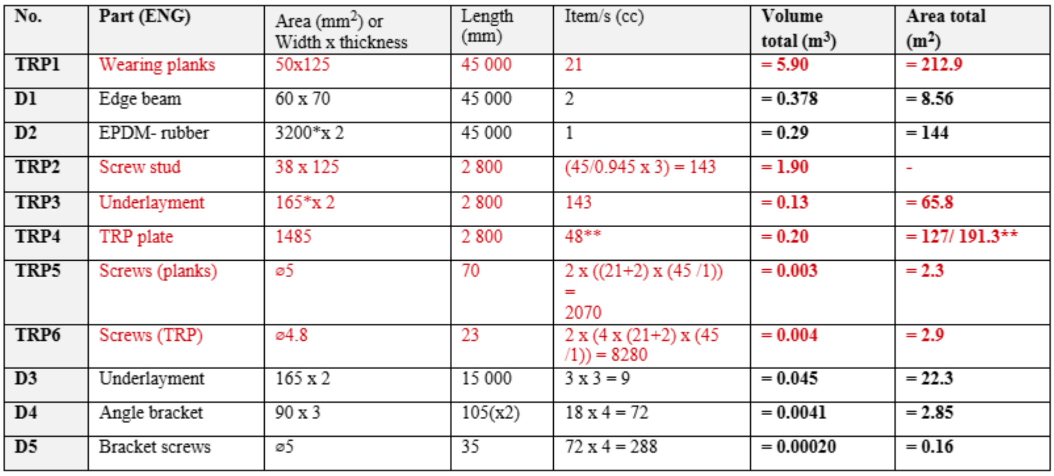
Table 9.16. Timber bridge railing end of life and beyond



Stages	End of life stage (C)		Beyond the building life cycle stage (D)		
Steel parts [min/max]	Transport	Waste	Reuse	Recovery	Recycling
Mass steel = 330/495 kg Mass zinc = 0.02 x mass steel Area for zinc: 76.8/115.2 m^2	Electricity, low voltage = 330 km	0%	20% mass	0%	80% mass/area
	Steel/zinc [min]	0	66/15.4	0	264/61.4
	Steel/zinc [max]	0	99/23	0	396/92.2
Timber parts [min/max]	Transport	Waste	Reuse	Recovery	Recycling
Pressure treated lumber = 8886/14810kg	Electricity, low voltage =90 km	20% of pt-lumber	100% of glulam	80 % pt-lumber	100 % of lumber
	Pt-lumber [min]	1777.2	0	7108.8	0
	Pt-lumber[max]	2962	0	11848	0

Bridge Deck- Initial Design (Trapezoidal Plate)

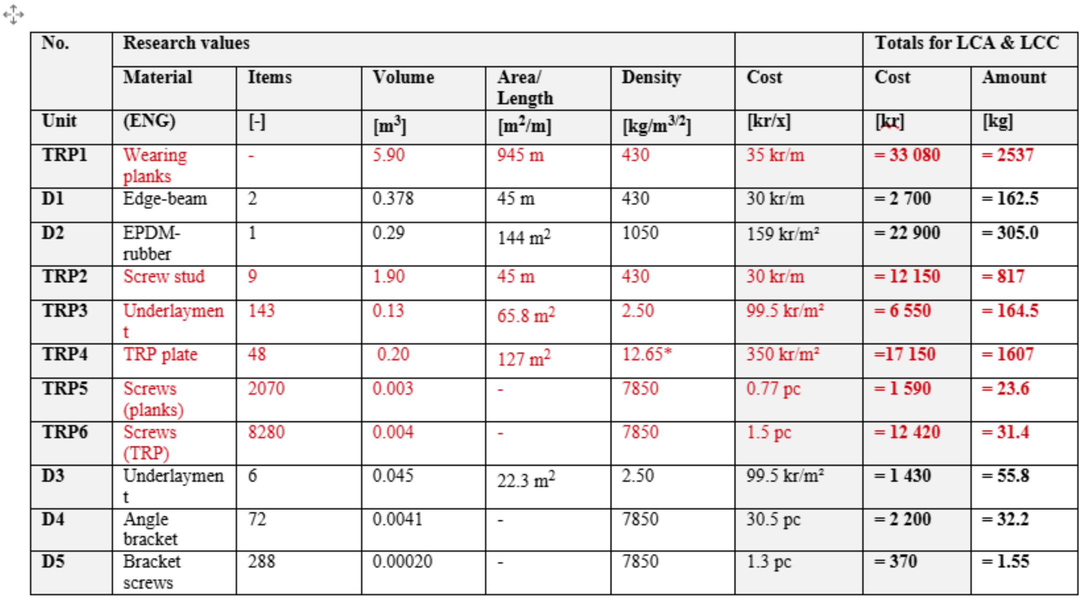
Table 9.17. Initial bridge volumes: Trapezoidal plate deck



No.	Part (ENG)	Area (mm^2) or Width x thickness	Length (mm)	Item/s (cc)	Volume total (m^3)	Area total (m^2)
TRP1	Wearing planks	50x125	45 000	21	**= 5.90**	**= 212.9**
D1	Edge beam	60 x 70	45 000	2	**= 0.378**	**= 8.56**
D2	EPDM- rubber	3200*x 2	45 000	1	**= 0.29**	**= 144**
TRP2	Screw stud	38 x 125	2 800	(45/0.945 x 3) = 143	**= 1.90**	-
TRP3	Underlayment	165*x 2	2 800	143	**= 0.13**	**= 65.8**
TRP4	TRP plate	1485	2 800	48**	**= 0.20**	**= 127/ 191.3****
TRP5	Screws (planks)	⌀5	70	2 x ((21+2) x (45 /1)) = 2070	**= 0.003**	**= 2.3**
TRP6	Screws (TRP)	⌀4.8	23	2 x (4 x (21+2) x (45 /1)) = 8280	**= 0.004**	**= 2.9**
D3	Underlayment	165 x 2	15 000	3 x 3 = 9	**= 0.045**	**= 22.3**
D4	Angle bracket	90 x 3	105(x2)	18 x 4 = 72	**= 0.0041**	**= 2.85**
D5	Bracket screws	⌀5	35	72 x 4 = 288	**= 0.00020**	**= 0.16**

Note.
* Dimensions including overlay and edge sealing
** Area for extended/flat trapezoidal plate

Table 9.18. Inventory bridge deck: Trapezoidal plate deck

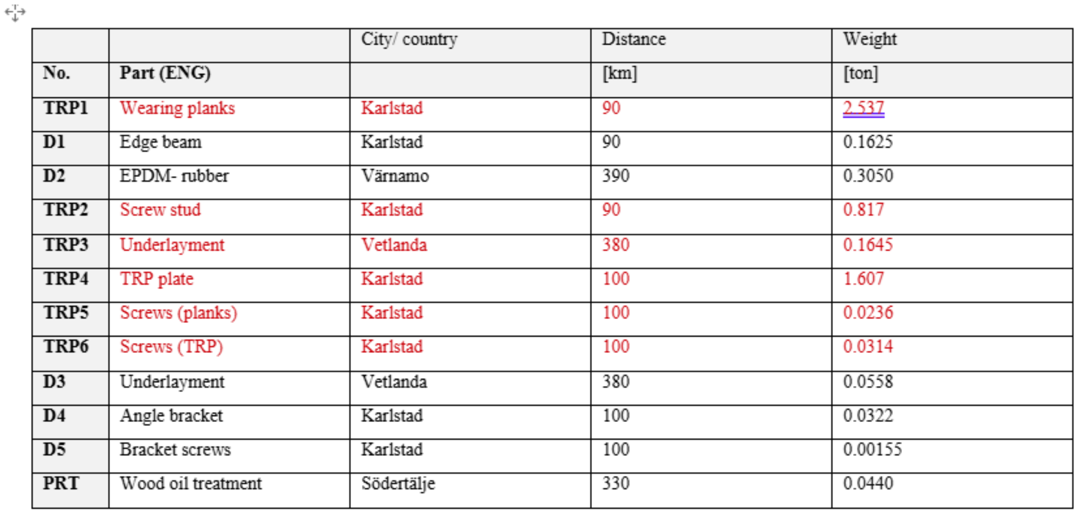


No.	Research values						Totals for LCA & LCC	
	Material	Items	Volume	Area/ Length	Density	Cost	Cost	Amount
Unit	(ENG)	[-]	[m^3]	[m^2/m]	[kg/m$^{3/2}$]	[kr/x]	[kr]	[kg]
TRP1	Wearing planks	-	5.90	945 m	430	35 kr/m	**= 33 080**	**= 2537**
D1	Edge-beam	2	0.378	45 m	430	30 kr/m	**= 2 700**	**= 162.5**
D2	EPDM-rubber	1	0.29	144 m^2	1050	159 kr/m^2	**= 22 900**	**= 305.0**
TRP2	Screw stud	9	1.90	45 m	430	30 kr/m	**= 12 150**	**= 817**
TRP3	Underlaymen t	143	0.13	65.8 m^2	2.50	99.5 kr/m^2	**= 6 550**	**= 164.5**
TRP4	TRP plate	48	0.20	127 m^2	12.65*	350 kr/m^2	**=17 150**	**= 1607**
TRP5	Screws (planks)	2070	0.003	-	7850	0.77 pc	**= 1 590**	**= 23.6**
TRP6	Screws (TRP)	8280	0.004	-	7850	1.5 pc	**= 12 420**	**= 31.4**
D3	Underlaymen t	6	0.045	22.3 m^2	2.50	99.5 kr/m^2	**= 1 430**	**= 55.8**
D4	Angle bracket	72	0.0041	-	7850	30.5 pc	**= 2 200**	**= 32.2**
D5	Bracket screws	288	0.00020	-	7850	1.3 pc	**= 370**	**= 1.55**

* Thickness: 0,70 - 1,50 mm Weight 8.8-19 kg/m Interpolate: tickness 1 mm= 12.625 kg/m^2

Note: the column "area total" comprises various kinds of areas depending on the material and what the area is needed for. In steel products it means all the volumes complete surface area since we need it as an input for the hot-dip galvanization in OpenLCA. The same goes for exposed timber parts that will need maintenance by oiling the surface area. The included areas are depended on the reachability of the surfaces. For the layered products such as underlayment and EPDM as well as the TRP the area is the out-layer surface since this is the unit that determines the cost for these products. To be able to account for all the screws and connection this study is missing, the number of screws is roughly doubled in the calculation table (appendix) to the inventory table.

Table 9.19. Bridge deck transport for stage A4, B2 and B4

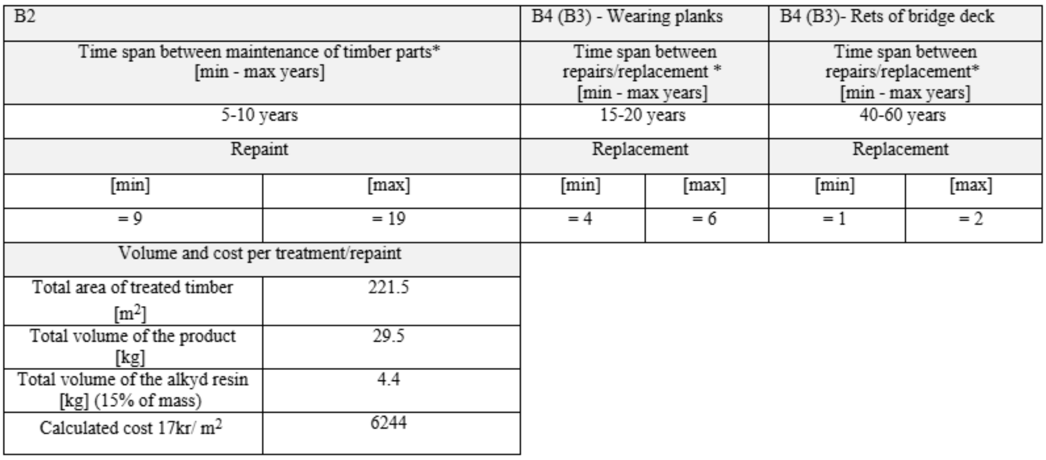


		City/ country	Distance	Weight
No.	**Part (ENG)**		[km]	[ton]
TRP1	Wearing planks	Karlstad	90	2.537
D1	Edge beam	Karlstad	90	0.1625
D2	EPDM- rubber	Värnamo	390	0.3050
TRP2	Screw stud	Karlstad	90	0.817
TRP3	Underlayment	Vetlanda	380	0.1645
TRP4	TRP plate	Karlstad	100	1.607
TRP5	Screws (planks)	Karlstad	100	0.0236
TRP6	Screws (TRP)	Karlstad	100	0.0314
D3	Underlayment	Vetlanda	380	0.0558
D4	Angle bracket	Karlstad	100	0.0322
D5	Bracket screws	Karlstad	100	0.00155
PRT	Wood oil treatment	Södertälje	330	0.0440

Assumptions regarding the price calculations can be found in Chapter 6.

For B2 and B4, the number of maintenance and replacement processes is assumed and presented in tables per bridge section. For B2, the volume, the area covered by the product and the cost per square meter are calculated. For B4, which to some extent includes B3, we assume that the entire bridge section is replaced at one time including all parts. This assumption does not correspond to a real scenario but is necessary for simplifications.

Table 9.20. Trapezoidal plate deck end of life



<table>
<tr><td colspan="2">B2</td><td colspan="2">B4 (B3) - Wearing planks</td><td colspan="2">B4 (B3)- Rets of bridge deck</td></tr>
<tr><td colspan="2">Time span between maintenance of timber parts* [min - max years]</td><td colspan="2">Time span between repairs/replacement * [min - max years]</td><td colspan="2">Time span between repairs/replacement* [min - max years]</td></tr>
<tr><td colspan="2">5-10 years</td><td colspan="2">15-20 years</td><td colspan="2">40-60 years</td></tr>
<tr><td colspan="2">Repaint</td><td colspan="2">Replacement</td><td colspan="2">Replacement</td></tr>
<tr><td>[min]</td><td>[max]</td><td>[min]</td><td>[max]</td><td>[min]</td><td>[max]</td></tr>
<tr><td>= 9</td><td>= 19</td><td>= 4</td><td>= 6</td><td>= 1</td><td>= 2</td></tr>
<tr><td colspan="2">Volume and cost per treatment/repaint</td></tr>
<tr><td>Total area of treated timber [m^2]</td><td>221.5</td></tr>
<tr><td>Total volume of the product [kg]</td><td>29.5</td></tr>
<tr><td>Total volume of the alkyd resin [kg] (15% of mass)</td><td>4.4</td></tr>
<tr><td>Calculated cost 17kr/ m^2</td><td>6244</td></tr>
</table>

*Time span between repairs/replacement retrieved by consultation with TBS.

Table 9.21. Mass over 100 years

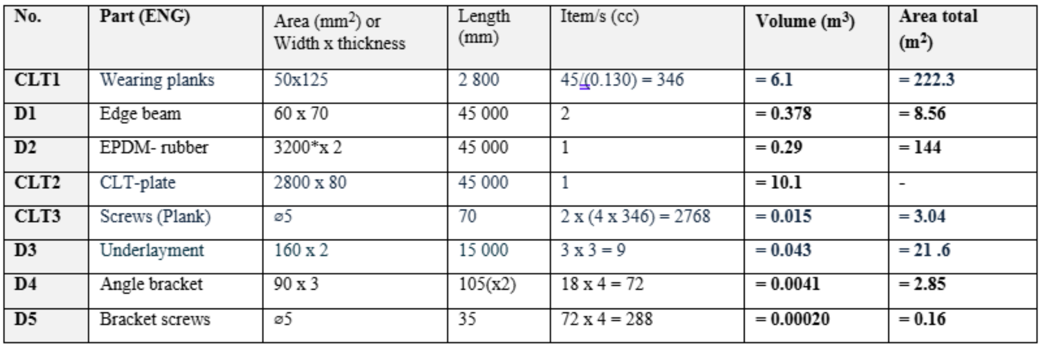
Parts	Steel [kg] Zinc [m^2]	Glulam [kg]	Lumber [kg]	Pressure treated lumber [kg]	EPDM [kg]	Underlayment [kg]
Mass from first production	1696/200	0	817	2700	305	218
Replacement rate [min]	1	-	1	4	1	1
Replacement rate [max]	2	-	2	6	2	2
Total mass after 100 years [min]	3392/400	0	1634	13 500	610	436
Total mass after 100 years [max]	5088/ 600	0	2451	18 900	915	654

Table 9.22. Trapezoidal plate deck end of life and beyond

Stages	**End of life stage (C)**		**Beyond the building life cycle stage (D)**		
Steel parts [min/max]	Transport, C2/D	Waste, C3	Reuse	Recovery	Recycling
Mass steel = 1696 kg Mass zinc = 0.02 x mass steel Total area for zinc: 200 m^2	Electricity, low voltage= 330km	0%	20%	0%	80% of steel 80% of zinc
	[min]	0	678.4/ 80	0	2713.6/320
	[max]	0	1017.6/120	0	4070.4/480
Timber parts [min/max]	Transport	Waste	Reuse	Recovery	Recycling
Glulam = 0 Lumber = 817 kg Pressure treated lumber = 2700 kg	Electricity, low voltage =90 km	20% of Pt-lumber	100% of glulam	80% pt-lumber	100 % of lumber
	[min]	2 700	0	10 800	1634
	[max]	3 780	0	15 120	2451
Other parts [min/max]	Transport	Waste	Reuse	Recovery	Recycling
EPDM- rubber = 323 kg Underlayment =218 kg	Electricity, low voltage = 90 km	20% of rubber & underlayment	0%	80% of rubber & underlayment	0%
	[min]	122 & 87.2	0	488 & 348.8	0
	[max]	183 &130.8	0	732 & 523.2	0

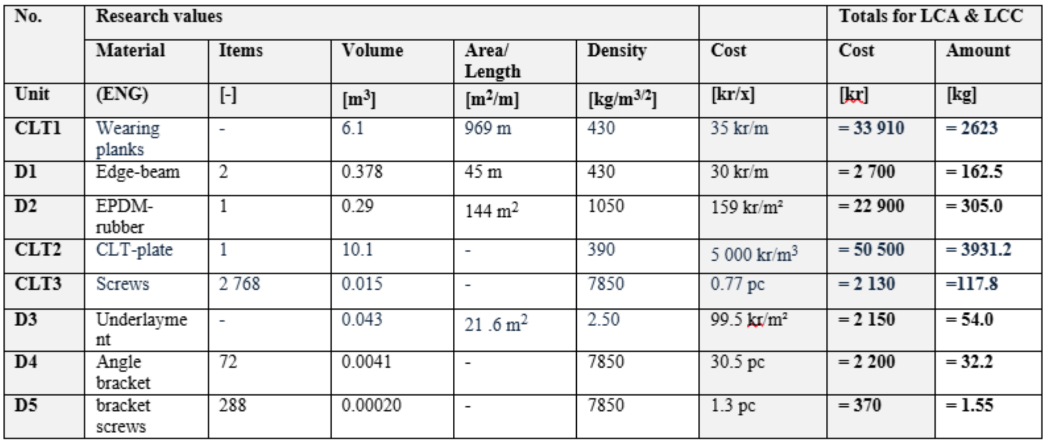
Bridge Deck - Alternative Design (CLT-plate)

Table 9.23. Alternative bridge volumes: Cross laminated plate deck



No.	**Part (ENG)**	Area (mm^2) or Width x thickness	Length (mm)	Item/s (cc)	**Volume (m^3)**	**Area total (m^2)**
CLT1	Wearing planks	50x125	2 800	45/(0.130) = 346	**= 6.1**	**= 222.3**
D1	Edge beam	60 x 70	45 000	2	**= 0.378**	**= 8.56**
D2	EPDM- rubber	3200*x 2	45 000	1	**= 0.29**	**= 144**
CLT2	CLT-plate	2800 x 80	45 000	1	**= 10.1**	-
CLT3	Screws (Plank)	⌀5	70	2 x (4 x 346) = 2768	**= 0.015**	**= 3.04**
D3	Underlayment	160 x 2	15 000	3 x 3 = 9	**= 0.043**	**= 21 .6**
D4	Angle bracket	90 x 3	105(x2)	18 x 4 = 72	**= 0.0041**	**= 2.85**
D5	Bracket screws	⌀5	35	72 x 4 = 288	**= 0.00020**	**= 0.16**

Table 9.24. Inventory bridge deck: Cross laminated plate deck



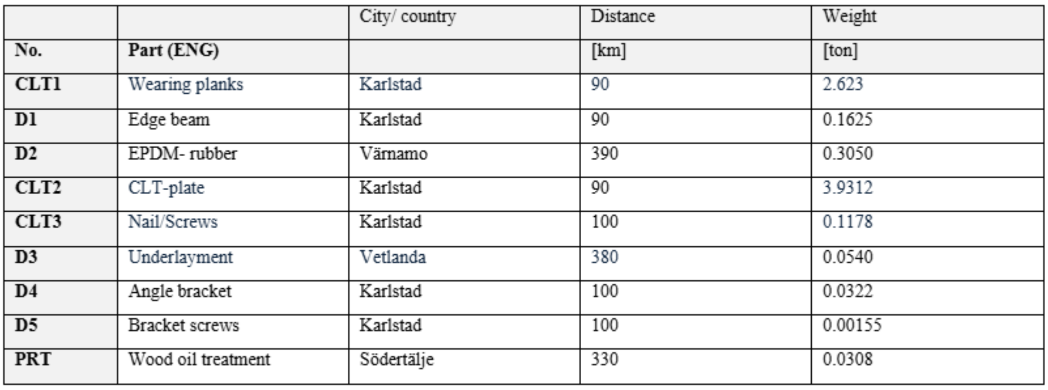
No.	**Research values**						**Totals for LCA & LCC**	
	Material	**Items**	**Volume**	**Area/ Length**	**Density**	**Cost**	**Cost**	**Amount**
Unit	**(ENG)**	**[-]**	**[m^3]**	**[m^2/m]**	**[kg/m$^{3/2}$]**	**[kr/x]**	**[kr]**	**[kg]**
CLT1	Wearing planks	-	6.1	969 m	430	35 kr/m	**= 33 910**	**= 2623**
D1	Edge-beam	2	0.378	45 m	430	30 kr/m	**= 2 700**	**= 162.5**
D2	EPDM-rubber	1	0.29	144 m^2	1050	159 kr/m²	**= 22 900**	**= 305.0**
CLT2	CLT-plate	1	10.1	-	390	5 000 kr/m^3	**= 50 500**	**= 3931.2**
CLT3	Screws	2 768	0.015	-	7850	0.77 pc	**= 2 130**	**=117.8**
D3	Underlayment	-	0.043	21 .6 m^2	2.50	99.5 kr/m²	**= 2 150**	**= 54.0**
D4	Angle bracket	72	0.0041	-	7850	30.5 pc	**= 2 200**	**= 32.2**
D5	bracket screws	288	0.00020	-	7850	1.3 pc	**= 370**	**= 1.55**

** 45000/945= 47.6 excluded overlap meaning we need 48 plates to fill the bridge length

* Dimensions including overlay and edge sealing

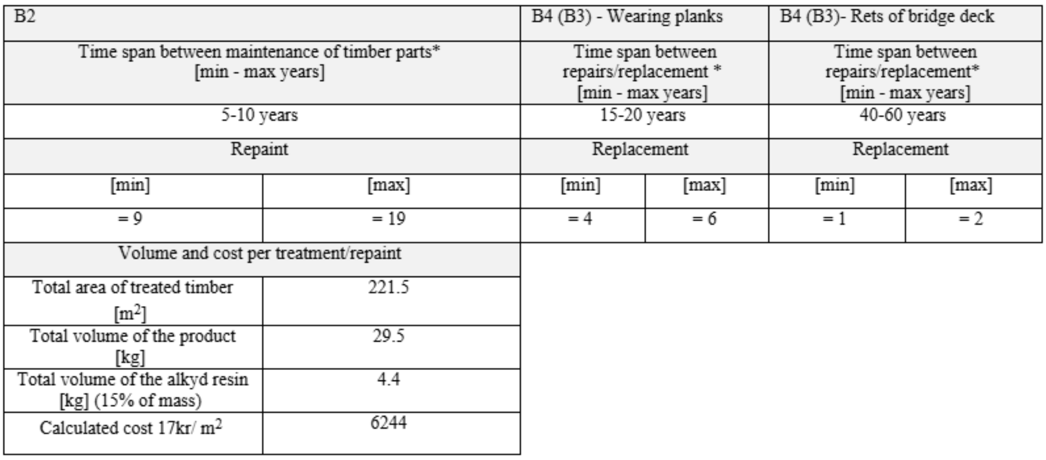
Dimension for Mataaki 15x0.67 including an overlay of 0.08 giving it a covering of 15x0.59. 2.8/0.59=4.7 meaning 5 units per 15 meters times 3 for 45 meters. 5x3x0.67x15= 150 m2. A thickness 0.005 gives a volume of 0.75 m2.

Table 9.25. Bridge deck transport for stage A4, B2 and B4



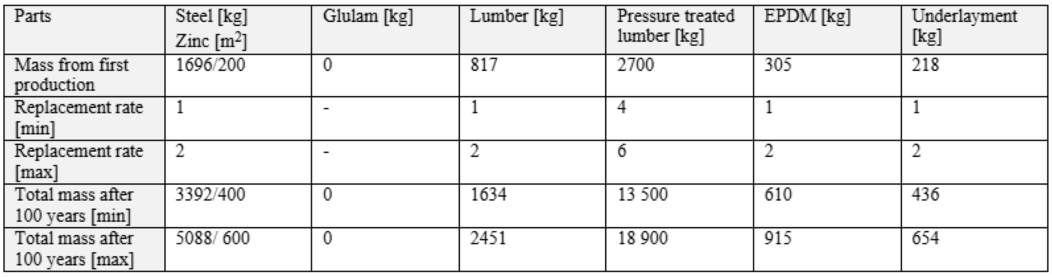
		City/ country	Distance	Weight
No.	**Part (ENG)**		[km]	[ton]
CLT1	Wearing planks	Karlstad	90	2.623
D1	Edge beam	Karlstad	90	0.1625
D2	EPDM- rubber	Värnamo	390	0.3050
CLT2	CLT-plate	Karlstad	90	3.9312
CLT3	Nail/Screws	Karlstad	100	0.1178
D3	Underlayment	Vetlanda	380	0.0540
D4	Angle bracket	Karlstad	100	0.0322
D5	Bracket screws	Karlstad	100	0.00155
PRT	Wood oil treatment	Södertälje	330	0.0308

Table 9.26. Bridge deck-alternative design end of life



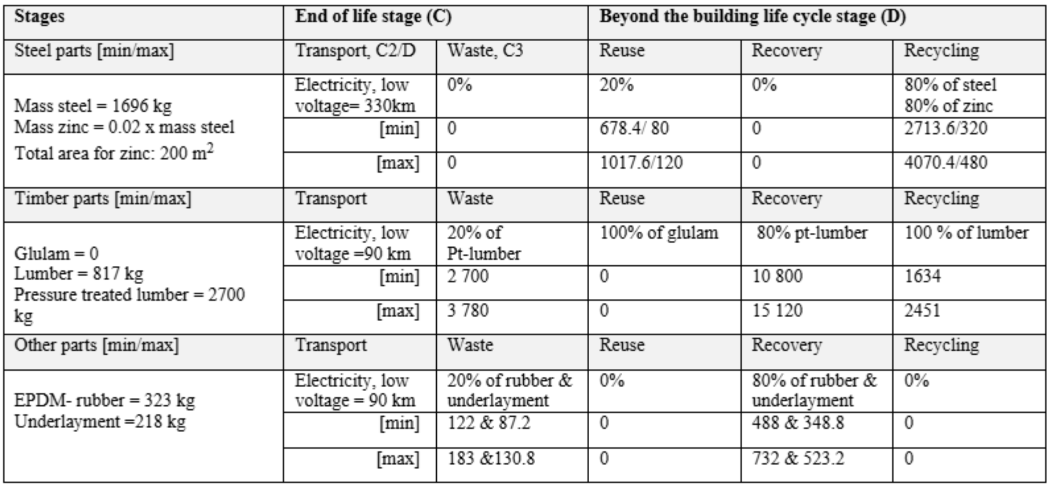
B2		B4 (B3) - Wearing planks		B4 (B3)- Rets of bridge deck	
Time span between maintenance of timber parts* [min - max years]		Time span between repairs/replacement * [min - max years]		Time span between repairs/replacement* [min - max years]	
5-10 years		15-20 years		40-60 years	
Repaint		Replacement		Replacement	
[min]	[max]	[min]	[max]	[min]	[max]
= 9	= 19	= 4	= 6	= 1	= 2
Volume and cost per treatment/repaint					
Total area of treated timber [m^2]	221.5				
Total volume of the product [kg]	29.5				
Total volume of the alkyd resin [kg] (15% of mass)	4.4				
Calculated cost 17kr/ m^2	6244				

Table 9.27. Mass over 100 years



Parts	Steel [kg] Zinc [m^2]	Glulam [kg]	Lumber [kg]	Pressure treated lumber [kg]	EPDM [kg]	Underlayment [kg]
Mass from first production	1696/200	0	817	2700	305	218
Replacement rate [min]	1	-	1	4	1	1
Replacement rate [max]	2	-	2	6	2	2
Total mass after 100 years [min]	3392/400	0	1634	13 500	610	436
Total mass after 100 years [max]	5088/ 600	0	2451	18 900	915	654

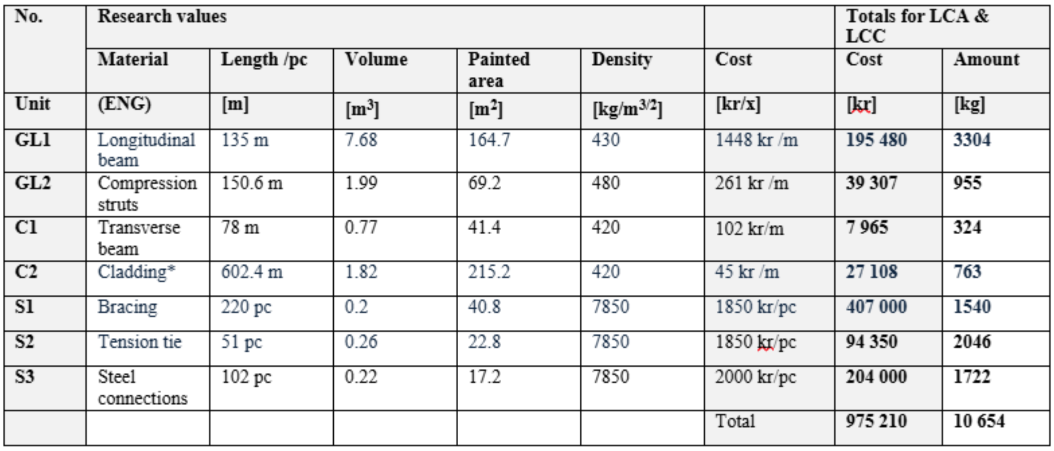
Table 9.28. Bridge deck end of life and beyond



Stages	End of life stage (C)		Beyond the building life cycle stage (D)		
Steel parts [min/max]	Transport, C2/D	Waste, C3	Reuse	Recovery	Recycling
Mass steel = 1696 kg Mass zinc = 0.02 x mass steel Total area for zinc: 200 m^2	Electricity, low voltage= 330km	0%	20%	0%	80% of steel 80% of zinc
	[min]	0	678.4/ 80	0	2713.6/320
	[max]	0	1017.6/120	0	4070.4/480
Timber parts [min/max]	Transport	Waste	Reuse	Recovery	Recycling
Glulam = 0 Lumber = 817 kg Pressure treated lumber = 2700 kg	Electricity, low voltage =90 km	20% of Pt-lumber	100% of glulam	80% pt-lumber	100 % of lumber
	[min]	2 700	0	10 800	1634
	[max]	3 780	0	15 120	2451
Other parts [min/max]	Transport	Waste	Reuse	Recovery	Recycling
EPDM- rubber = 323 kg Underlayment =218 kg	Electricity, low voltage = 90 km	20% of rubber & underlayment	0%	80% of rubber & underlayment	0%
	[min]	122 & 87.2	0	488 & 348.8	0
	[max]	183 &130.8	0	732 & 523.2	0

Bridge Superstructure- Initial Design

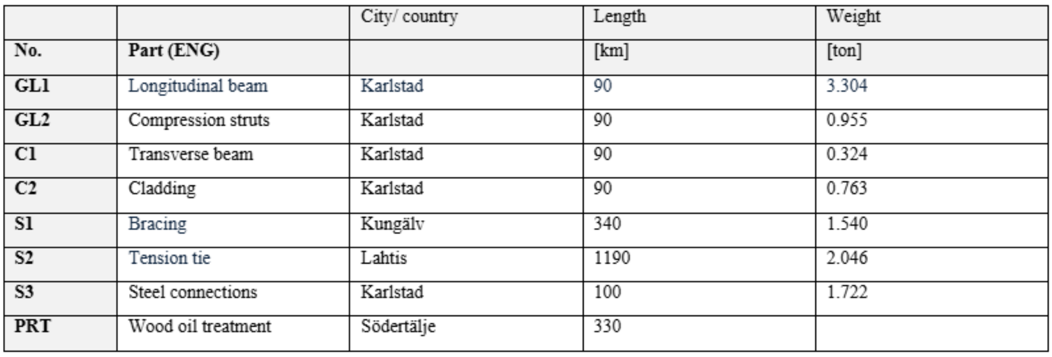
Table 9.29. Inventory bridge superstructure



No.	Research values						Totals for LCA & LCC	
	Material	**Length /pc**	**Volume**	**Painted area**	**Density**	**Cost**	**Cost**	**Amount**
Unit	**(ENG)**	**[m]**	**[m³]**	**[m²]**	**[kg/m$^{3/2}$]**	**[kr/x]**	**[kr]**	**[kg]**
GL1	Longitudinal beam	135 m	7.68	164.7	430	1448 kr /m	**195 480**	**3304**
GL2	Compression struts	150.6 m	1.99	69.2	480	261 kr /m	**39 307**	**955**
C1	Transverse beam	78 m	0.77	41.4	420	102 kr/m	**7 965**	**324**
C2	Cladding*	602.4 m	1.82	215.2	420	45 kr /m	**27 108**	**763**
S1	Bracing	220 pc	0.2	40.8	7850	1850 kr/pc	**407 000**	**1540**
S2	Tension tie	51 pc	0.26	22.8	7850	1850 kr/pc	**94 350**	**2046**
S3	Steel connections	102 pc	0.22	17.2	7850	2000 kr/pc	**204 000**	**1722**
						Total	**975 210**	**10 654**

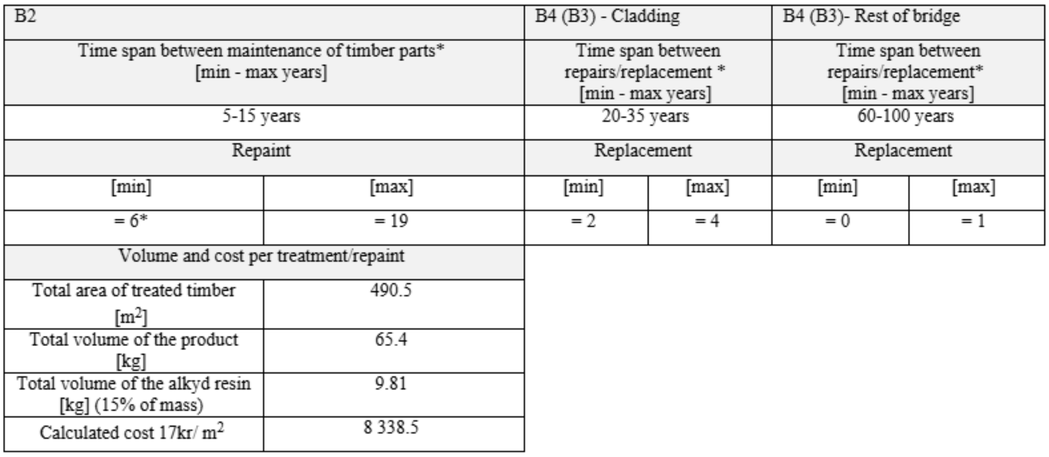
Note: All values, except for cladding and steel connections, are extracted from the model in FEM-Design and are given as totals for each element group.
*Cladding is assumed on all four sides of the compression struts.
*The amount of steel connections is estimated by calculating the volume ratio between the bracing/tension tie and the connections, with an additional 185kg added for the connection of the glulam beam.

Table 9.30. Bridge deck transport for stage A4, B2 and B4



		City/ country	Length	Weight
No.	**Part (ENG)**		[km]	[ton]
GL1	Longitudinal beam	Karlstad	90	3.304
GL2	Compression struts	Karlstad	90	0.955
C1	Transverse beam	Karlstad	90	0.324
C2	Cladding	Karlstad	90	0.763
S1	Bracing	Kungälv	340	1.540
S2	Tension tie	Lahtis	1190	2.046
S3	Steel connections	Karlstad	100	1.722
PRT	Wood oil treatment	Södertälje	330	

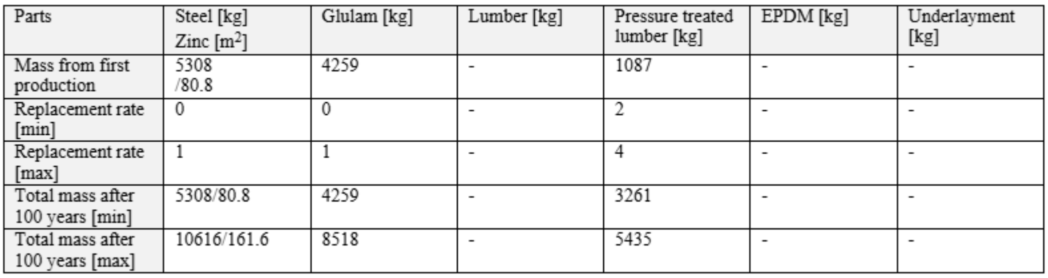
Table 9.31. Bridge superstructure- end of life



B2		B4 (B3) - Cladding		B4 (B3)- Rest of bridge	
Time span between maintenance of timber parts* [min - max years]		Time span between repairs/replacement * [min - max years]		Time span between repairs/replacement* [min - max years]	
5-15 years		20-35 years		60-100 years	
Repaint		Replacement		Replacement	
[min]	[max]	[min]	[max]	[min]	[max]
= 6*	= 19	= 2	= 4	= 0	= 1
Volume and cost per treatment/repaint					
Total area of treated timber [m^2]	490.5				
Total volume of the product [kg]	65.4				
Total volume of the alkyd resin [kg] (15% of mass)	9.81				
Calculated cost 17kr/ m^2	8 338.5				

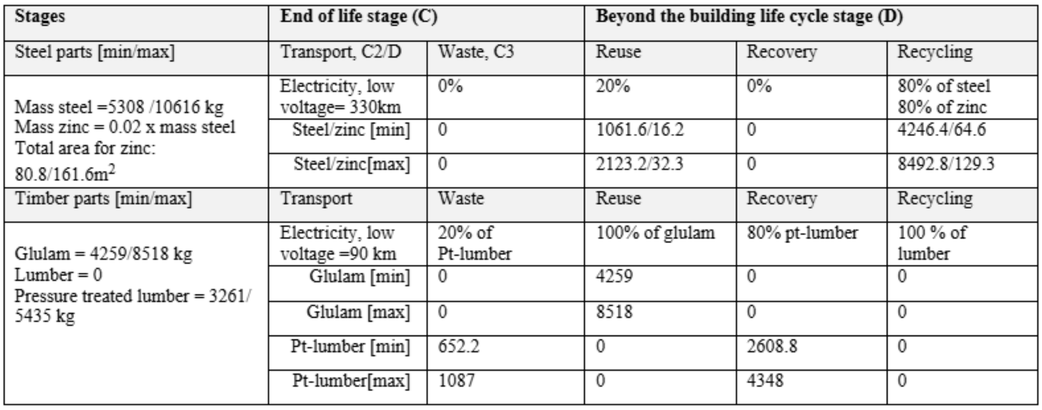
*Given that the wear planks are assumed to be oiled every 5–10 years, the maintenance interval for the cladding is estimated at 5–15 years due to its vertical orientation and reduced exposure. If the same ratio is applied to the replacement of the cladding, the span becomes 20-35 years. Regarding replacing other parts of the bridge, assuming the max years to be 100 the span will be 60-100 years.

Table 9.32. Mass over 100 years



Parts	Steel [kg] Zinc [m^2]	Glulam [kg]	Lumber [kg]	Pressure treated lumber [kg]	EPDM [kg]	Underlayment [kg]
Mass from first production	5308 /80.8	4259	-	1087	-	-
Replacement rate [min]	0	0	-	2	-	-
Replacement rate [max]	1	1	-	4	-	-
Total mass after 100 years [min]	5308/80.8	4259	-	3261	-	-
Total mass after 100 years [max]	10616/161.6	8518	-	5435	-	-

Table 9.33. Bridge superstructure- end of life and beyond



Stages	**End of life stage (C)**		**Beyond the building life cycle stage (D)**		
Steel parts [min/max]	Transport, C2/D	Waste, C3	Reuse	Recovery	Recycling
Mass steel =5308 /10616 kg Mass zinc = 0.02 x mass steel Total area for zinc: 80.8/161.6m^2	Electricity, low voltage= 330km	0%	20%	0%	80% of steel 80% of zinc
	Steel/zinc [min]	0	1061.6/16.2	0	4246.4/64.6
	Steel/zinc[max]	0	2123.2/32.3	0	8492.8/129.3
Timber parts [min/max]	Transport	Waste	Reuse	Recovery	Recycling
Glulam = 4259/8518 kg Lumber = 0 Pressure treated lumber = 3261/ 5435 kg	Electricity, low voltage =90 km	20% of Pt-lumber	100% of glulam	80% pt-lumber	100 % of lumber
	Glulam [min]	0	4259	0	0
	Glulam [max]	0	8518	0	0
	Pt-lumber [min]	652.2	0	2608.8	0
	Pt-lumber[max]	1087	0	4348	0

Bridge - Heat treatment

Heating, timber: The specific heat capacity for timber is according to TräGuiden (n.d.) 1,5 kJ/kg·°C and the density as previously stated 430 kg/m3 giving the following equation for energy consumption per cubic meter. 430 kg/m3 · (100°C · 5h + 30°C ·13h + 82°C ·9h) · 1,5 kJ/kg·°C / 3600 = 292 kWh/m^3

Heating, surrounding air (20-212°C) The furnace is assumed to be 100 m^3 and carry 20 m^3 timber products.

100 m^3 · 1,2 kg/m^3 = 1200 kg air

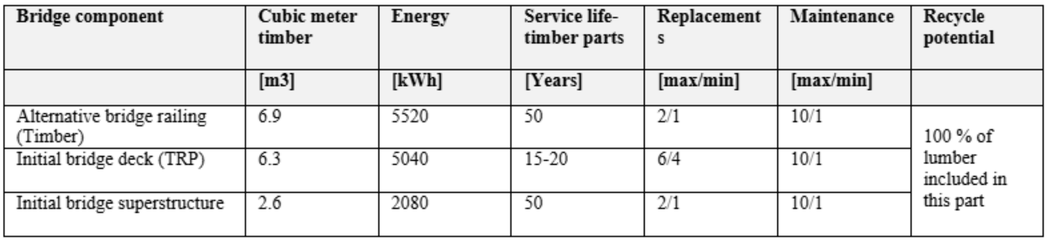
1200 kg · (192 °C ·9h) 1,0 kJ/kg·°C /3600 =576 kWh / 20 m^3 = 29 kWh/m^3

Cooling surrounding air (212-20 °C) The cooling is assumed to be held within the furnace with a cooling system.

100 m^3 · 1,2 kg/m^3 = 1200 kg air

1200 kg · (192 °C ·9h) 1,0 kJ/kg·°C /3600 =576 kWh / 20 m^3 = 29 kWh/m^3

Table 9.34. Bridge- Heat treatment



Bridge component	**Cubic meter timber**	**Energy**	**Service life- timber parts**	**Replacements**	**Maintenance**	**Recycle potential**
	[m3]	**[kWh]**	**[Years]**	**[max/min]**	**[max/min]**	
Alternative bridge railing (Timber)	6.9	5520	50	2/1	10/1	100 % of lumber included in this part
Initial bridge deck (TRP)	6.3	5040	15-20	6/4	10/1	
Initial bridge superstructure	2.6	2080	50	2/1	10/1	

Appendix C- Implementations in OpenLCA

A1-A3: Production Material Assumption

Glulam: “glued laminated timber, average glue mix” and provider “glued laminated timber production, average glue mix | glued laminated timber, average glue mix | Cutoff, S - Europe without Switzerland”

Lumber: “sawnwood, softwood, raw, dried (u=20%)” and provider “sawnwood production, softwood, raw, dried (u=20%) | sawnwood, softwood, raw, dried (u=20%) | Cutoff, S - Europe without Switzerland”

Pressure treated lumber: “wood preservation, vacuum pressure method, inorganic salt, containing Cr, outdoor use, ground contact” provider “wood preservation, vacuum pressure method, inorganic salt, containing Cr, outdoor use, ground contact | wood preservation, vacuum pressure method, inorganic salt, containing Cr, outdoor use, ground contact | Cutoff, S – RER".

Galvanized steel: General steel products are modelled as “steel, low-alloyed" with the provider “steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, S - Europe without Switzerland and Austria”. Steel plates such as TRP-plate and drip plat has been modelled as ”sheet rolling, steel” with the provider “sheet rolling, steel | sheet rolling, steel | Cutoff, S – RER". All steel products have been been coated zinc during hot-dip galvanizaion which has been modelled as surface area of these part with the dataset “zinc coat, coils” and the provider “zinc coating, coils | zinc coat, coils | Cutoff, S – RER".

EPDM-rubber: In openLCA the “synthetic rubber” is choosen to represent EPDM-rubber. The provider is set to “synthetic rubber production | synthetic rubber | Cutoff, S – RER"

Underlayment: the underlayment YEP2500 is a strong polyester base with SBS bitumen cover that is water resistant. In OpenLCA the dataset “bitumen seal, V60” is chosen. According to the description it is applicable in the construction building sector and used to protect the construction against water intrusion. The provider is “bitumen seal production, V60 | bitumen seal, V60 | Cutoff, S- RER"

A4, B2-B4 and C2- Transport assumption

The approach in OpenLCA for modeling 50% electric trucks is to half the distance allocated to diesel trucks and instead assign that half as 0.0275 kWh/(ton x km) electricity (Volvo trucks, 2023), using the low vaulted renewable flow to represent the electric portion. 0.0275 kWh/(ton x km)

50% assumed “Lorry 16-32 metric ton, EURO6” with the provider “transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, S – RER" 50% assumed “Electricity, low voltage” with the provider “market for electricity, low voltage | electricity, low voltage | Cutoff, S-SE"

B2-B3 Replacement Rate and Material Assumption

B2 is modelled in OpenLCA the flow “alkyd resin, long oil, without solvent, in 70% white spirit solution state” represent the alkyd oil that stand for 10-25 of the products based on its product declaration. The rest of the content consists mainly of water and is therefore neglected in this study. Material consumption is 5 - 10 m^2/l and with a density similar to water its 5-10 m^2/kg or 7.5 m^2/kg in total and times 0.15 (15%) of alkyd resin. The cost of wood oil is according to retailer around 1549 kr/9l and for simplification we assume that it’s around 170kr/l or 17kr/m2.

B4-B4: Is a modelled as a multiple of A1-A4 for each bridge element since it is assumed that it is produced once or multiple time more.

C2-C4 Waste Treatment Assumption

Pressure treated timber is mainly modelled as “waste wood, untreated”, however since the dataset for the product actually do contain some hazardous chemicals and to compensate for the treatment that’s missing in the dataset, “untreated “hazardous waste, for incineration” is set for 5% of the waste. The provider is set to treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Cutoff, S - RoW" and “treatment of hazardous waste, hazardous waste incineration, with energy recovery | hazardous waste, for incineration | Cutoff, S - Europe without Switzerland”

Note that "hazardous waste, ..." includes 18.9% of landfill which will be neglected or excluded from the results. Each dataset includes energy consumption for incineration, and it’s thereby not included separately.

EPDM-Rubber: Is modeled “waste rubber, unspecified” with the provider “treatment of waste rubber, unspecified, municipal incineration | waste rubber, unspecified | Cutoff, S- Europe without Switzerland”

Underlayment: Is modeled “waste bitumen sheet” with the provider “treatment of waste bitumen sheet, municipal incineration | waste bitumen sheet | Cutoff, S- RoW"

D Reuse, Energy Recovery and Recyling Assumptions

Recycling of timber parts is modeled through the dataset “wood chips, from post-consumer wood, measured as dry mass” that includes transportation and electricity. The provider is set to “treatment of waste wood, post-consumer, sorting and shredding | wood chips, from post-consumer wood, measured as dry mass | Cutoff, S – RoW". Energy for the sawmill is excluded.

Recycling of steel part is divided into its initial outputs, steel and zinc, both are marked as “avoided product”. Steel is modelled as “ferrous metal, in mixed metal scrap” with the provider “market for ferrous metal, in mixed metal scrap | ferrous metal, in mixed metal scrap | Cutoff, S- Europe without Switzerland”. The zinc is modelled as “zinc scrap, post-consumer" with the provider “market for zinc scrap, post-consumer | zinc scrap, post-consumer | Cutoff, S - GLO "

In OpenLCA the energy is added as “electricity, medium voltage, renewable energy products” since Scrap-based steel production can be assumed to you exclusively electricity (Jernkontoret, 2019).

For the energy recovery of timber products, the dataset “heat, district or industrial, other than natural gas “is chosen as the outputs and marked as “avoided product”. The provider for timber products is “heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | heat, district or industrial, other than natural gas | Cutoff, S- SE". The provider for other products is “heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Cutoff, S - SE". Both include district heat and wood chips include electricity.

Reuse of steel parts are modelled as “steel, low-alloyed" and “zinc coat, coils” as they were initially modelled. Reuse of glulam is modelled as “glued laminated timber, average glue mix” and “sawnwood, softwood, raw, dried (u=20

No transportation is added for module D.

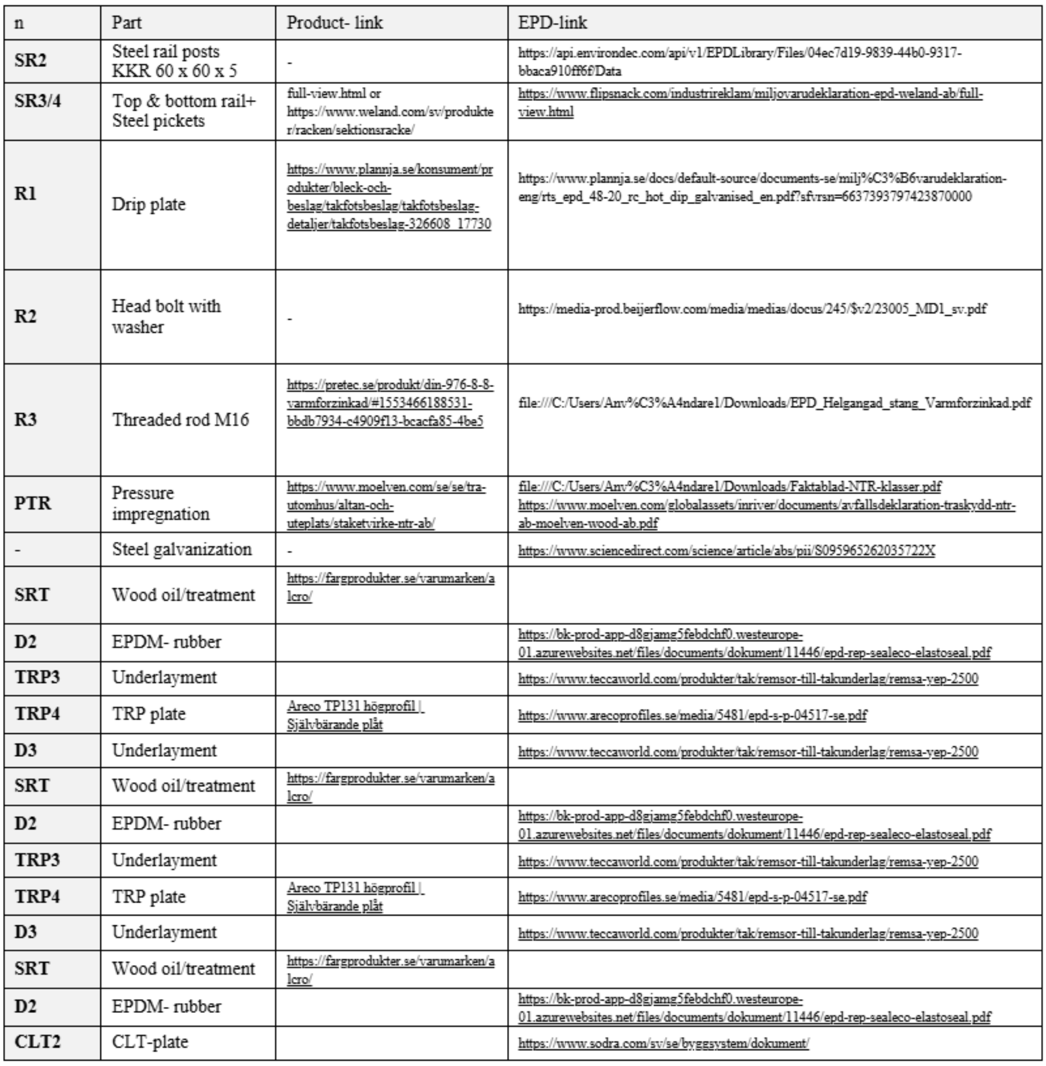
Heat Treatment

The process of heat treatment uses the dataset “heat, district or industrial, other than natural gas” and the provider “heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | heat, district or industrial, other than natural gas | Cutoff, S – SE"

The process for recycling the lumber is the same as for untreated timber.

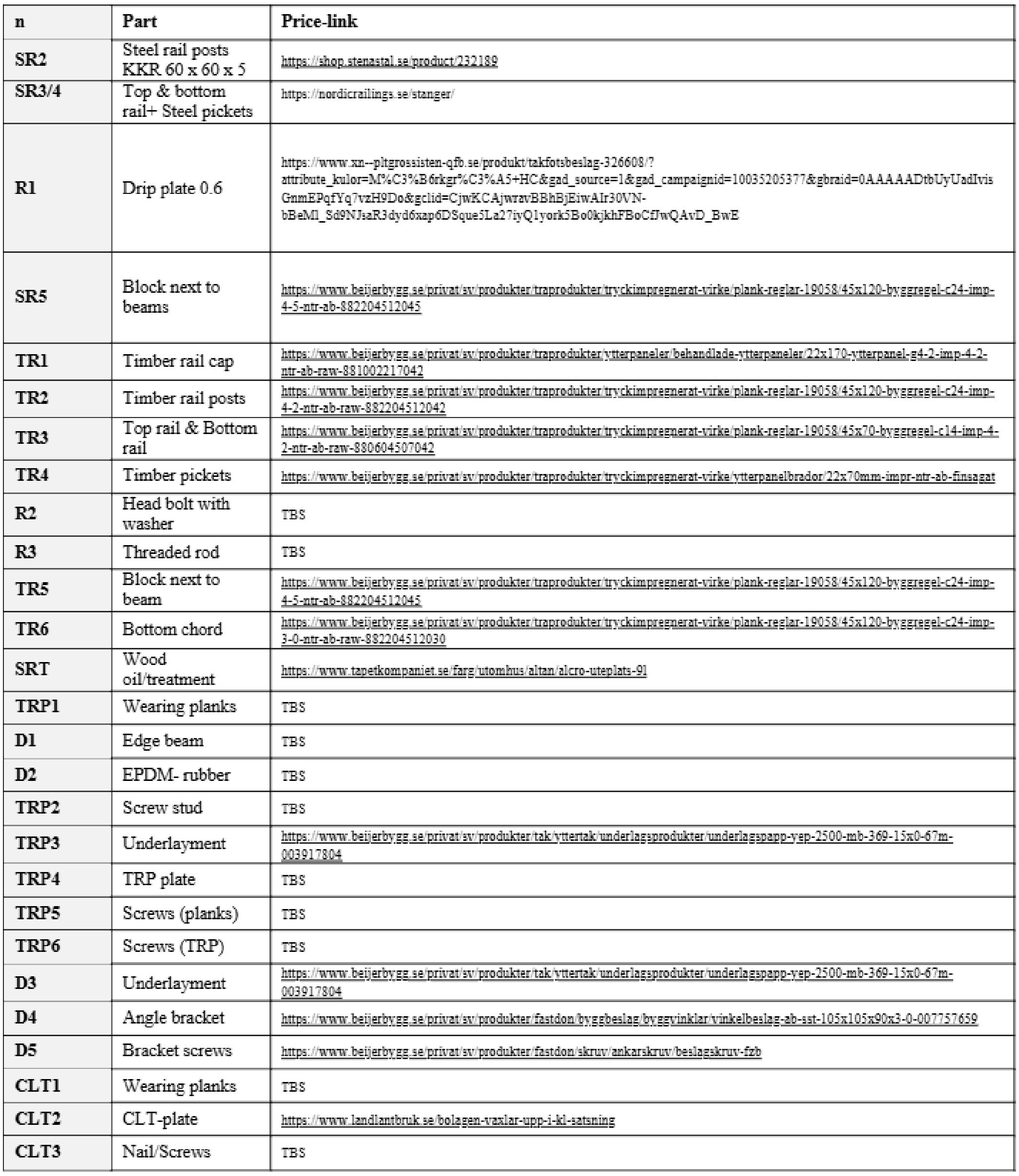
Appendix D- Product References

References table: EPD-links



n	Part	Product- link	EPD-link
SR2	Steel rail posts KKR 60 x 60 x 5	-	https://api.environdec.com/api/v1/EPDLibrary/Files/04ec7d19-9839-44b0-9317-bbaca910ff6f/Data
SR3/4	Top & bottom rail+ Steel pickets	full-view.html or https://www.weland.com/sv/produkter/racken/sektionsracke/	https://www.flipsnack.com/industrireklam/miljovarudeklaration-epd-weland-ab/full-view.html
R1	Drip plate	https://www.plannja.se/konsument/produkter/bleck-och-beslag/takfotsbeslag/takfotsbeslag-detaljer/takfotsbeslag-326608_17730	https://www.plannja.se/docs/default-source/documents-se/milj%C3%B6varudeklaration-eng/rts_epd_48-20_rc_hot_dip_galvanised_en.pdf?sfvrsn=6637393797423870000
R2	Head bolt with washer	-	https://media-prod.beijerflow.com/media/medias/docus/245/$v2/23005_MD1_sv.pdf
R3	Threaded rod M16	https://pretec.se/produkt/din-976-8-8-varmforzinkad/#1553466188531-bbdb7934-c4909f13-bcacfa85-4be5	file:///C:/Users/Anv%C3%A4ndare1/Downloads/EPD_Helgangad_stang_Varmforzinkad.pdf
PTR	Pressure impregnation	https://www.moelven.com/se/se/tra-utomhus/altan-och-uteplats/staketvirke-ntr-ab/	file:///C:/Users/Anv%C3%A4ndare1/Downloads/Faktablad-NTR-klasser.pdf https://www.moelven.com/globalassets/inriver/documents/avfallsdeklaration-traskydd-ntr-ab-moelven-wood-ab.pdf
-	Steel galvanization	-	https://www.sciencedirect.com/science/article/abs/pii/S095965262035722X
SRT	Wood oil/treatment	https://fargprodukter.se/varumarken/alcro/	
D2	EPDM- rubber		https://bk-prod-app-d8gjamg5febdchf0.westeurope-01.azurewebsites.net/files/documents/dokument/11446/epd-rep-sealeco-elastoseal.pdf
TRP3	Underlayment		https://www.teccaworld.com/produkter/tak/remsor-till-takunderlag/remsa-yep-2500
TRP4	TRP plate	Areco TP131 högprofil | Självbärande plåt	https://www.arecoprofiles.se/media/5481/epd-s-p-04517-se.pdf
D3	Underlayment		https://www.teccaworld.com/produkter/tak/remsor-till-takunderlag/remsa-yep-2500
SRT	Wood oil/treatment	https://fargprodukter.se/varumarken/alcro/	
D2	EPDM- rubber		https://bk-prod-app-d8gjamg5febdchf0.westeurope-01.azurewebsites.net/files/documents/dokument/11446/epd-rep-sealeco-elastoseal.pdf
TRP3	Underlayment		https://www.teccaworld.com/produkter/tak/remsor-till-takunderlag/remsa-yep-2500
TRP4	TRP plate	Areco TP131 högprofil | Självbärande plåt	https://www.arecoprofiles.se/media/5481/epd-s-p-04517-se.pdf
D3	Underlayment		https://www.teccaworld.com/produkter/tak/remsor-till-takunderlag/remsa-yep-2500
SRT	Wood oil/treatment	https://fargprodukter.se/varumarken/alcro/	
D2	EPDM- rubber		https://bk-prod-app-d8gjamg5febdchf0.westeurope-01.azurewebsites.net/files/documents/dokument/11446/epd-rep-sealeco-elastoseal.pdf
CLT2	CLT-plate		https://www.sodra.com/sv/se/byggsystem/dokument/

References table: Item prices



n	Part	Price-link
SR2	Steel rail posts KKR 60 x 60 x 5	https://shop.stenastal.se/product/232189
SR3/4	Top & bottom rail+ Steel pickets	https://nordicrailings.se/stanger/
R1	Drip plate 0.6	https://www.xn--pltgrossisten-qfb.se/produkt/takfotsbeslag-326608/?attribute_kulor=M%C3%B6rkgr%C3%A5+HC&gad_source=1&gad_campaignid=10035205377&gbraid=0AAAAADtbUyUadIvisGnmEPqfYq7vzH9Do&gclid=CjwKCAjwravBBhBjEiwAIr30VN-bBeMl_Sd9NJsaR3dyd6xap6DSque5La27iyQ1york5Bo0kjkhFBoCfJwQAvD_BwE
SR5	Block next to beams	https://www.beijerbygg.se/privat/sv/produkter/traprodukter/tryckimpregnerat-virke/plank-reglar-19058/45x120-byggregel-c24-imp-4-5-ntr-ab-882204512045
TR1	Timber rail cap	https://www.beijerbygg.se/privat/sv/produkter/traprodukter/ytterpaneler/behandlade-ytterpaneler/22x170-ytterpanel-g4-2-imp-4-2-ntr-ab-raw-881002217042
TR2	Timber rail posts	https://www.beijerbygg.se/privat/sv/produkter/traprodukter/tryckimpregnerat-virke/plank-reglar-19058/45x120-byggregel-c24-imp-4-2-ntr-ab-raw-882204512042
TR3	Top rail & Bottom rail	https://www.beijerbygg.se/privat/sv/produkter/traprodukter/tryckimpregnerat-virke/plank-reglar-19058/45x70-byggregel-c14-imp-4-2-ntr-ab-raw-880604507042
TR4	Timber pickets	https://www.beijerbygg.se/privat/sv/produkter/traprodukter/tryckimpregnerat-virke/ytterpanelbrador/22x70mm-impr-ntr-ab-finsagat
R2	Head bolt with washer	TBS
R3	Threaded rod	TBS
TR5	Block next to beam	https://www.beijerbygg.se/privat/sv/produkter/traprodukter/tryckimpregnerat-virke/plank-reglar-19058/45x120-byggregel-c24-imp-4-5-ntr-ab-882204512045
TR6	Bottom chord	https://www.beijerbygg.se/privat/sv/produkter/traprodukter/tryckimpregnerat-virke/plank-reglar-19058/45x120-byggregel-c24-imp-3-0-ntr-ab-raw-882204512030
SRT	Wood oil/treatment	https://www.tapetkompaniet.se/farg/utomhus/altan/alcro-uteplats-91
TRP1	Wearing planks	TBS
D1	Edge beam	TBS
D2	EPDM- rubber	TBS
TRP2	Screw stud	TBS
TRP3	Underlayment	https://www.beijerbygg.se/privat/sv/produkter/tak/yttertak/underlagsprodukter/underlagspapp-yep-2500-mb-369-15x0-67m-003917804
TRP4	TRP plate	TBS
TRP5	Screws (planks)	TBS
TRP6	Screws (TRP)	TBS
D3	Underlayment	https://www.beijerbygg.se/privat/sv/produkter/tak/yttertak/underlagsprodukter/underlagspapp-yep-2500-mb-369-15x0-67m-003917804
D4	Angle bracket	https://www.beijerbygg.se/privat/sv/produkter/fastdon/byggbeslag/byggvinklar/vinkelbeslag-ab-sst-105x105x90x3-0-007757659
D5	Bracket screws	https://www.beijerbygg.se/privat/sv/produkter/fastdon/skruv/ankarskruv/beslagskruv-fzb
CLT1	Wearing planks	TBS
CLT2	CLT-plate	https://www.landlantbruk.se/bolagen-vaxlar-upp-i-kl-satsning
CLT3	Nail/Screws	TBS

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