Integrated Design with Reclaimed Steel

Development of a Design Workflow and Computational Tool to Facilitate the Reuse of Structural Steel in New Building Designs

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by

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ABSTRACT

The rapid growth in building stock and the demand for new construction present significant challenges in terms of material scarcity, waste production, and greenhouse gas emissions. To address these challenges, a fundamental shift in the construction industry's approach is needed, viewing waste as a resource through circularity principles. This research focuses on the application of circular principles and resource efficiency in the reuse of structural steel within the European construction industry. However, the utilization of reclaimed steel in construction projects faces significant challenges, including the condition of reclaimed elements, the need for repairs and refurbishment, unclear stakeholder responsibilities, and the absence of contractual frameworks. Communication gaps and coordination complexities further compound these challenges.

Despite these obstacles, the research demonstrates that reclaimed steel can be successfully integrated into projects with proper planning, coordination, and expertise. A comprehensive analysis of existing practices and challenges, interviews with industry professionals, and literature review inform the development of a design framework and a computational tool.

The proposed design workflow incorporates strategies to address the identified challenges and promote efficient steel reuse within the different project phases. Additionally, a computational tool facilitates the integration of reclaimed steel through a digital inventory and matching algorithm. The matching algorithm enables the retrieval of stock information from a digital inventory. A matching algorithm is implemented to compare the list of design elements needed for a project with the available stock list. This tool efficiently identifies possible substitutions, enabling designers and engineers to find suitable reclaimed steel sections for their projects. Lastly, the design workflow and computational tool were successfully tested through a design case study, demonstrating their effectiveness and environmental impact results to allow users to make informed design decisions.

Overall, this thesis project offers valuable insights and practical solutions to advance the implementation of steel reuse in the construction industry, making a significant contribution to the field of sustainable construction.

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0 INTRODUCTION

0.1 CONTEXT

According to the World Building Council, the global population is projected to reach 10 billion by 2050, which will result in a significant expansion of the global building stock, estimated to double in size (World Building Council, 2019). This expansion brings forth significant environmental challenges, particularly concerning the emission of greenhouse gases (GHG). The building industry is responsible for 39% of the total GHG emissions in the world, of which 11% are embodied carbon emissions from material production and construction (World Building Council, 2019). Of the material production emissions, the steel sector is responsible for 7% of emissions (IEA, 2020), making it one of the most energy consuming and CO2 emitting industrial activities in the world (World Steel Association, 2020).

Steel is one of the most utilized materials for engineering and construction due to its high tensile strength, durability, and cost effectiveness (World Steel Association, 2022). Additionally, steel is a material that can be endlessly recycled, although the recycling process itself is energy intensive. According to circularity principles, prioritizing the reuse of products over remanufacturing and recycling is a more efficient and sustainable option. However, the process of reusing structural steel for new construction poses significant challenges. Some of these include: the lack of history information from existing buildings, lack of expertise in deconstruction and construction with reclaimed materials, and lack of a well-established workflow process among the different parties involved in a project. Addressing these challenges requires collaboration, research, and the development of guidelines and best practices for the reuse of structural steel. It involves the collective efforts of industry professionals, researchers, policymakers, and organizations to promote and facilitate the integration of reclaimed steel into the construction industry.

0.1.1 STEEL IN THE CONSTRUCTION INDUSTRY

The Industrial Revolution, with its advancements in steel production, revolutionized the construction industry by making steel one of the most preferred materials for construction due to its low costs and versatility. The mass production of steel at affordable prices, facilitated by technological developments in the late 19th century, allowed for the construction of tall and complex buildings using steel structural frameworks. This transformation was significant as load-bearing structures typically constitute around 60% of a building's weight (Terwel et al., 2021a). As a result, steel plays a crucial role in the construction industry, accounting for more than 50% of the total steel resource consumption in the building sector as illustrated in Figure 1.

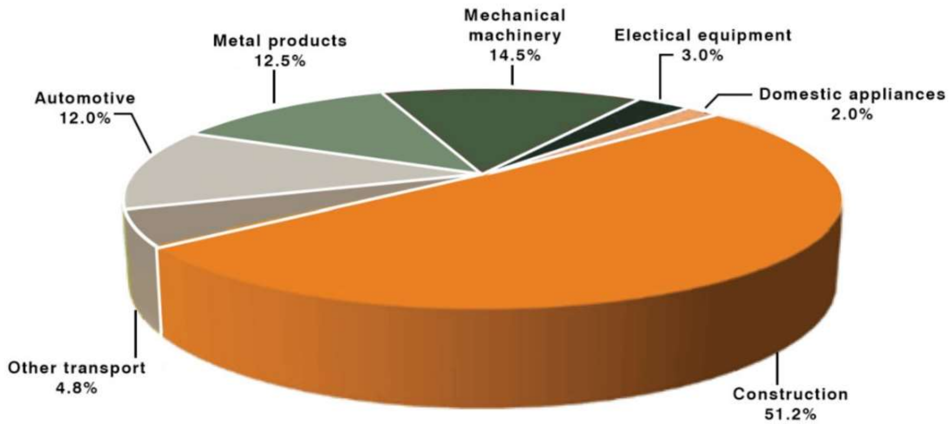

Figure 1: Global Steel Utilization – own diagram based on (Basson & X. Zhang, 2012)

STEEL PRODUCTION

As steel plays a crucial role in the construction industry, it is essential to understand the complex process involved in its production. The production of steel, as explained by the American Iron and Steel Institute, involves several stages (American Iron and Steel Institute, 2021). The initial stage involves converting iron ore into pig iron using a blast furnace by combining it with coke and limestone. The resulting molten pig iron is then refined using the Bessemer process or the open-hearth process to eliminate impurities. The pig iron is further processed into steel through either the basic oxygen furnace (BOF) process or the electric arc furnace (EAF) process. The desired steel product is obtained through various forming processes such as extrusion, rolling and other finishing operations.

In addition to the complexity of the steel production process, the steel industry consumes a significant amount of iron ore. According to The World Counts, an online platform with real-time data sourced from various research institutions and organizations, the mining of iron ore is “the world’s third most produced commodity by volume” (The World Counts, 2023). This production is highly energy intensive and causes air and water pollution. The steel industry accounts for approximately 95% of the annual mining tonnage of over 2000 million tons (The World Counts, 2023). Figure 2 provides an overview of the workflow of crude steel production, highlighting the extensive resources involved in the steel production process.

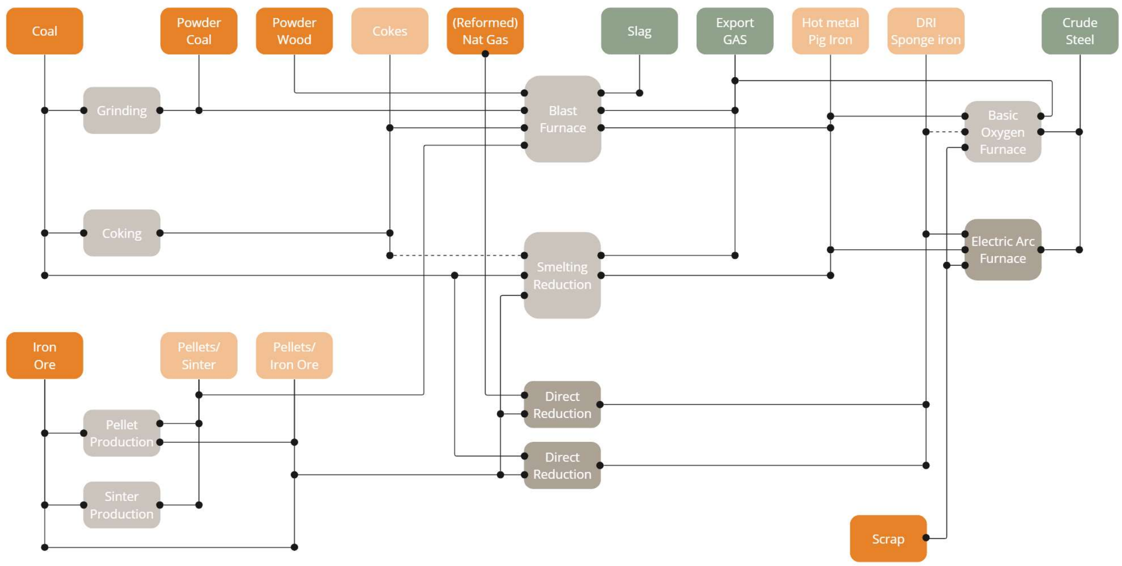

Figure 2: Material flow for the production of iron and steel – own diagram based on (Van Wortswinkel & Nijs, 2010)

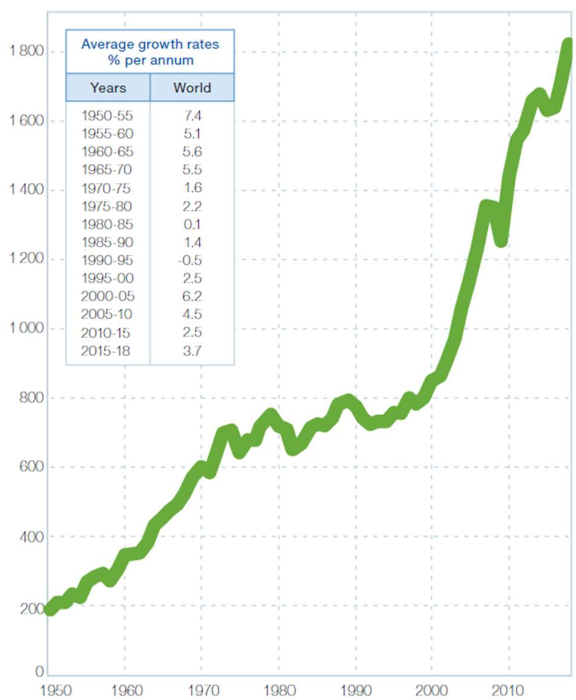

Figure 3: Crude Steel Production (million tons) (World Steel Association, 2019)

This resource-intensive process has significant environmental implications, particularly in terms of carbon emissions. The World Steel Association, with members representing 85 percent of the global steel industry, publishes an annual report to show official production, usage, and distribution declarations of steel tonnage (World Steel Association, 2019). From their 2019 report, the growth of the steel production industry over the past 70 years can be seen in Figure 3. Along with this growth rate, the CO2 emissions should be considered. The association recorded that in 2022, 1.91 tons of CO2 were emitted for every ton of crude steel produced (World Steel Association, 2022). Based on these estimates, the total emissions associated with annual steel production in 2022 reach approximately 3,400 million tons of CO2.

These substantial carbon emissions stress the environmental challenges posed by the steel industry. According to the 2017 Sustainability Indicator Data, the steel industry has reduced by 61 percent its energy intensity per ton of steel produced since the 1960's (World Steel Association, 2019). However, the iron and steel production sectors are still the second largest industrial consumer of energy and the largest industrial emitter of CO2 in the world, as it accounts for 20 percent of the industrial energy consumption (Van

Wortswinkel & Nijs, 2010). Given steel's critical role in construction and infrastructure, it becomes imperative to address these environmental concerns and explore sustainable practices in steel production.

0.1.2 CIRCULAR ECONOMY IN THE CONSTRUCTION INDUSTRY

The main global challenges we face today are rooted in the so-called “take-make-dispose” model of the linear economy, which involves extracting materials, manufacturing products, and discarding them as waste (Baporikar, 2020). With that said, more than half of all global non-renewable natural resources are consumed by the construction industry (Willmott Dixon, 2010). To address these issues, there is a need to transition towards a circular economy (Ross, 2019), which aims to mitigate material scarcity, waste production, and greenhouse gas emissions by promoting resource reuse and reducing reliance on the linear model.

There are three fundamental principles of the circular economy: preventing waste and pollution, keeping products and materials in use, and regenerating natural systems (Ellen Macarthur Foundation, n.d.). To maximize the value of materials, extend their lifespan, and reduce the amount of waste sent to landfills, products must be designed to be durable, and after their intended use, these must be reused, refurbished, or recycled – in that order of priority. Traditionally, the end use of a building was seen as waste, destined for disposal in landfills or possibly recycled through down-cycling. However, the concept of waste has shifted under the lens of circularity principles, where waste is recognized as a resource. This new perspective considers construction and deconstruction as part of the same industrial cycle, forming a closed loop (Thomsen et al., 2011). In light of this, alternative approaches to building design, construction, and demolition are vital in reducing waste generation and promoting sustainability throughout the entire life cycle of buildings.

To facilitate the development of effective circular material and product flows, the 10R strategies in Figure 4 provide a valuable framework. These strategies rely on various business models, infrastructures, stakeholder relationships, and policies to be successful. By embracing the principles of the circular economy, adopting the 10R strategies, and reimagining the life cycle of buildings, the construction industry can actively contribute to a more sustainable and circular future. These approaches offer opportunities to minimize waste, conserve resources, and mitigate the environmental impact of the built environment.

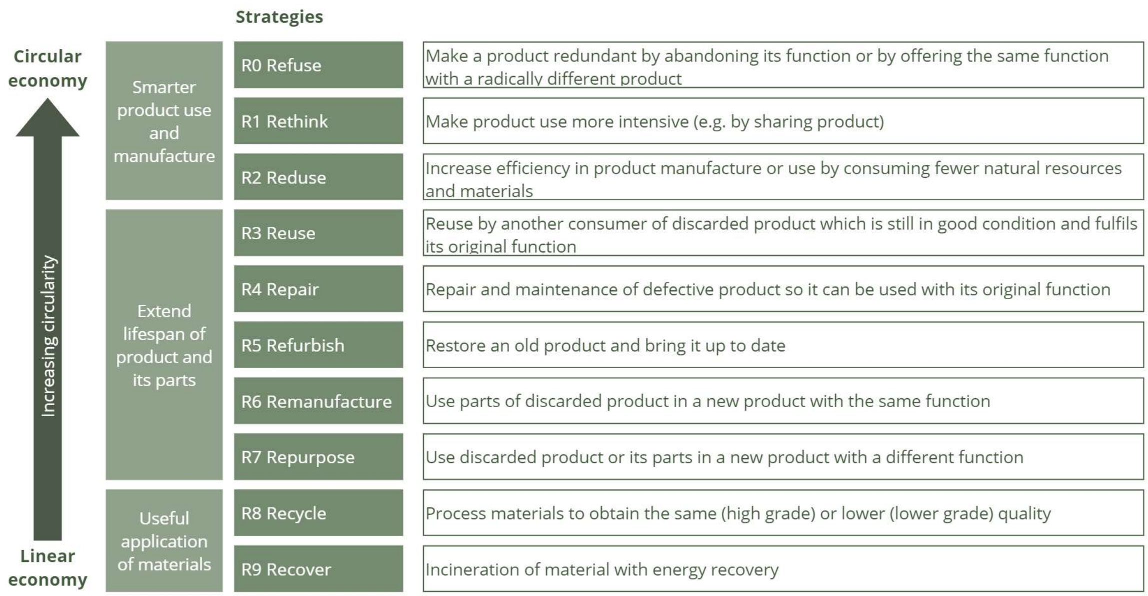

Figure 4: 10R's circular economic framework – own diagram based on (CE Grow Circular, 2022)

MATERIAL EFFICIENCY

Stuart Walker, a researcher at the University of Sheffield, emphasizes the relationship between resource scarcity and material efficiency in the context of the circular economy. He highlights that the circular economy aims to optimize the utility of materials and products throughout their life cycle (Walker et al., 2018). This approach focuses on delivering the same or greater functionality while using fewer resources, with an emphasis on strategies such as product durability and design that facilitate material recovery at the end of the product's life (Walker et al., 2018). This shift from quick and cheap manufacturing to producing high-quality, long-lasting products requires more energy upfront but results in reduced energy consumption during the product's life cycle and facilitates material reuse and recycling, thereby improving resource efficiency and diverting materials from landfill or incineration.

Steel, known for its high recycling rate and circularity, exemplifies the potential of the circular economy. However, there remain untapped opportunities for greater material efficiency in the steel industry that have yet to be widely implemented (Walker et al., 2018). It is important to consider trade-offs when extending the lifespan of a product, as the manufacturing process may require more energy initially but can significantly reduce the environmental burden throughout its entire life cycle (Walker et al., 2018).

LEGISLATIONS TOWARDS A CIRCULAR ECONOMY

The United Nations (UN) Brundtland Commission has defined sustainability as meeting present needs without compromising future generations' ability to meet their own needs (Ravago et al., 2015). To address this, the UN adopted the 2030 Agenda for Sustainable Development, which includes the Sustainable Development Goals focused on combating climate change and preserving the planet. (United Nations, n.d.). The Netherlands has introduced the National Climate Agreement, aiming to reduce greenhouse gas emissions by 49 percent by 2030 (*Climate Agreement*, 2019). In line with these efforts, the Dutch government and construction industry have set the goal of making the entire building process circular by 2050 (Ministerie van Infrastructuur en Waterstaat, 2022). It is apparent that governmental legislation is pushing for a circular economy to reduce GHG emissions and mitigate climate change. However, in order to move towards a completely circular economy by 2050, a framework of short-term goals must be established as steps to achieve the long-term objectives.

Governmental regulations have increased awareness of the environmental impacts of construction materials and energy usage in buildings. Sustainable certifications such as LEED (U.S. Green Building Council Institute, 2023) and BREEAM (BRE Group, 2023) play a crucial role in promoting sustainable building practices and environmental responsibility. While LEED v4.1 and BREEAM provide a comprehensive framework for certifying sustainable buildings, they have yet to establish a framework for incorporating reused or salvaged structural elements into building design and construction. Both certifications have a Materials category that evaluates the environmental impact of construction materials and encourages the use of recycled and reused materials. Additionally, both certifications have specific credits for circular economy principles that reward projects for diverting waste from landfills and utilizing reclaimed materials. However, there is currently no established protocol for integrating reusable building components into building design.

The European Circular Economy Stakeholder Platform, a joint initiative by the European Commission and the European Economic and Social Committee, includes the Netherlands Institute of Circular Building (NICB). NICB provides knowledge and guidance for a circular construction process(NICB, 2020). To achieve a circular built environment, NICB recommends a construction process that prioritizes high-quality reuse through assembling and disassembling, transitioning to central use business models, involving dismantling workers during design, developing technical innovations, and updating governmental contracts to stimulate the market for circular alternatives.

In conclusion, governmental regulations, along with sustainable certifications like LEED and BREEAM, are driving increased awareness of the environmental impacts of construction and promoting sustainable practices. However, there is still a need to establish protocols for integrating reusable building components into design. The involvement of organizations like NICB and their recommendations for a circular construction process can play a crucial role in accelerating the transition to a circular economy in the construction industry.

0.2 PROBLEM STATEMENT

The anticipated growth in building stock and the demand for new construction pose significant challenges in terms of material scarcity, waste production, and greenhouse gas emissions. The International Council for Research and Innovation in Building and Construction (CIB) predicts that the depletion of natural resources will intensify pressure on the production flow of building materials, leading to a significant rise in costs for raw materials (CIB, 2023). In Europe, the construction and demolition (C&D) waste stream has been identified as a critical issue, with an estimated 10% - 30% of greenhouse gas emissions indirectly attributed to the production, transport, and demolition of buildings. (Gorgolewski, 2006). Due to this, regulatory bodies are showing a growing interest in enhancing resource efficiency and mitigating the substantial volumes of waste generated by the construction and demolition sector.

It is evident that a fundamental shift is needed in the construction industry's approach. The end use of a building was initially viewed as waste that would be disposed in landfills or possibly recycled through down-cycling. However, waste is now seen as a resource through circularity principles. This circularity perspective recognizes that construction and deconstruction are part of the same industrial cycle, forming a closed loop (Thomsen et al., 2011). Therefore, alternative approaches to building design, construction, and demolition that reduce waste and promote sustainability must be considered. Given that the construction industry represents over 50% of the worldwide demand for steel and that structural steel sections constitute 25% of steel usage in buildings, focusing on the challenges and opportunities surrounding structural steel becomes imperative for addressing resource efficiency and promoting sustainable practices in the construction sector (World Steel Association, 2022).

The circularity of steel and the application of circular principles in the construction industry are areas of increasing importance for achieving sustainable practices. A survey conducted in the UK in 2012 suggests that steel has an average recycling rate of 91% and 5% reused rate (Sansom & Avery, 2014). While there is potential for steel reuse, the current practice faces significant challenges. The lack of a well-defined process and workflow inhibits the effective implementation of steel reuse strategies. Additionally, there is limited awareness and expertise among stakeholders regarding the application of circular principles in the context of steel reuse. The absence of comprehensive regulations and guidelines further hinders the widespread adoption of steel reuse practices (Gorgolewski, 2006). As a result, the full potential of steel reuse in contributing to resource conservation and mitigating environmental impacts remains untapped. To realize the benefits of steel reuse and promote a more circular economy, it is crucial to address the current challenges and develop effective strategies that integrate steel reuse into construction processes while considering regulatory frameworks. By doing so, the construction industry can move closer to achieving sustainability goals and enhancing resource efficiency in the use of steel.

0.3 DOMAIN AND SCOPE

This research primarily focuses on the application of circular principles and resource efficiency in the context of reusing structural steel, as it is the world's most crucial engineering and construction material (World Steel Association, 2022). Additionally, the focus is on reusing the larger steel components with high embodied energy to maximize savings (Gorgolewski & Morettin, n.d.). Specifically, the investigation will center around the reuse of reclaimed H and I structural steel sections within the European construction industry. While the specific focus is on Europe, it is important to note that the concept and findings can be applicable and valuable in other regions as well. Structural steel sections play a significant role in the construction industry, accounting for a substantial portion of steel usage in buildings. By examining the challenges and opportunities associated with the circularity of structural steel, this research aims to contribute to the development of sustainable practices and resource conservation in the construction sector. The investigation encompasses various aspects such as material scarcity, waste production, greenhouse gas emissions, and the implementation of circular design, construction, and demolition approaches. By gaining insights into these areas, it is expected that this research will provide valuable recommendations and guidelines for stakeholders involved in the structural steel supply chain, enabling the industry to move towards more sustainable and circular practices.

0.4 OBJECTIVES

The main objective of this research is to promote and facilitate the circularity of materials, with a specific focus on structural steel, in the built environment. Figure 5 illustrates the intended workflow of the research and development for this thesis.

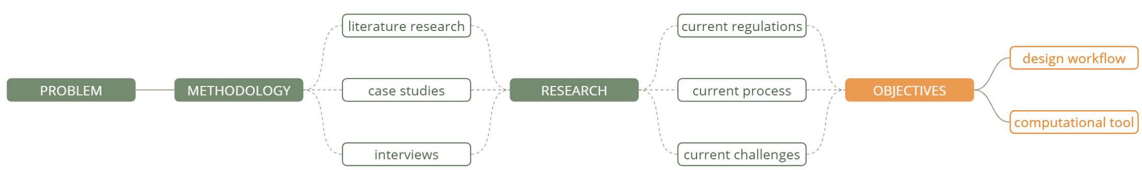

Figure 5: Diagram of thesis process and objectives

To achieve this goal, the research aims to accomplish the following objectives:

Determine the current process and challenges associated with incorporating reused steel sections in new construction: This objective involves conducting a comprehensive analysis of the existing practices and processes involved in reusing structural steel for new construction. By identifying the key challenges and barriers, the research seeks to gain insights into the specific issues that need to be addressed for successful implementation.

Propose a design framework for facilitating the integration of reused steel sections: Building upon the understanding of the challenges, this objective involves developing a design framework that streamlines the design and coordination process when incorporating reused steel sections. The framework will provide guidelines and best practices to ensure efficient integration and optimal utilization of reclaimed steel components.

Develop a computational tool to facilitate the integration of reclaimed steel in new architectural projects: This objective involves creating a computational tool that establishes a connection between the structural Building Information Modeling (BIM) models and an inventory of available reused steel sections. The tool will enable engineers and designers to access real-time information about the availability and properties of reclaimed steel, facilitating informed decision-making during the design phase.

By achieving these objectives, the research aims to contribute to the advancement of circular construction practices by addressing the challenges of incorporating reused steel sections and providing practical solutions through a design framework and a computational tool. Ultimately, the integration of these tools and strategies into the construction industry has the potential to promote resource efficiency, reduce waste, and support sustainable design and construction practices.

0.5 RESEARCH QUESTION & SUB-QUESTIONS

The main research question is formulated as follows:

How to facilitate the design process when integrating reclaimed steel structural profiles for new construction with the use of computational tools?

The following sub-questions will contribute to the main research question:

1. What are the current limitations of reusing load-bearing steel components, more specifically H and I steel sections?
2. What is the current process of analyzing and evaluating the structural integrity of reclaimed steel sections?
3. What are the current challenges in the different project phases, in terms of project coordination, to integrate reclaimed steel sections?
4. How can computational tools and digital data help to better integrate the available reclaimed steel sections in new construction?

0.6 METHODOLOGY

The methodology for this graduation thesis project follows a systematic approach to achieve its objectives. It starts with a comprehensive literature review and case study analysis to establish a solid understanding of the topic's relevance in the construction industry. This review provides insights into the current application of steel reuse and identifies the existing workflow process and challenges encountered when integrating reclaimed steel. In addition, interviews are conducted with industry professionals from different roles in the value chain either in person, when possible, or through digital video calls. These interviews provide valuable firsthand information about the practical implementation of steel reuse, as well as insights into the challenges faced by professionals in the field. The accuracy of the information gathered through interviews is ensured as the interviewees are given the opportunity to review their post-interview reports, which are referenced in Appendix B: Interview Reports. The knowledge gained from the literature review, case studies, and interviews provides understanding of what the current process, regulations and challenges are when designing with reclaimed steel. These findings serve as the foundation for the subsequent stages of the thesis project.

The research analysis and interviews led to the development of a design workflow that can improve the process of implementing steel reuse in the design process by addressing the individual challenges. The design workflow identifies the different project stages and encourages an integration of the entire project team to enhance the collaboration and flow of information among the different project stakeholders. Strategies are proposed to streamline the incorporation of reclaimed steel and optimize its use, considering factors such as project cost, time, and coordination. In parallel with the design workflow, a computational tool is created. This tool consists of a digital inventory and matching system designed to overcome the industry's challenges and facilitate the integrated design process proposed in the design workflow. It facilitates the exchange of information between material providers and material seekers, enabling efficient matching of available reclaimed steel with project requirements. This tool is specifically developed to improve the overall efficiency of the steel reuse process and mitigate the barriers faced in the industry.

Lastly, a design case study is conducted to validate the effectiveness of the design workflow and computational tool. The design case study provides a practical application of the proposed methodologies and allows for the demonstration of their proof of concept. Additionally, the matching algorithm generates valuable data for calculating environmental impacts, such as transportation emissions and energy consumption required for repairs of reclaimed steel elements.

1 LITERATURE REVIEW

1.1 CIRCULARITY OF STEEL

Steel, known for its strength and durability, lends itself well to circularity. By embracing the 10R principles, which include reuse and recycling, we have the potential to significantly decrease the demand for new steel production. This, in turn, will help conserve valuable resources, reduce energy consumption, and mitigate greenhouse gas emissions associated with the manufacturing process of steel. As previously mentioned, the recycling rate of steel stands at an impressive 91%, with an additional 5% being reused (Sansom & Avery, 2014). These statistics indicate substantial progress, considering that only approximately 4% of steel is currently disposed of. However, it is crucial to further reduce this 4% and enhance the reuse rate, as recycling steel remains an energy-intensive endeavor.

1.1.1 RE-CYCLE STEEL

With the objective of reducing primary steel production and helping mitigate greenhouse gas emissions, recycling of steel is a common practice which involves the remelting of the material to be remanufactured. Robert Frosch and Nicholas Gallopoulos, both laboratory researchers at General Motors, state "in an ideal industrial ecosystem, resources are not depleted any more than those in a biological ecosystem: a piece of steel could potentially show up one year in a drink can, the next year in an automobile, and 10 years later in the structural frame of a building" (Frosch & Gallopoulos, 1989). With that said, steel is in an open-loop recycling system where it can be remelted and used for any product application regardless of its origin (Walker et al., 2018). This means that steel is a material that can be continuously recycled without degradation to its properties, "no matter the product or form it takes" (Bennett, 2020).

The American Institute of Architects (AIA) published in their Environmental Resource Guide that for every kilogram of steel produced from recycled sources, rather than from raw materials, 12.5 MJ of energy is saved. This means 47 percent less oil is used, 86 percent fewer emissions are produced, 76 percent less water is contaminated, 40 percent less water is used, and 97 percent less mining waste is created (AIA, 1997). In addition to the energy savings, the figure 6 below shows the economical savings between new steel sections and scrap sections of structural steel. By incorporating recycled steel into construction projects, not only are valuable resources conserved, but it also offers a more cost-effective solution for builders and developers. This highlights the dual advantage of recycling steel in terms of both environmental sustainability and economic viability.

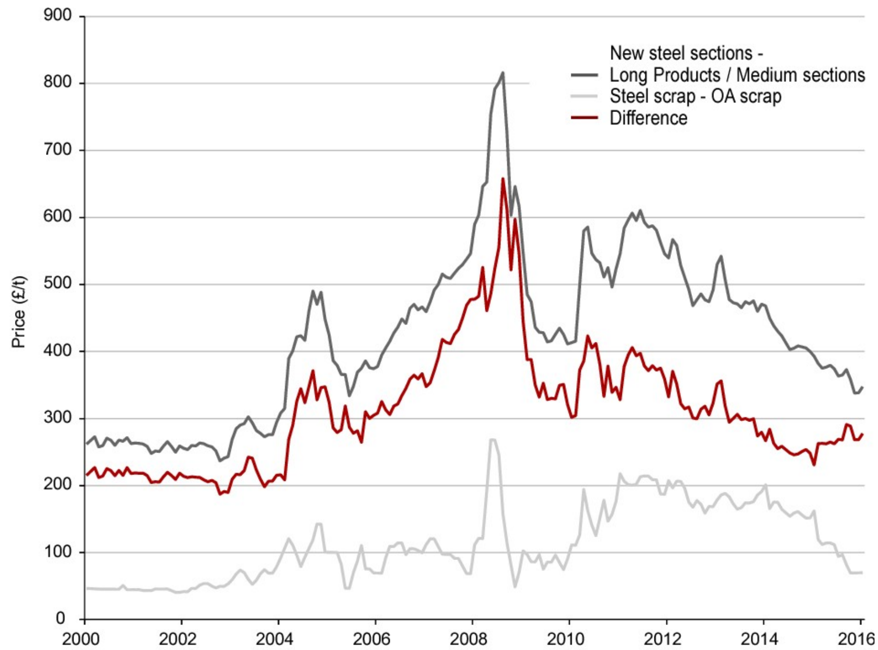

Figure 6 - Price Range Between New and Scrap Steel (Dunant et al., 2018).

The process of steel recycling, as discussed by Donovan Bennett, Waste Diversion Manager of Rubicon, involves salvaging steel and selling it to scrap yards for sorting, cleaning, and subsequent processing in mills or factories. The steel is then cut or shredded into smaller pieces, purified to remove contaminants, and melted in a furnace operating at temperatures nearing 1,600 degrees Celsius (Bennett, 2020). Lastly, the newly recycled steel is sent to different factories to be remanufactured, and the cycle begins again. While recycling steel reduces the use of primary resources, the process is nevertheless very energy intensive (Walker et al., 2018).

In an effort to address the energy-intensive nature of steel production, researchers at the Massachusetts Institute of Technology (MIT) have discovered a promising alternative called molten oxide electrolysis (MOE). MOE utilizes electricity to break down iron oxide, enabling the production of carbon-free steel with no CO2 emissions. This process involves heating the iron oxide in a furnace and then passing electricity through electrodes (*Scientists Discover Green Way to Produce Steel*, n.d.) While the MOE process is a great improvement, the production of steel is still very energy intensive. However, despite the advancements offered by MOE, the overall production of steel remains highly energy-intensive. Paul Behrens, a researcher at Leiden University, explains that decarbonizing the steel production sector is challenging due to the difficulty of achieving the high temperatures required for steel production using electricity (Xiaoyang Zhong et al, 2021). Therefore, it is crucial to explore additional approaches and strategies to mitigate the GHG emissions associated with the steel industry.

1.1.2 RE-USE STEEL

Reusing steel involves extending the product life by utilizing it again in the same or different applications, rather than sending it for remelting at a steel manufacturing site. This shift in mindset reframes the perception of reusing steel from something old with diminished value to an extension of its life cycle and salvaging its usefulness (Walker et al., 2018). However, the broader adoption of recycled materials and used components in the construction industry faces challenges. These include economic concerns, technical considerations, perception issues, and a lack of information and clear guidance, which can be exacerbated by prejudice (Gorgolewski, 2006). In some cases, remanufacturing may be necessary before reusing steel, highlighting the diverse facets and approaches to reuse (Walker et al., 2018). Although the idea of reusing salvaged steel is not new (Sansom, 2017), addressing these challenges and fostering a greater acceptance of reuse in the construction industry can contribute to more sustainable practices.

BENEFITS OF REUSING STEEL

Reusing steel in the construction industry offers significant benefits, providing an opportunity to address resource depletion and reduce environmental impacts. Existing buildings represent vast reservoirs of materials and components that can be efficiently repurposed, extending their lifespan and conserving resources (Gorgolewski & Morettin, n.d.). Reuse requires minimal reprocessing, with repairs and transportation being the main energy-intensive aspect (Gorgolewski, 2006). Additionally, as the costs of landfill disposal continue to rise, coupled with evolving legislation in Europe, where producers are increasingly responsible for product end-of-life management, there is a growing need to embrace reuse practices (Gorgolewski, 2006).

Reuse of steel has demonstrated significant environmental benefits and considerable reductions in greenhouse gas emissions compared to recycling (Steel Construction Institute, n.d.). The recognition of the environmental and cost advantages of such practices by organizations such as the Steel Construction Institute (SCI) and the British Constructional Steelwork Association (BCSA) in the UK indicates that the market will drive the development of efficient models for reclamation and reuse (Morby, 2022). Given the increasing demand for steel and the depletion of natural resources, reusing steel in existing buildings becomes an attractive solution, especially considering the longevity of steel structures.

However, mechanisms are needed to stimulate the market for recovered resources and facilitate the incorporation of materials from demolition projects into new construction. The value of salvaged components should be recognized by salvage contractors, leading to increased awareness of their importance (Gorgolewski Vera Straka Jordan Edmonds Carmela Sergio, 2006). Additionally, analyzing structural systems presents opportunities and constraints that require effective management. Notably, steel's ferromagnetic properties simplify the extraction of steel scraps from the waste stream (Gorgolewski, 2006). Yet, to ensure successful steel reuse, understanding the fabric of existing buildings through surveys, sample removal, and laboratory testing is essential. Testing procedures for steel may include positive materials identification, tensile testing, intumescent determination, and microstructural examination

(Burdett, 2023). Designers and construction professionals can overcome challenges related to the reuse of steel by adopting specific strategies which are proposed in Section 3.3.

The practice of upscaling building elements, specifically reusing salvaged structural steel, offers a sustainable solution to the challenges faced by designers in the construction industry. It involves leveraging existing materials instead of manufacturing new ones, thereby reducing the environmental impact of new construction and the associated carbon emissions (International EPD System Technical Committee, 2022). The reuse of steel not only reduces material costs but also increases the value of salvaged components (Gorgolewski, 2006). By eliminating the remelting process, long-distance transportation, and the use of iron ore, reusing steel elements can significantly reduce carbon emissions by approximately 97.5% compared to the average emissions associated with steel production (Arksey, 2023). This emphasizes the environmental benefits of adopting a reuse approach in construction projects.

Overall, the reuse of steel in construction presents an opportunity to reduce environmental impacts, lower costs, and maximize the value of salvaged components, contributing to a more sustainable and resource-efficient building industry. However, there are still challenges in promoting the use of reclaimed steel due to a lack of clear information and guidance for designers and owners (Gorgolewski, 2006), as well as the prevailing focus on fast, easy, and economical construction and demolition practices. Nevertheless, the exceptional properties and versatility of steel make it a valuable material for a range of industries and applications, and its continued development and use will be essential for future innovation and progress.

1.2 APPLICATION OF CIRCULAR PRINCIPLES

The concept of circularity in steel reuse encompasses various state-of-the-art principles and approaches aimed at maximizing the value and lifespan of steel structures. Some notable applications include: urban mining, design for modularity and disassembly, and material databases that enable quantifiable environmental information on the life cycle of a product.

1.2.1 URBAN MINING

Urbanist Jane Jacobs proclaimed that “cities are the mines of the future” (Graedel, 2011) leading to the development of urban mining to utilize the existing materials in our current building stock. Urban mining refers to the process of recovering valuable resources, such as steel, from existing built environments. It involves systematically identifying, dismantling, and extracting reusable materials from buildings and infrastructure, treating them as "above-ground" mines. Prof. Gorgolewski stated that existing buildings are vast reservoirs of materials which can potentially be extracted and serve as valuable resources to meet essential needs (Gorgolewski & Morettin, n.d.). He further suggests that this concept can generate new jobs and business opportunities as the market expands. This is backed up by the fact that metals are the most monetary valuable materials in the construction and demolition waste (Mulders, 2013). An example of such initiative is the project "Prospecting the Urban Mines of Amsterdam" (PUMA) by Waag Futurelab in collaboration with TU Delft and Leiden University. They utilize a geological map to quantify the current metal resources in existing buildings and estimate when they will become available (Waag Futurelab, n.d.). Figure 7 below is an example of the prospect of kilograms of steel and copper within the city of Amsterdam. While the accuracy of this geological map is still being tested and improved, it is a step in the right direction as it could help determine available materials for future construction.

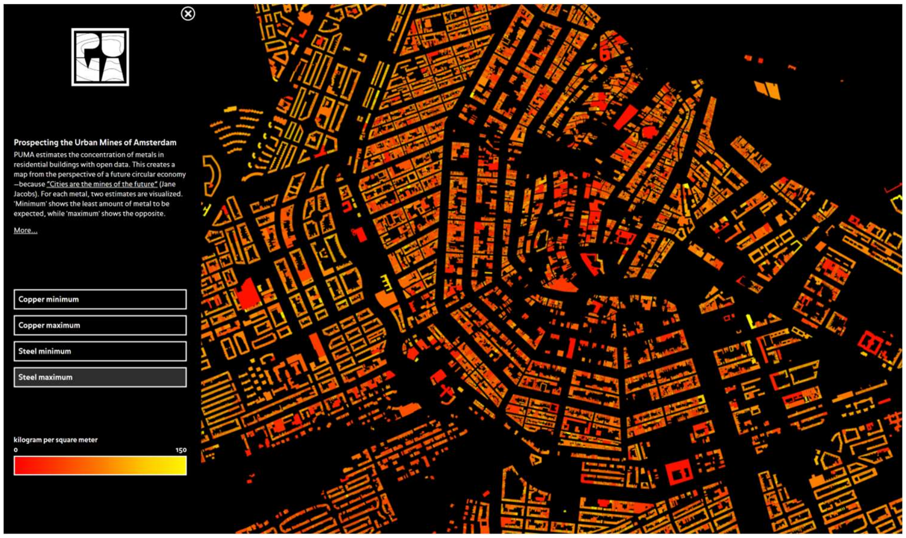

Figure 7: PUMA prospecting the urban mines of Amsterdam (Waag Futurelab, n.d.)

1.2.2 DESIGN FOR MODULARITY AND DISSASEMBLY

The current practice of demolishing buildings often neglects the preservation of reusable building components. The potential for reusing these components greatly depends on the original construction methods employed. While there is a growing awareness of sustainability and embodied energy in material selection, little consideration is given to how these components can be effectively disassembled. It is crucial to highlight the significance of this aspect as it greatly facilitates the future reusability of building components (Sansom, 2017).

Design for modularity and disassembly is a fundamental principle of circularity, aiming to extend the life cycle of a product through easy disassembly and subsequent reuse. Modular design involves the use of standardized and interchangeable components, allowing for flexibility and adaptability in future uses or modifications. By incorporating design strategies that prioritize disassembly, such as modular construction, standardized connections, and reversible assembly methods, the lifespan and value of steel components can be extended. To begin with, the types of materials selected for a construction should be able to be taken apart by following a "layering approach" (Sansom, 2017). Steel is a suitable material for this especially when designed with mechanical connections. Furthermore, Sansom (2017) emphasizes the importance of providing both construction and deconstruction plans, which identify load transfer systems and aid in planning for disassembly after a building's life cycle.

Design for modularity and disassembly facilitates the efficient separation of different materials and encourages the use of non-permanent fasteners and techniques that enable easy access for maintenance, repair, and replacement. By applying circularity principles through design for disassembly, not only is the environmental impact of steel structures reduced, but it also fosters a more sustainable and resource-efficient approach to construction, where materials can be repurposed or recycled, contributing to the circular economy.

1.2.3 BUILDING LIFE-CYCLE ASSESSMENT

Building life cycle stages encompass the various phases a building goes through from conception to demolition or renovation. In European markets, EN 15978 and EN 15804 standards define these stages (Masson, 2023). With growing awareness of building environmental impacts and the availability of technological tools, Life Cycle Assessments (LCAs) are employed to evaluate and provide insights into a building's performance throughout its life cycle (Nwodo & Anumba, 2019). Figure 8 illustrates the product, construction, usage, and end-of-life stages, representing a building's life cycle from “cradle to grave.” However, stage D was added to implement the cradle-to-cradle circularity principle. In the context of this research, the assessment of reclaimed steel elements would be carried out within the framework of life cycle stage D, considering the benefits it offers in terms of reduced resource consumption, energy usage, waste generation, and greenhouse gas emissions compared to the production and disposal of new materials.

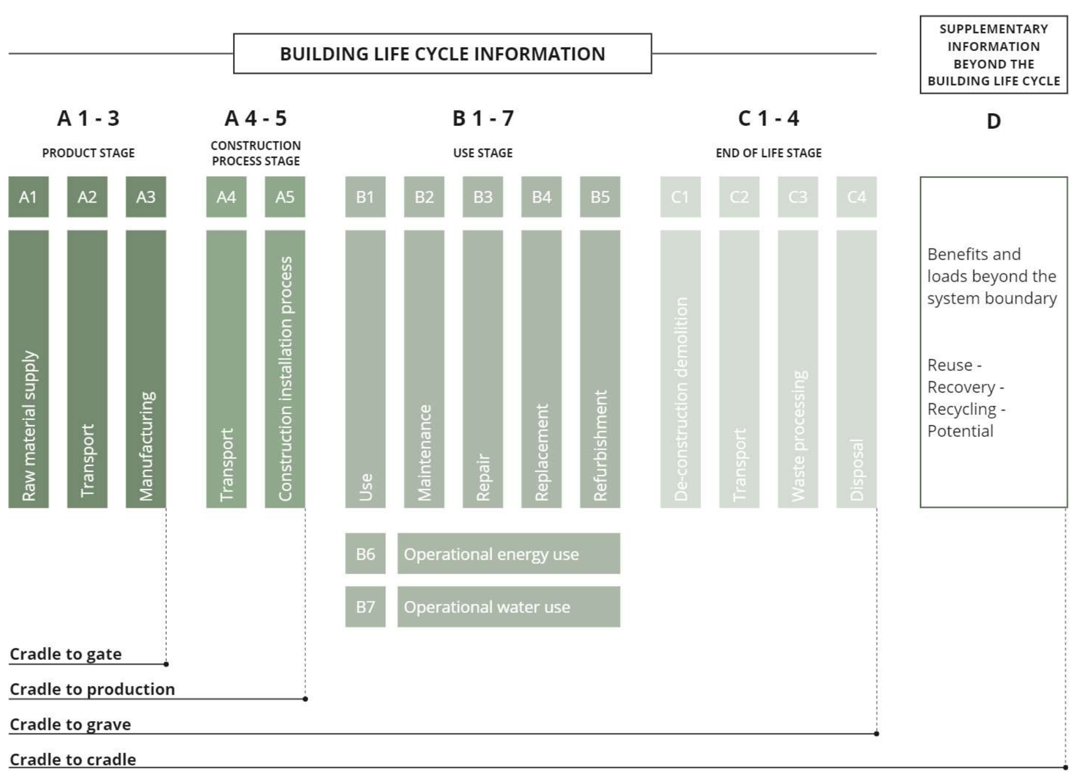

Figure 8: Life-Cycle Stages per EN Standards – own diagram based on (Masson, 2023)

1.2.4 ENVIRONMENTAL PRODUCT DECLARATION FOR RECLAIMED STEEL

European Metal Recycling (EMR) partnered with Metsims Sustainability Consultancy to produce the world's first Environmental Product Declaration (EPD) for its reclaimed steel elements. The EPD is a standardized document that provides comprehensive information about a product's environmental impact to guarantee a global warming potential (GWP) score measured in kilograms of CO2 equivalent (kgCO2e). This is based on verified data obtained from life cycle assessments (LCA) or life cycle inventories (LCI), following the guidelines of ISO 14040 and ISO 14044 (International EPD System Technical Committee, 2022).

EMR's EPD specifically focuses on 1 ton of reusable steel in 2021, utilizing the Ecoinvent 3.5 database and the SimaPro 9.0 LCA software. It's important to note that for reusable steel, the construction process stage and usage stage are not considered relevant in the LCA results as they are undertaken by other parties in the supply chain (International EPD System Technical Committee, 2022). The LCA analysis provided in the EPD document, found in Appendix C, highlights specific stages that contribute to the overall environmental impact of reusable steel. These stages are illustrated on Figure 9.

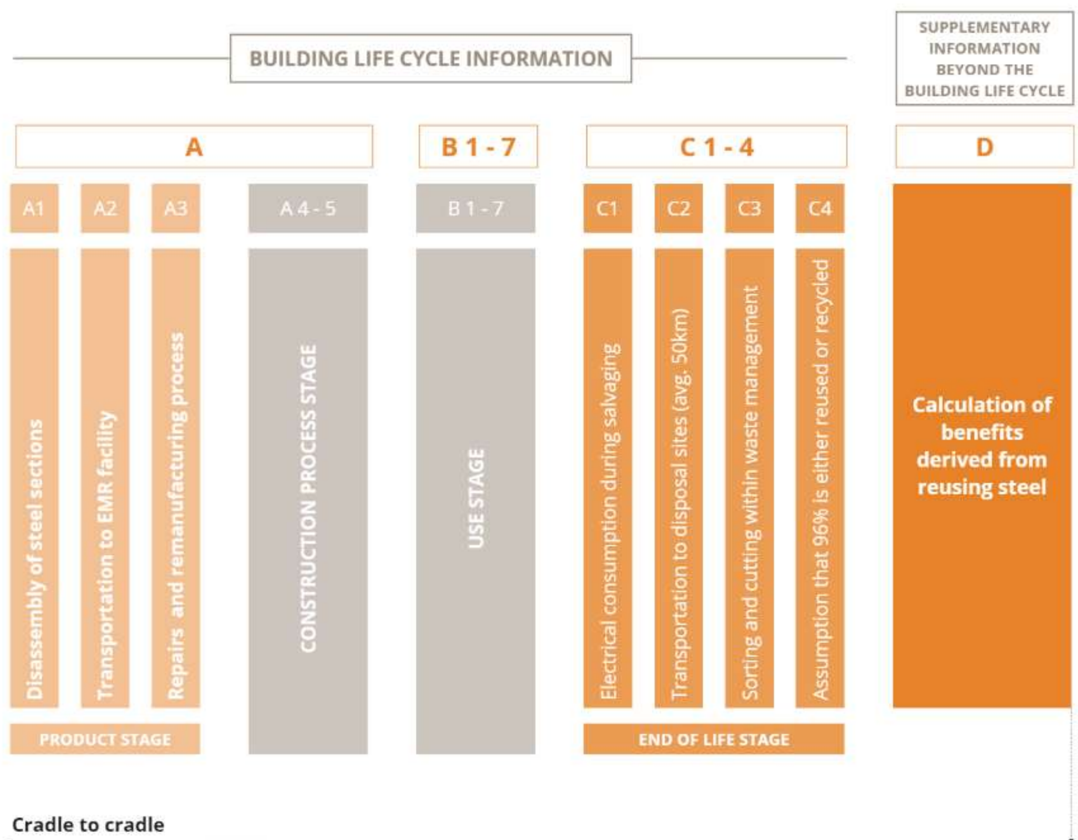

Figure 9: Life Cycle Stages for Reclaimed Steel – own diagram based on (International EPD System Technical Committee, 2022)

In conclusion, the EPD and LCA analysis for reusable steel provide valuable insights into the environmental performance of this sustainable construction material, empowering customers with essential information to make informed decisions, compare independently verified low carbon steel with traditional products, and promote the use of reclaimed materials.

1.2.5 MATERIAL PASSPORT

Material passports are digital record that provides detailed information about the composition, quality, and origin of building materials used in a structure. These records enable the identification and tracking of building materials throughout their lifecycle. They utilize data from the EPD's to assess the life cycle environmental performance of products, including their carbon footprint, energy consumption, and resource depletion. Furthermore, material passports can integrate digital technologies, such as BIM, to create a comprehensive digital representation of the materials used in a structure. This valuable resource benefits designers, contractors, and other stakeholders by providing easy access to information, which can be shared and accessed by multiple users at any point in time. These tools promote responsible sourcing of materials and encourage the circular usage of building components.

There following are three companies focusing on material passports, which were research and compared:

BAMB (Buildings as Material Banks): is a project, funded by the European Commission within Horizon 2020, uniting 15 parties across Europe with the goal of enabling a systemic shift in the building sector through the creation of circular solutions, contributing to the development of a sustainable economy and growth (BAMB, 2019). Drees & Sommer, a sustainability consultancy company, and the Environmental Protection Encouragement Agency (EPEA), an environmental consulting firm, are consortium members involved in the development of the BAMB project. In an interview with Kunal Harale (2023) and Matthias Bolza-Schuenemann (2023) from Drees & Sommer, they explained that the process of utilizing BAMB in an architectural project involves matching a material passport ID code with the "family component" codes used in Revit Autodesk. Once finalized, the BIM model is imported into the BAMB platform to obtain a performance overview, including information on material health, sourcing, demountability percentage, carbon footprint, material recovery, and separability. The BAMB database sources information from Madaster, discussed in the following paragraph, and Building Material Scout.

Madaster: is an advanced digital platform that enables meticulous registration and documentation of building materials. Through the platform, detailed information about building materials, including EPD's, can be stored, ensuring transparency and traceability throughout the building's life cycle. Madaster further promotes the principles of the circular economy by facilitating a marketplace for the exchange and trading of materials, fostering a more sustainable approach to resource management. In a demo presented by Mees Van Rhijn (2023), Junior Product Manager at Madaster, the workflow process within the platform was showcased. Users can utilize BIM (IFC) files or Excel documents to assess the reuse potential of specific elements. The system allows for the upload of Revit models, generating certificates and creating digital twins of building structures. Hamed Khalidi (2023), Senior Architect at Arup (Berlin), explained that this process can be time-consuming. The Revit model needs to include complete details about the materials and components and be categorized per the "6 building layers," according to Stewart Brand, as each layer has different lifespans. While Madaster's innovative approach holds significant potential, there are challenges related to liability, particularly in non-public projects, that need to be addressed for broader adoption. In addition, Madaster only operates in the Netherlands, Belgium, Norway, Germany, Austria, and Switzerland.

EC3 (Embodied Carbon in Construction Calculator): is a project funded by the Carbon Leadership Forum and 50 other industry-leaders that focuses on measuring and disclosing the embodied carbon of building materials (Carbon Leadership Forum, n.d.). Through its database and software tool, EC3 provides an embodied carbon calculator that allows users to access and compare the embodied carbon values of different materials, enabling informed decision-making for sustainable material choices. The calculations are verified by EPD's and supply chain data, ensuring accuracy and reliability. EC3 actively incentivizes manufacturers to be transparent about their material utilization and carbon emissions. To facilitate the assessment of embodied carbon, EC3 utilizes the "tallyCAT" public beta tool, a Revit plug-in that enables designers to assess embodied carbon and generate reports directly within the Revit software. This user-friendly approach eliminates the need for transitioning to another software, allowing designers to seamlessly incorporate sustainability considerations into their ongoing design process.

To conclude, these three projects offer user-friendly platforms that enable the utilization of environmental and product data for informed decision-making during the design and material selection process. This encourages designers and contractors to prioritize building components based on their environmental impact and potential for disassembly, reuse, or recycling. While EC3 focuses on embodied carbon assessment and lacks a comprehensive material passport system like BAMB and Madaster, its data and tools can be integrated into material passports to enhance environmental impact assessments and advance sustainable construction practices. However, the implementation of material passports faces challenges such as acquiring historical data for disassembled buildings, the lack of standardized reuse processes, concerns regarding liability, and varying standards across countries. It is important to note that material passports primarily focus on environmental factors and the disassembly percentage of a building, rather than providing detailed information about individual components. For instance, when considering a structural steel framework, the results would indicate the embodied carbon of the components and the detachability percentage based on the overall building design, but they would not include specific data about material properties or structural details. Furthermore, the current implementation of material passports is primarily geared towards new building projects, incorporating new EPD data. As a result, they are not yet suitable for existing buildings or those with reclaimed components. However, there is an opportunity to bridge this gap by linking data from new projects with existing information as shown in Figure 10. This is further discussed further in Section 3.3 and Section 4.7.

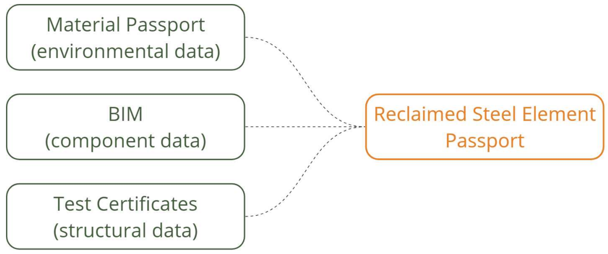

Figure 10: Reclaimed Steel Element Passport utilizing material passport data

1.3 APPLICATION OF STEEL REUSE

1.3.1 REUSE BUSINESS MODELS

The reuse of building elements has become an increasingly popular strategy in sustainable construction. The different business models for reusing steel structures in new buildings are same-site reuse, site-to-site reuse, and reclamation market (Brütting, De Wolf, et al., 2019). These different methods are further explained in the section below. Overall, the choice of business model for reusing steel structures will depend on various factors, including the condition and suitability of the existing building, the requirements and constraints of the new project, and the availability and cost of resources for dismantling, transportation, and reuse. Figure 11 illustrates the different business models that can be employed for reusing building elements. The solid lines depict the typical process flow for each method of reusing, recycling, or discarding building elements, while the dashed line represents a possible decision point.

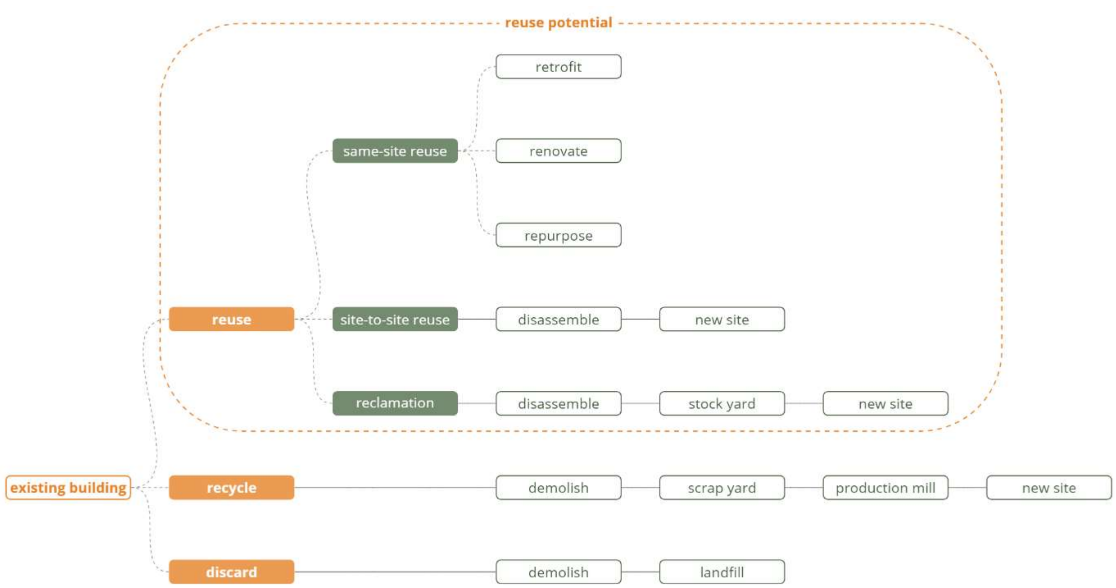

Figure 11: Reuse Potential Business Models

SAME-SITE REUSE

Adaptive reuse on the original location through retrofitting, repurposing, and renovating is a common model for reusing steel structures. This approach involves repurposing the existing building for a new use or updating the building to meet modern standards. The benefits of this approach include preserving the building's historic or cultural value, reducing waste and carbon emissions associated with demolition, and potentially saving costs compared to building a new structure. However, this method also includes the ability to disassemble the existing structure and reassemble the reused structure in a new building design. For this research, the following definitions are considered for the following terms: Retrofitting is to upgrade a building's systems to improve performance and sustainability. Renovating refers to the process of making repairs or improvements to update or modernize the building. Repurposing is to change the functional use of the building for a new purpose.

SITE-TO-SITE REUSE

Reuse from donor building involves dismantling the existing building and transporting the steel components to a new location for reuse. This approach can save costs compared to building a new structure and can be a good option for structures that are well-suited for the new use and buildings that are not suitable for renovation or retrofitting. However, this approach requires more effort and resources for dismantling and transportation as well as adapting the new building to the previous structure. The *Biopartner 5 Lab* project, further explained in Section 1.4.1, is an example of utilizing a donor building for the design and construction of a new building in a different site location.

RECLAMATION MARKET

Reuse through salvaging and resale involves using individual reclaimed steel components from a stock yard for new construction projects. The *Mundo Lab LLN* project analyzed in Section 1.4.1 is an example of such business model. This approach can be a good option for structures that require specific components or for projects with limited space or access for large-scale reuse. However, this approach may require more effort and resources for sourcing and selecting components and may not be feasible if the required components are not available or in good condition.

With that in mind, the focus of this thesis research is on the reclamation market business model. This method presents a level of complexity and associated challenges involving various stakeholders in a project team. Moreover, it offers unique opportunities for incorporating reclaimed materials into new construction projects, fostering circularity, and addressing sustainability challenges.

1.4 CASE STUDIES

1.4.1 PROJECTS WITH RECLAIMED STEEL

The use of reclaimed steel elements in new construction is an increasingly viable option due to its environmental benefits, but still remains a relatively uncommon practice. To understand the reasons for this and to identify strategies for increasing the use of reclaimed steel, it is essential to study successful projects that have reused steel elements. By examining the experiences of such projects, including their successes and challenges, valuable insights can be gained that can inform future reuse efforts. This chapter, presents case studies of projects that have successfully incorporated reclaimed steel elements into their construction, providing a comprehensive understanding of the design and construction process, as well as the economic and environmental impacts of these initiatives.

CASE STUDY 1 – MUNDO LAB LLN, BELGIUM

Figure 12: Mundo LLN (A2M architects)

Figure 13: Stocked steel sections (Swanenberg IJzer Groep)

Mundo Lab, Louvain-la-Neuve offers private and professional workspaces, meeting rooms, and a restaurant (Mundo Lab, n.d.). The building consists of a renovated barn and a new construction designed by A2M Architects. For this project, 150 reclaimed steel sections were used, which were salvaged and resold by Swanenberg IJzer Groep, a stock company based in the Netherlands. This innovative use of reclaimed steel sections made Mundo Lab the first building in Belgium to successfully implement this sustainable practice (Architectura, 2022). Julien Willem, a project manager at Mundo Lab, explained that the use of reclaimed steel reduced the project's environmental impact by approximately 20% compared to using new steel (de Wasseige, 2022). In addition to reclaimed steel, Mundo Lab incorporated other sustainable choices such as recovered bricks, furniture, doors, light fixtures, and glass partitions. It is important to note that while the overall project cost was lower, the primary motivation behind these sustainable choices was not cost but rather environmental considerations (Architectura, 2022).

During the research process, an interview was done with Alice Herman (2023), a Sustainability Consultant at Drees & Sommer and former Project Manager at A2M Architects. Herman mentioned that Mundo Lab extensively searched various stock yards to source the steel sections required for the project. In an interview with Frank Van Der Loop (2023), Sales Purchase Manager at Swanenberg Ijzer Groep, he mentioned that Mundo Lab requested a stock list of the available elements from the stock yard. The sections were manually selected based on their compatibility with the structural design before the purchase was made. Van Der Loop stated that the stock company did not require extensive coordination in this process (2023). After purchasing the reclaimed elements, a company near the project site in Charleroi was responsible for sanding, shot-blasting, repainting, and cutting the 75 tons of steel sections to the required dimensions (de Wasseige, 2022).

The project adhered to the P427 standards of the Steel Construction Institute, which are further explained in Section 1.5.4. A technical report discussed during the interview highlighted the properties and characteristics of the reclaimed steel, confirming its suitability for the Mundo Lab LLN project. The report also mentioned considerations for further testing and weldability based on the chemical composition results. Additionally, a damage report was produced by a third-party inspection company to ensure quality control. This report identified any defects and referred to EN1993 to estimate the previous functionality of the reclaimed elements. It helped determine the suitability of the elements for the project, and if there were concerns, additional testing or repairs were recommended to verify their structural integrity.

While the project successfully utilized reclaimed elements, it faced inevitable challenges. According to Herman (2023), since the priority was circularity, the client was willing to take risks and manage the challenges associated with designing with reclaimed elements. These challenges included sourcing specific steel sections and obtaining their historical information, as the sections came from different deconstructed buildings in the Netherlands. Structural oversizing to accommodate the reuse of available stock and the testing required to ensure the structural viability of the reclaimed sections were additional challenges encountered during the process.

CASE STUDY 2 - BIOPARTNER 5, NETHERLANDS

Figure 14: reused structural skeleton (Terwel et al., 2021b)

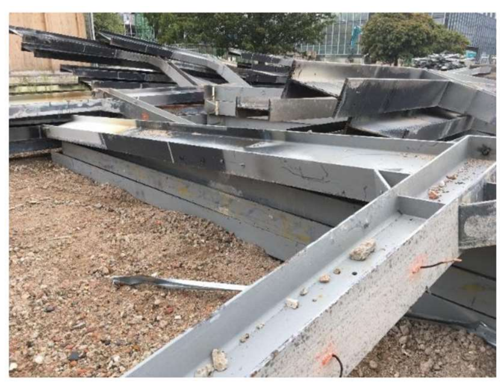

Figure 15: damaged beams (Terwel et al., 2021b)

The Biopartner 5 Lab project involved the reuse of steel components from a donor building to construct a new building at a different site. The process began with an investigation of the building and its components to assess their potential for reuse. A comparison was then made between the existing building design and the new design to determine the feasibility of incorporating the existing structural elements. Once the building was identified as a suitable donor skeleton, the new design was modified to align with the design of the existing building, with grid lines set at 3.6m for optimal reuse efficiency.

During the design phase, a BIM 3D model was created to integrate the existing and new structural elements, assigning each element a unique "element code" to establish critical dimensions and allowable tolerances. To enhance stability, a portal frame was added in one direction, considering the moment resisting connections of the existing structure. The design was further assessed, and wind braces and a structural truss made of new steel were incorporated where deemed more cost-effective and labor efficient. Finally, the existing building was carefully disassembled for reuse, and destructive tests were conducted on the reclaimed materials. The chemical composition of the steel was analyzed to ensure its suitability for welding connections, and existing welded connections were reinforced with bolted connections. In the end, approximately two-thirds of the steel structure (165,000 kilograms) consisted of reclaimed structural steel (IMd_BioPartner 5, 2022). The new building was designed with bolted connections and smart detailing to facilitate future disassembly.

However, the process of reusing steel components in the construction of the Biopartner 5 lab presented several challenges. Coordinating allowable deviations with the contractor proved to be difficult, and some elements suffered more damage than acceptable during disassembly. Improper storage of disassembled elements also led to additional deformations. Discrepancies between existing drawings and actual connection details required the reconsideration of several connection details. Unforeseen challenges arose during construction, demanding improvisation to resolve issues, including the reinforcement of connections. Despite these difficulties, the project team demonstrated close collaboration and resourcefulness to overcome the challenges encountered during the reuse of steel components in the construction process.

CASE STUDY 3 - ENERGIE KOSMOS BUILDING, SWITZERLAND

Figure 16: Tagging of reclaimed elements (EPFL, 2022)

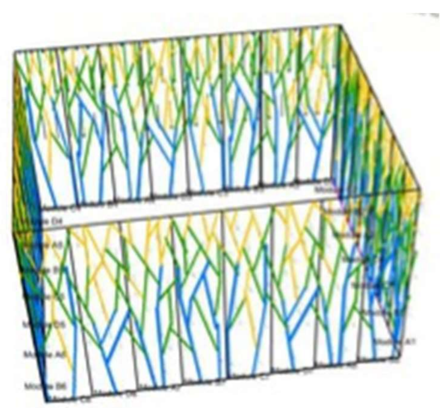

Figure 17: EPFL implementing Phoenix 3D (EPFL, 2022)

This case study examines the use of Phoenix 3D software, which is further discussed in Section 1.4.2. The computational software was utilized to determine the design and layout of the reclaimed steel members that were purchased from the network operator, Swissgrid, as scrap material. The reuse of these elements was planned at an early stage and the design was based on the availability and dimensions of the existing components and adapted accordingly. It is important to note that this project did not reuse structural steel sections for the building's framework. Instead, the electricity pylons were repurposed as façade formwork where green vegetation could grow to provide shade and climate control. The design team collaborated with Structural Xploration Lab, who provided algorithms to optimize the layout of the steel members per their various cross sections and masses (EPFL, 2022). The Phoenix 3D software was utilized to test its efficiency and demonstrated that a digital process can simplify and streamline the design process more efficiently.

LESSONS LEARNED

Based on the process and challenges discussed in the case study project above, the following can be determined:

Sourcing Specific Steel Sections: Finding the required reclaimed steel sections with specific dimensions and properties can be challenging, as they often come from various deconstructed buildings or stock yards. This process involves checking available stocks and cross-reference with the list of design items needed for the new project. This can be very time consuming and prone to discrepancies if done by hand.

Historical Information and Documentation: Obtaining accurate historical information about the reclaimed steel sections, such as their previous usage, manufacturing date, and quality, can be difficult. This information is crucial for assessing their structural integrity and suitability for reuse.

Structural Oversizing: Reclaimed steel sections may have different dimensions and properties compared to new steel, requiring structural oversizing or modifications to accommodate their reuse. Ensuring the structural viability of the reclaimed sections while optimizing the design can be a challenge.

Testing and Quality Control: Verifying the quality and structural integrity of reclaimed steel sections often requires destructive and non-destructive testing, as well as inspections by third-party companies. Coordinating and conducting these tests to ensure compliance with safety and performance standards can be complex.

Coordination and Collaboration: Coordinating with various stakeholders, including suppliers, contractors, designers, and clients, to ensure smooth procurement, fabrication, and installation of reclaimed steel sections can pose challenges. Effective collaboration and communication are essential to address issues that may arise during the process.

Weldability and Chemical Composition: Assessing the weldability of reclaimed steel sections, particularly if the date of manufacture is unknown, requires analyzing the chemical composition. Ensuring that the reclaimed steel sections meet the necessary welding requirements and compatibility with existing connections can be challenging.

Preservation and Storage: Proper preservation and storage of reclaimed steel sections, both before and after their use, is crucial to maintain their quality and prevent further degradation or damage. Developing suitable preservation techniques and storage practices can be a challenge, especially for large quantities of reclaimed steel.

Cost Considerations: While reclaimed steel sections may offer cost savings compared to new steel, evaluating the overall economic feasibility and balancing it with other project priorities can be a challenge. Cost assessments should consider not only the procurement of reclaimed steel but also any necessary modifications, testing, and additional coordination efforts.

Building Code Compliance: Ensuring that reclaimed steel sections meet the required building codes, regulations, and industry standards can be a challenge. Adhering to structural design requirements, safety standards, and environmental regulations is essential for successful implementation.

Knowledge and Awareness: Promoting knowledge and awareness among stakeholders, including architects, engineers, contractors, and clients, about the benefits, challenges, and best practices of utilizing reclaimed steel is crucial. Building expertise and understanding regarding reclaimed materials can facilitate their broader adoption in construction projects.

With an understanding of these case studies, the next section will delve into the role of computational case studies and how technology can facilitate the implementation of reclaimed steel in new construction projects.

1.4.2 COMPUTATIONAL TOOLS TO DESIGN WITH RECLAIMED STEEL

In an interview with Michael Sansom (2023), he states the potential of utilizing BIM technologies to provide reliable information on material properties, provenance, and traceability. This advancement has the potential to eliminate the need for extensive testing when reusing steel in the future. BIM models offer a cost-effective approach to enable and streamline future reuse for several reasons. These include efficient refurbishment and structural extension of existing structures, safe deconstruction, detailed inventory of reclaimed steel sections with complete traceability and relevant material properties, and optimization of the recycling process through a comprehensive understanding of steel metallurgy. To explore the potential of such tools in facilitating the integration of reclaimed steel elements in new construction, the following section presents three computational case studies that were conducted.

CASE STUDY 1 – "BALANCING DESIGN & CIRCULARITY"

Geke Rademaker (2022), a TU Delft alumna, focused her master's thesis on optimizing the reuse of steel elements in the design of frame structures. The development of a Python script was utilized to aid in the design process of load-bearing structures when reusing steel H sections. The script was tested on a theoretical case study with guidance from TU Delft professors and the engineering company, Arcadis. The proposed optimization process involved defining the available reusable elements and the initial geometry composed of nodes and connecting lines, as well as implementing constraints such as minimum UC-value and maximum deviation in length. To analyze different geometrical shapes – tringle, quadrilateral, and pentagon – the load calculations were done in a triangular form as opposed to an equal distributed load, which added some complexities to the calculations. The available stock was organized by ID information, such as the structural material, type of profiles, count of elements, and lengths. The script then ran several iterations to find the closest matches between the available stock and the design elements.

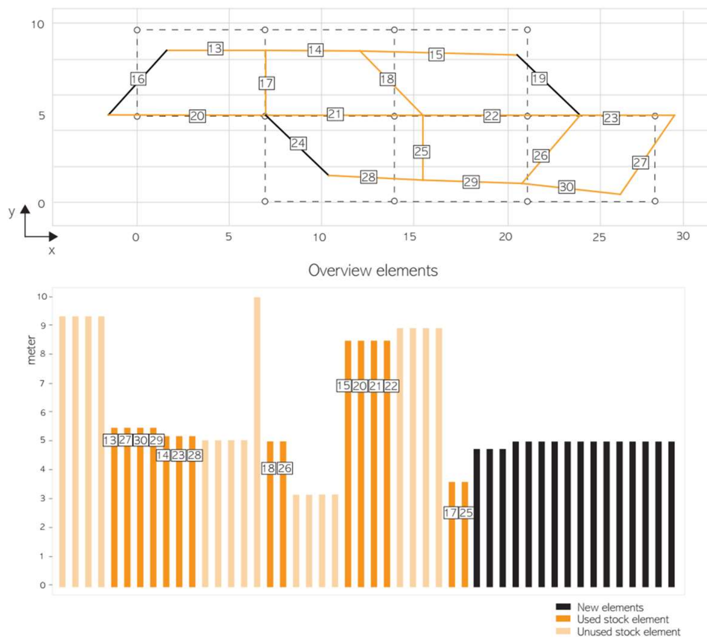

Figure 18: Result of circular element-configuration (Rademaker, 2022).

Figure 18 above illustrates the results when substituting reclaimed steel members within the set design. However, Rademaker's (2023) process does not account for the remanufacturing or cutting of steel elements to match the needed lengths of the design. This results in large modifications to the design, creating varying grid size lengths and irregular angles. These would cause complications during construction and building system coordination in a real project scenario. To address this issue, improvements could include implementing the cutting of elements that fit the criteria but are not exact in size. This approach would prioritize the design and modularity of frame structures by maintaining a regular grid size and angles. Although the remanufacturing process might increase project cost and time, it would allow for easier future reusability of the structure.

CASE STUDY 2 – "QUANTIFYING LIFE CYCLE ENVIRONMENTAL BENEFITS OF CIRCULAR STEEL BUILDING DESIGNS"

Joris van Maastrigt (2019), also TU Delft alumna, along with the engineering firm, ARUP, developed an environmental assessment tool for the reuse of steel members in building designs. The computational tool developed is specifically designed to analyze load-bearing structural steel elements, specifically H and I profiles, within the building industry. Its primary use is intended for early design stages before connection details and finishes have been determined. The purpose of the tool is to serve as a design check, specifically for substituting new steel elements with circular steel elements. It is important to note, however, that the tool is not intended for structural layout optimization.

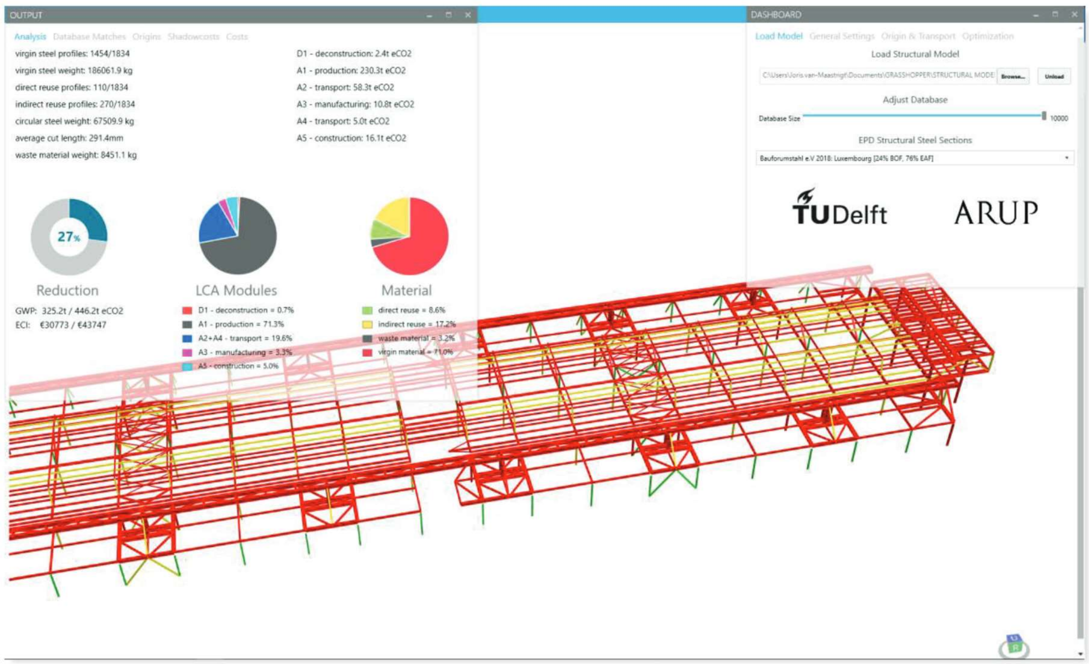

Figure 19: Digital interface of environmental assessment tool (Van Maastrigt, 2019)

The resulting tool, shown in Figure 19, has three components: a dashboard, an output window, and a 3D model. The dashboard is used to adjust the tool's settings according to project preferences. The output is a 3D visualization of the structural steel design where elements are highlighted based on reused, recycled, and virgin material. The output window displays environmental assessment results, such as the percentage of reused and virgin material, CO2 emissions, cost savings, and a life cycle analysis of the structural design.

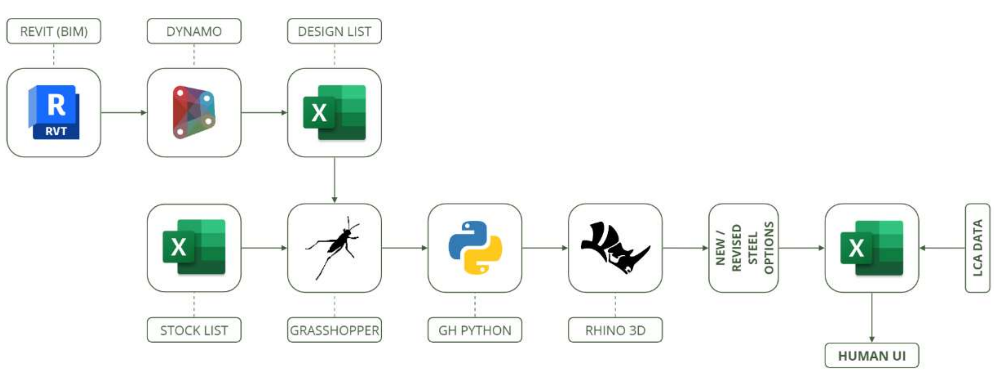

Figure 20: Interpreted workflow of Maastrigt's tool (Van Maastrigt, 2019)

Figure 20 illustrates the interpreted workflow from Van Maastrigt's (2023) computational tool, which involves the exchange of information among multiple digital software. Although the user interface seems straightforward, gathering information from different software can be complex. A potential solution to simplify this process would be to combine IFC open file from Revit Autodesk software and the data from Excel within a Grasshopper script. Moreover, creating live data from both softwares would facilitate the process during the design phase and ensure a constant flow of information. In a personal discussion with Van Maastrigt, he mentioned that the tool was intended to serve as a design check at the end of the design phase to provide environmental and cost assessments for the project. However, the current workflow is not suitable for making informed design decisions throughout the project due to the multi-step process involved in different software tools.

CASE STUDY 3 – PHOENIX 3D

The Phoenix 3D software, developed by Jan Brutting (2020), EPFL's Structural Xploration Lab, and Assistant Professor Corentin Fivet, promotes a circular design approach in the structural design process by incorporating reclaimed steel elements in complex truss structures. The tool is a plug-in for Grasshopper that offers real-time feedback and fast design variations for optimized structural layouts.

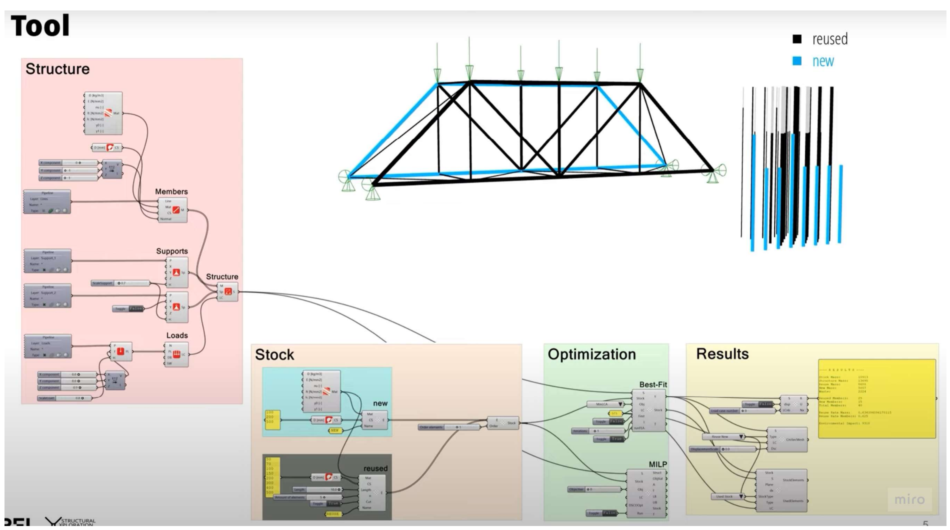

Figure 21: Phoenix 3D tool workflow (Phoenix 3D)

Similarly to the Karamba 3D plug-in tool, Phoenix 3D performs structural analysis to illustrate force distributions and stresses in the assembled structure model. Once verified, the available stock of reclaimed steel elements connects to the tool, providing information on structural material, cross section, count per element, and length. The final output consists of a structural analysis and a colored stock utilization map indicating where reclaimed steel elements can substitute new steel elements. This workflow is shown on Figure 21 above.

One of the key capabilities of the Phoenix 3D software is its ability to combine stocks of new and reclaimed components seamlessly to ensure an efficient use of resources and minimize the environmental footprint of the design (Brütting et al., 2020a). Additionally, the tool serves as a structural geometry and topological optimizer that provides various design iterations to aid in the decision-making process. The software's optimization algorithms play a crucial role in achieving the most effective combination of both new and reclaimed components. Designers can then define various design criteria, such as structural performance, cost, or environmental impact, and the software will generate multiple design variations based on these criteria. Van Brutting's concept is that design should follow availability (Brütting, Senatore, et al., 2019), and the Phoenix 3D tool offers a powerful means of achieving this goal.

1.5 CURRENT REGULATIONS

1.5.1 CURRENT EUROPEAN STANDARDS

When reusing steel H & I sections, it is important to ensure that the sections meet the requirements of code regulations in terms of their structural integrity, material properties, and fabrication quality. This can be achieved through appropriate inspection, testing, and documentation. Currently, European standards such as EN 1993, EN 1090, EN 10204, and EN 10168 primarily focus on the design, manufacturing, and quality control aspects of new steel sections and products.

EN 1993 (European Commission, n.d.): This is the European standard for the design of steel structures, also known as Eurocode 3. It provides guidelines for the structural design and calculations of steel structures. It covers aspects such as material properties, load-bearing capacity, and structural integrity to ensure the safety and performance of such structures.

EN 1090: This is a standard for the execution of steel structures, which specifies the technical requirements for the fabrication and assembly of steel components, including H & I sections. It covers aspects such as welding, surface treatment, and quality control. Part 1 of the EN 1090 are the requirements for conformity assessment for structural components regarding CE marking. Part 2 entails the technical requirements for steel products.

EN 10204: This is a standard for metallic products that specifies the types of inspection documents required for the verification of product conformity. It covers aspects such as material testing, traceability, and certification. Table A.1 – Summary of Inspection Documents is referenced in Appendix C.

EN 10168: is a European standard that outlines the requirements for inspection documents related to steel products. It provides guidelines for the content and format of these documents, ensuring they contain accurate and reliable information about the product's characteristics, compliance with standards, and manufacturer details. The standard aims to facilitate communication and understanding among suppliers, customers, and regulatory authorities regarding the quality and conformity of steel products. However, it is important to note that EN 10168 focuses on inspection documents and does not cover certification or specific testing procedures, as this is covered in the EN 10204.

These standards provide guidelines and requirements for the production and use of new steel in construction projects, ensuring that the materials meet specified safety and quality criteria. However, there is a lack of specific code regulations or standards that address reclaimed steel sections in construction projects. This means that when it comes to utilizing second-hand steel sections, there are no standardized guidelines or requirements in place to evaluate their suitability, structural integrity, or quality assurance. As a result, the assessment and implementation of reused steel sections often rely on individual case studies, project-specific evaluations, and the expertise of engineers and professionals involved. The absence of dedicated code regulations for reused steel sections highlights the need for further development and standardization in this area to ensure consistent and reliable practices for incorporating reclaimed steel in construction projects while maintaining safety and quality standards.

1.5.2 CURRENT MATERIAL CERTIFICATES

The European Standards specify various material certificates that are mandatory for both new and reclaimed steel. However, it is worth noting that these certificates are primarily established for newly produced steel sections. Applying these certificates to reclaimed steel sections introduces the challenge of assigning liability among different stakeholders to provide the required documentation. The complexities associated with this challenge will be further explored in Section 2.2.

Mill Test Certificate (MTC) per EN 1090: This is a document that certifies the chemical, mechanical, and physical properties of a material, which includes weight, dimensions, chemical composition, mechanical properties, heat treatment status, test values, heat traceability. The steel manufacturer provides the Mill Test Certificate to the buyer declaring the quality of steel products is satisfied.

Certificate type 2.1 per EN 10204: This is a certificate of compliance (COC) provided by the manufacturer. However, this certification does not include any tests results.

Certificate type 2.2 per EN 10204: This is a test report provided by the manufacturer based on previous test result data. However, this certificate does not include the individual material's test results as this does not call for specific inspection. This document states compliance with the purchase order requirements.

Certificate type 3.1 per EN 10204: This is an inspection certificate certified by the manufacturer with actual test value, provided by an accredited testing laboratory. By conducting tests on the actual material being supplied to the purchaser, the 3.1 certificate ensures that the material meets the material standard requirements.

Certificate type 3.2 per EN 10204: This certificate involves two inspectors: one appointed by the manufacturer's certification department and another appointed by the purchaser. These inspectors independently verify that the supplied products, including test results, align with the industry standards and requirements specified in the purchase order.

The specific application of these certificates to projects with reclaimed steel depends on project specifications, contractual agreements, and the level of assurance required by the stakeholders involved.

It is essential to ensure that the appropriate certificates are obtained and that they align with the necessary quality and compliance standards for the reclaimed steel being used.

1.5.3 NEW REGULATIONS FOR RECLAIMED STEEL IN THE UK

The British Constructional Steelwork Association (BCSA) has released the *Model Specification for the Purchase of Reclaimed Steel* (BCSA, 2022). This specification model is designed for the procurement of reclaimed steel sections, specifically for suppliers who offer these sections for use in structural steelwork fabrication. It outlines the requirements that the supplier must adhere to, unless otherwise agreed upon with the purchaser. The specification applies to the contractual agreement between the supplier (stockholder) and the purchaser (steelwork contractor). In terms of testing requirements, this document refers to regulation P427.

Publication P427 Structural Steel Reuse (SCI, 2019), established by the Steel Construction Institute (SCI), provides guidelines for reusing reclaimed steel in new construction projects in the UK. Furthermore, an updated version of the P427 has been drafted and is being reviewed by the BCSA. This update is expected to be released by mid-2023 and will incorporate the reuse of steel sections dating back to 1932, as opposed to 1970. This is significant because it expands the range of eligible steel for reuse in construction projects. The date of steel production is important to regulate since older steel may have different characteristics, such as different chemical compositions or manufacturing methods, which can affect its structural properties and performance.

The Institution of Structural Engineers will publish in June of 2023 their new guidance: *Circular Economy and Reuse: Guidance for Designers* (P Gowler et al., 2023). This publication consists of four sections and offers practical advice on integrating circular principles into engineering projects. It aims to empower structural engineers to play a leading role in guiding clients and project teams through this important transition towards a circular economy. The table (Jones, 2023) below in figure 22 highlights the available guiding documentation relating to the reuse of steel per Chapter 15 of the Circular Economy and Reuse: Guidance for Designers.

Organisation	Document	Summary
British Construction Steel Association (BCSA)	*Model specification for the purchase of reclaimed steel sections*	Applies to suppliers of steel products placed on the market as reclaimed structural steel sections for the fabrication of structural steelwork
BCSA	NSSS Annex J – *Sustainability Specification*	Specifies general requirements and practices for achieving environmentally sustainable steel building construction
Steel Construction Institute (SCI)	Publication P427 *Structural Steel Reuse*	Protocol for reusing structural steelwork which provides a route to re-certification of reclaimed structural steelwork
SCI	Publication P138 *Appraisal of Existing Iron and Steel Structures*	Deals mainly with building structures in cast and wrought iron, and in steel up to 1968
UK Building Regulations	*Materials and Workmanship: Approved Document 7*	Existing materials can be reused if the material can perform the function for which it is intended
European Convention for Constructional Steelwork	*European recommendations for reuse of steel products in single-storey buildings*	Guidance for structural engineers relating to design using reclaimed steelwork and designing structures for future adaptability, demountability and reuse with an emphasis on single-storey industrial buildings
Institution of Structural Engineers	*Appraisal of existing structures* (3rd edition)	Guidance for structural engineers on appraising and testing existing structures for refurbishment

Figure 22: Available Documentation for Guidance on Reusing Steel (Jones, 2023).

1.5.4 P427: EVALUATING THE REUSABILITY OF STEEL

The P427 regulation specifies that the reclaimed steel must meet certain criteria in terms of quality and condition. The reclaimed steel must also undergo testing to ensure that it meets structural requirements and complies with building codes. Additionally, the regulation outlines the responsibilities of the various parties involved in the project, including the engineer, contractor, and steel fabricator. These guidelines aim to ensure the safety and structural integrity of buildings that incorporate reclaimed steel. Figure 23 below states the following criteria to determine whether the reclaimed steel can be acceptable for reuse according to the P427 standards.

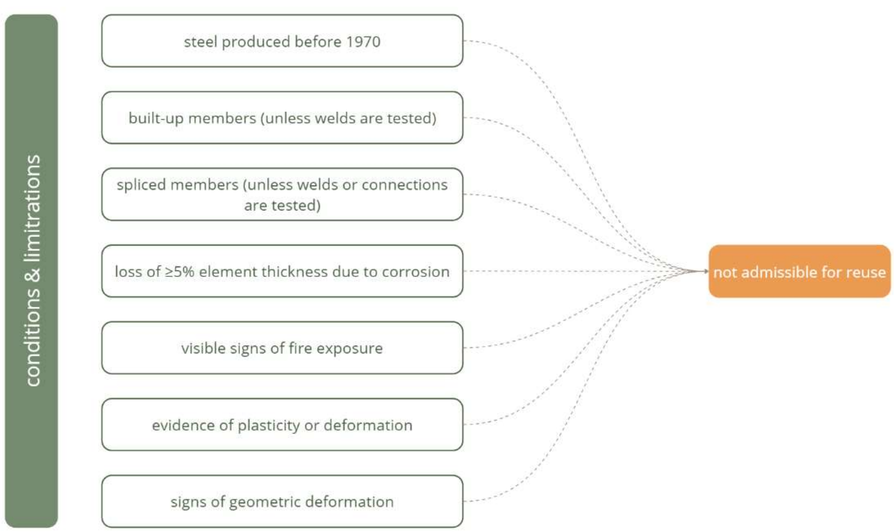

Figure 23: Diagram representing SCI P427 admissibility of reclaimed steel

The workflow below on figure 24 was developed based on the P427 recommendations. First, the building is assessed to determine the feasibility of salvaging the steelwork. Factors such as the acceptability of elements, the demountability of the structure, and the additional cost of demolition are considered. Once the decision is made to proceed, a business case is established between the stockholder and the disassembly company. The reclaimed steel is then received by the stockholder, who groups, inspects and tests the material. The stockholder is responsible for declaring necessary characteristics, such as material properties, as the elements are sold. This process ensures that the reclaimed steel is of high quality and can be safely reused in new construction projects. Furthermore, the structural designer shall check compatibility of material characteristics per project design based on the corresponding European Standards. Lastly, the material is sold with an official declaration for the fabricated steelwork to be CE marked according to BS EN 1090. The structural design and member verification is completed to ensure that the material is suitable for its intended use. It is worth noting that the repairs of the reclaimed sections can be carried out either by the stockholders or the fabricators involved in the project. Since the regulations do not explicitly specify which party is responsible for performing the repairs, this responsibility has been negotiated between both parties per the information gathered from the interviews conducted. Finally, the steelwork fabricator is responsible for issuing the CE mark of re-fabricated or reclaimed steel to indicate that the material has met the necessary safety standards. These steps are crucial in maintaining the safety and quality of the reused steel components in new construction projects.

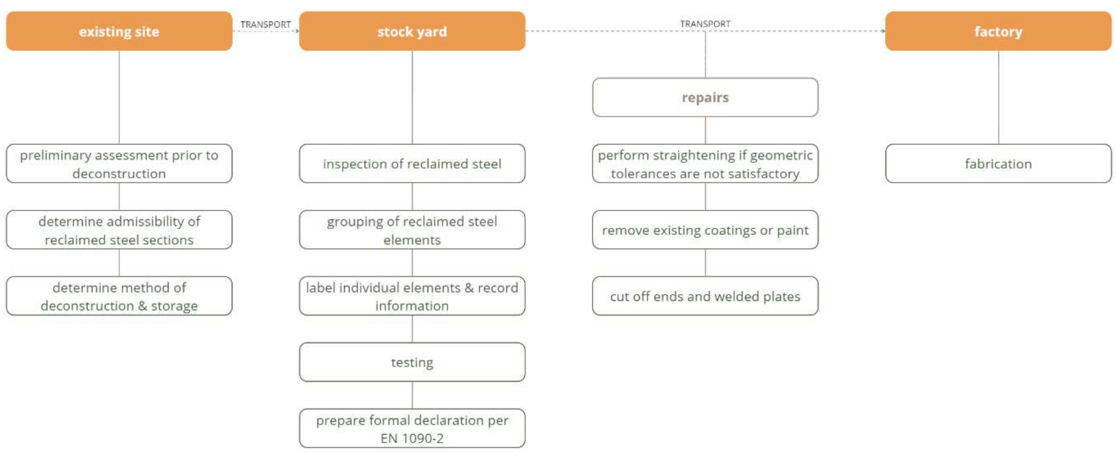

Figure 24: diagram of workflow based on P427 standards

P427: STOCKHOLDER RESPONSIBILITIES

When the reclaimed steel is in the possession of the stockholder, it is inspected for dimensions, straightness, loss of section, damage, and plastic strain. The reclaimed steel is then grouped based on its form, size, original function, and source structure, as outlined in section 6.1 of the P427. The structural design for the reclaimed steel calculates an additional 15% buckling resistance, denoted as $\gamma_{M1,mod}=1.15\ \gamma_{M1}$. The steel stockholder shall maintain traceability by grouping and labeling the members, with groups consisting of a maximum of 20 tons. The grouping criteria is based on serial size, structural function (e.g. beams, columns, bracings), and identical detailing (length and connections). Record information is to be maintained for each group, and a formal declaration or certificate per BS EN

1090-2 is prepared. This ensures that similar characteristics can be established when testing one member of the group.

P427: TESTING REQUIREMENTS

The testing requirements include determining yield strength, ultimate strength, elongation, and impact toughness (if necessary). It also involves product analysis to determine the carbon equivalent value (CEV), section dimensions, and member thickness. Roy Fishwick (2023), from Cleveland Steel Tubes, states that the testing of the steel elements issued by stock companies allows the fabricators to know that the material is fit for purpose, which then allows the fabricators to be able to CE mark the steel structure. The following testing methods are listed below:

Non-destructive testing – this technique can detect defects and variations in material properties without damaging or altering the steel beam.

Non-statistical testing – involves destructive testing of one member of the group to determine the material characteristics. This method is typically done for structures in Consequence Class 1 or 2, where the consequences of structural failure are relatively low and the risk of failure can be managed through appropriate design and maintenance.

Statistical testing – involves more extensive and destructive testing that is analyzes statistically from a larger number of samples. This is typically done for structures in Consequence Class 3, when the provenance or quality of the original source material is unreliable. The testing exceeds the requirements for 'new' steel specified in the product standard.

P427: REPAIRS

Coatings – It is recommended to remove existing coatings entirely due to potential hazardous substances in the existing corrosion protection, which are prohibited by current regulations. Alternatively, if the corrosion protection needs remedial work or if fire protection coatings are subject to humidity, they should also be removed.

Bolt holes and welds - For existing bolt holes or welds, member verification must consider the reduction of the cross-section by more than 15% if the holes are located within the critical cross-section, following BS EN 1993-1-1 and BS EN 1993-1-8. Additionally, new connections should be avoided within 100 mm of existing holes. Larger holes must be assessed for member verification. Welding should be carefully inspected and tested.

2 CURRENT PRACTICE OF STEEL REUSE

2.1 CURRENT PROCESS

The implementation of reclaimed steel in new construction projects involves a complex process that encompasses various stages, considerations, and stakeholders. This section delves into the current workflow of utilizing reclaimed steel by drawing insights from extensive literature review, analyzed project case studies, and conducted interviews with industry professionals. By examining the practical application of reclaimed steel in real-world scenarios, a comprehensive understanding of the existing process is sought. With that understanding, opportunities for improvement can be identified and informed strategies can be developed to maximize the potential of reclaimed steel as a sustainable and resource-efficient solution.

2.1.1 INTERVIEWS

Following a similar approach as the study conducted by Dunant et al. in the article *Options to Make Steel Reuse Profitable* (2018), several interviews were conducted with various professionals aimed to gather insights and perspectives on the topic of reusing steel in the building industry. The objective was to understand the process and flow of information across the value chain and to provide insights into the workflows and collaboration among stakeholders. Figure 25 below shows the roles of the interviewees in orange color. These individuals were selected to participate in the study based on their expressed interest in steel reuse within the supply chain. The interviews were conducted either in person, when possible, or through digital video calls if an in-person meeting was not feasible. The accuracy of the information gathered through interviews was ensured as the interviewees were given the opportunity to review their post-interview reports, which are referenced in Appendix B: Interview Reports. Lastly, the interviewees represent the construction industry in Europe, mostly focused in the Netherlands and the United Kingdom.

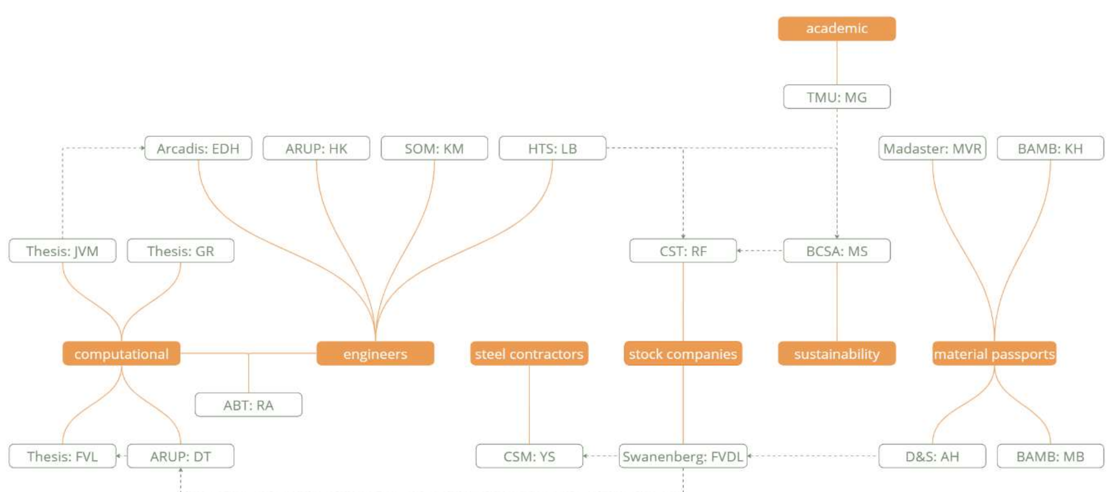

Figure 25: Diagram of conducted interviews

2.1.2 CURRENT WORKFLOW

Based on the interviews conducted, the existing regulations for reclaimed steel in the UK, the literature review, and the analysis of project case studies, the following workflow on figure 26 was developed to illustrate the flow of information and material when reusing steel sections.

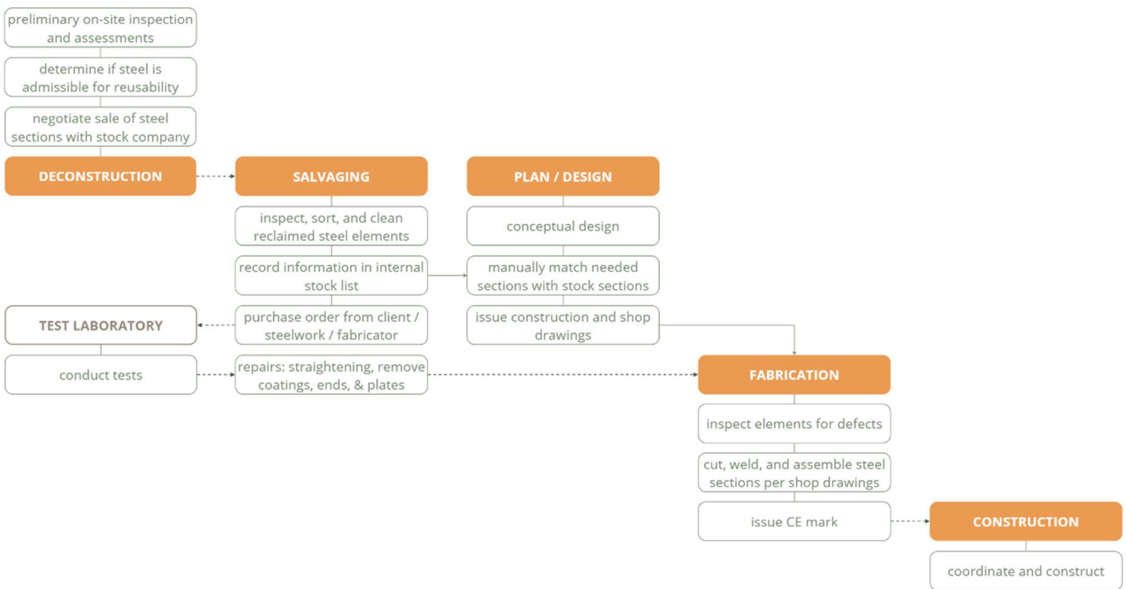

Figure 26: Worflow diagram of interpreted process

The research revealed that most of the challenges and expenses associated with steel reuse are primarily borne by steelwork contractors and stockholders. These challenges are further explained in Section 2.2. Therefore, this section will primarily focus on the salvaging and fabrication process, drawing insights from interviews with stakeholders in these fields to provide a step-by-step understanding of their work processes.

2.1.3 SALVAGING

According to Sansom, it is important to note that CST's business model sometimes extends beyond being a stockholding company, as they also undertake certain responsibilities typically associated with a fabrication company. This complexity in their business process may differ from SIG, which primarily focuses on the trading and storage of materials. Recognizing these distinctions highlights the diverse approaches within the industry when it comes to material handling and fabrication. The current process of salvaging and storing reclaimed steel, based on interviews with Swanenberg Ijzer Groep (SIG) and Cleveland Steel Tubes (CST) stock companies, involves the following steps:

1. Firstly, a price for the steel sections is negotiated between the stockholders and disassembly contractors before the building is deconstructed. This ensures that the disassembly contractor recognizes the value of the steel sections prior to initiating the deconstruction process. Although

CST mentioned they are not directly involved in the disassembly process, they may provide advice on deconstruction techniques to the disassembly company. It's important to note that during the deconstruction process, the responsibility for the reclaimed steel elements lies with the contractor. However, the transportation of the steel sections to the stock yard is a negotiable aspect, determined between the stock company and the disassembly contractor. SIG stated they usually offer to handle the transportation, but if the contractor prefers to manage it, SIG will adjust the offer price accordingly.

2. Once the elements arrive at the stock yard, the stockholders examine them to determine which ones to purchase and which ones to exclude. If there are elements that have been significantly damaged during the disassembly process, they will not be purchased. In regards to confirming the purchase of the reclaimed steel, Van Der Loop (2023), from SIG, emphasized the importance of maintaining a positive collaboration with the disassembly contractors. He stated, "it is a matter of a good working relationship because I am their customer. If they are losing money on me, next time they will not call me. It is not always a one-way direction. If a good relationship is established, there will be future business."
3. After the purchase is completed, the reclaimed steel undergoes a process of sorting, cleaning, and inspection. The sorting is based on size and characteristics of each element, requiring careful inspection. According to Van Der Loop (2023), the sorting process relies heavily on professional experience. For example, distinguishing between a new profile, identified by its H shape, and an old profile referred to as an IPB profile. When the profile is a newer H profile, it can be assumed that the steel grade is at least S255 according to DIN 1025 regulations. Additionally, rust manifests in different colors and produces distinct noises when comparing an S235 grade to an S355 grade. To estimate the steel grade before official testing, a hardness tester is often employed. All of this information is manually recorded on the internal stock list, and in some cases, corresponding pictures are included for clarity. CST mentioned that this information is always saved in their database, even after the elements have been purchased.
4. Furthermore, the stockholder is responsible for performing any simple repairs, such as cutting off ends, removing welded plates, and straightening bent beams. The stockholder may also handle the removal of paint or coatings. CST mentioned that they are involved in this process, while SIG noted that it is typically the responsibility of the contractor since they are aware of the project requirements and will be responsible for applying new coatings.
5. Once the steel elements are purchased, testing is arranged by the stock company and is conducted by a testing laboratory. Prior to purchase, the stockholders do not conduct testing on every element since it would be costly and impractical. This testing is essential in order for the steelwork fabricator to issue a CE mark on the steel elements, indicating their compliance with relevant standards. Sansom (2023), clarified that CE marking is governed by EN1090, which mandates that constituent products, such as steel elements, must be CE marked if they were manufactured after 2012. Therefore, the steelwork fabricator relies on the stock company to conduct proper testing to ensure the product's compliance since the fabricator is responsible for

warranting the structure. The testing of steel elements conducted by stock companies allows fabricators to verify the material's fitness for its intended purpose, enabling them to CE mark the steel structure. Van Der Loop (2023) further clarified that the 3.1 or 3.2 certificates are issued by the fabricator, while the 2.1 or 2.2 certificates are provided by the production mill. These certificates are explained in Section 1.5. As a result, the stockholder does not provide any certification. However, CST mentioned that they do offer an official declaration along with the test results when selling elements to a client. In regard to who bears the cost of testing, SIG mentioned that this is negotiated with the client. Van Der Loop (2023) provided the following example: if SIG sells beams assuming they are S355 but the testing reveals otherwise, SIG will cover the cost of those tests. The client, on the other hand, bears the cost of tests that confirm the agreed specifications during purchase. A sample test result can be found in Appendix B in the interview report with Van Der Loop (2023).

6. Lastly, once the elements have been purchased and tested, the remanufacturing process will be handled by the steelwork fabricator and managed by the construction contractor.

2.1.4 FABRICATION

The fabrication process is an essential stage in a construction project as it involves transforming the steel sections into finished components that are ready for installation. The following process is based on the interview with Constructie Staalbouw Maatwerk (CSM), while the interviews with CST, SIG, and HTS also helped to provide some input.

1. Firstly, the selected reclaimed steel elements are transported from the stock yard to the fabrication plant. This transportation requires coordination and careful handling to ensure the elements arrive safely.
2. Once at the fabrication plant, the reclaimed steel elements undergo a thorough inspection and assessment to evaluate their condition and quality. This inspection helps identify any potential defects, damage, or structural issues that may need to be addressed before the elements can be fabricated. Based on HTS's experience when working with different fabrication companies, they have determined that smaller fabrication companies are more willing to perform repairs, even if it is more labor-intensive, whereas larger companies tend to avoid such tasks. This is a challenge that is discussed in the following Section 2.2.
3. With that said, if repairs or modifications are necessary, skilled fabricators and welders carry out the required work to restore the reclaimed steel elements to a suitable condition. This process may involve cleaning, removing rust or corrosion, reinforcing weak areas, or even cutting and reshaping the elements to meet specific project requirements. After the necessary repairs and modifications are completed, the reclaimed steel elements are integrated into the fabrication process.
4. When fabricators decide to use new steel sections, they take the responsibility of placing the order with the production mill. According to Yannick Smolders (2023), Engineering Manager at CSM,

structural engineers and steelwork fabricators utilize Tekla Structures to access the structural design, coordinate assembly and shop drawings, and generate a material list. This material list includes important specifications for the new steel sections, such as the cross-section type, steel grade, length, weight, as well as the required plates and connectors. By having this comprehensive list, fabricators can easily order the necessary materials and accurately calculate the amount of paint needed for the project.

5. Following the acquisition of the steel sections, the fabrication process involves cutting, welding, and assembling the elements according to the design specifications provided by the project team. Skilled fabricators ensure precise measurements, proper alignment, and secure connections to achieve the desired structural integrity and functionality.
6. Throughout the fabrication phase, quality control measures are implemented, including non-destructive testing or load testing, to verify compliance with required standards and specifications. This is then issued within the 3.1 or 3.2 certificate. Smolders (2023) mentioned that CSM typically issues the 3.2 inspection certificate, which involves a third-party inspector and includes all test results. He also clarified that this certificate is not specific to individual elements but instead applies to the overall work done by the fabricator to develop the structure.
7. Once the fabrication of the reclaimed steel elements is complete, they are typically transported to the construction site for installation. Proper handling, packaging, and transportation methods are employed to protect the fabricated elements during transit and minimize the risk of damage or deterioration.

2.2 CURRENT CHALLENGES

Research on literature review, project case studies and interviews with industry professionals indicate that there is a growing interest in reusing reclaimed steel components in new construction projects. However, this approach still presents significant challenges that affect different stakeholders in the project team as well as different phases of the project. The standard construction and demolition process prioritizes speed, ease, and affordability. However, when this is combined with a lack of clear information and guidance for designers and owners regarding the significances of using reclaimed components and recycled materials, it creates barriers towards a more environmentally responsible use of resources (Gorgolewski & Morettin, n.d.). During an interview with Laura Batty (2023), an associate at Heyne Tillet Steel (HTS) engineering firm, she mentioned “the challenges are not necessarily technical but mostly logistical” since the industry professionals are used to working a certain way.

Challenges can differ depending on the role of each member within the project team. In other words, a challenge that is significant to an architect may not be as important to a contractor or fabricator. Likewise, a challenge that is important during the design phase may not have the same impact during the construction phase. Dr. Cyrille Dunant, a Research Associate for the Use Less Group at the University of Cambridge (Use Less Group, 2015), along with Michael Sansom (2023), and others published a study about the perceived challenges throughout the construction value chain in the UK when reusing steel (Dunant et al., 2017). The results were obtained from an online survey and interviews of 30 individuals in the UK value chain in 2016. To illustrate this research, the results were analyzed and then illustrated in Figure 27, which ranks the challenges according to the perception of importance by each member of the project team. The scores indicate the relative importance of each challenge for each role, with higher scores indicating greater perceived significance. By analyzing these rankings, it becomes clear that there are different perspectives on the most important challenges and that these may vary depending on the individual and their role within the project team.

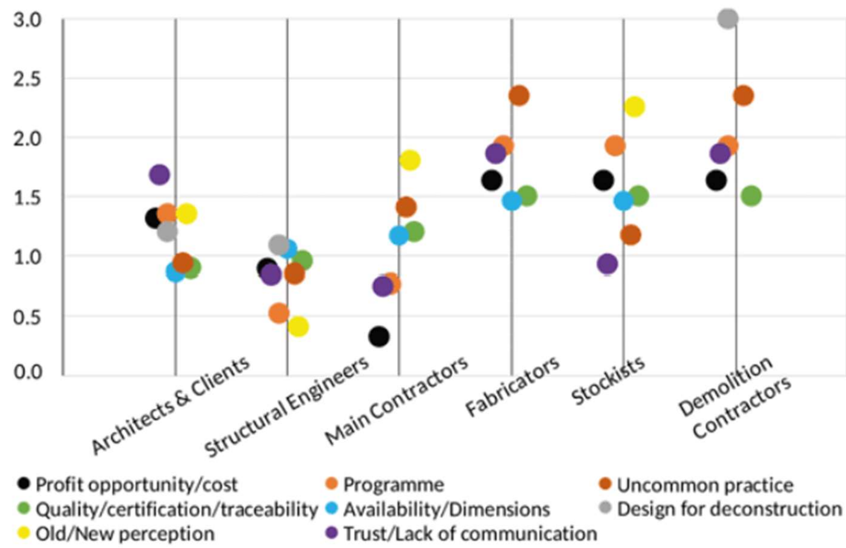

Figure 27: Challenges Ranking per Party (Dunant et al., 2017).

This following section presents the gathered challenges, in figure 28, from the previously mentioned research and interviews (Ajouz, 2023; Batty, 2023; Bolza-Schünemann, 2023; Den Hartog, 2023; Dunant et al., 2017; Fishwick, 2023; Gorgolewski, 2006, 2023; Gorgolewski & Morettin, n.d.; Gorgolewski Vera Straka Jordan Edmonds Carmela Sergio, 2006; Harale, 2023; Herman, 2023; Khalidi, 2023; Micallef, 2023; Rademaker, 2023; Sansom, 2023; Smolders, 2023; Terwel et al., 2021a; Tuinstra, 2023; Van Der Loop, 2023; Van Maastrigt, 2023; Van Rhijn, 2023). These are categorized per project phase, specially focusing on the stages of salvaging the elements, planning and designing, and remanufacturing and fabricating the structure. Despite these challenges, the use of reclaimed steel in construction shows potential as a sustainable solution, and continued research and development is needed to address the current limitations and ensure the safe and effective use of reclaimed materials in construction.

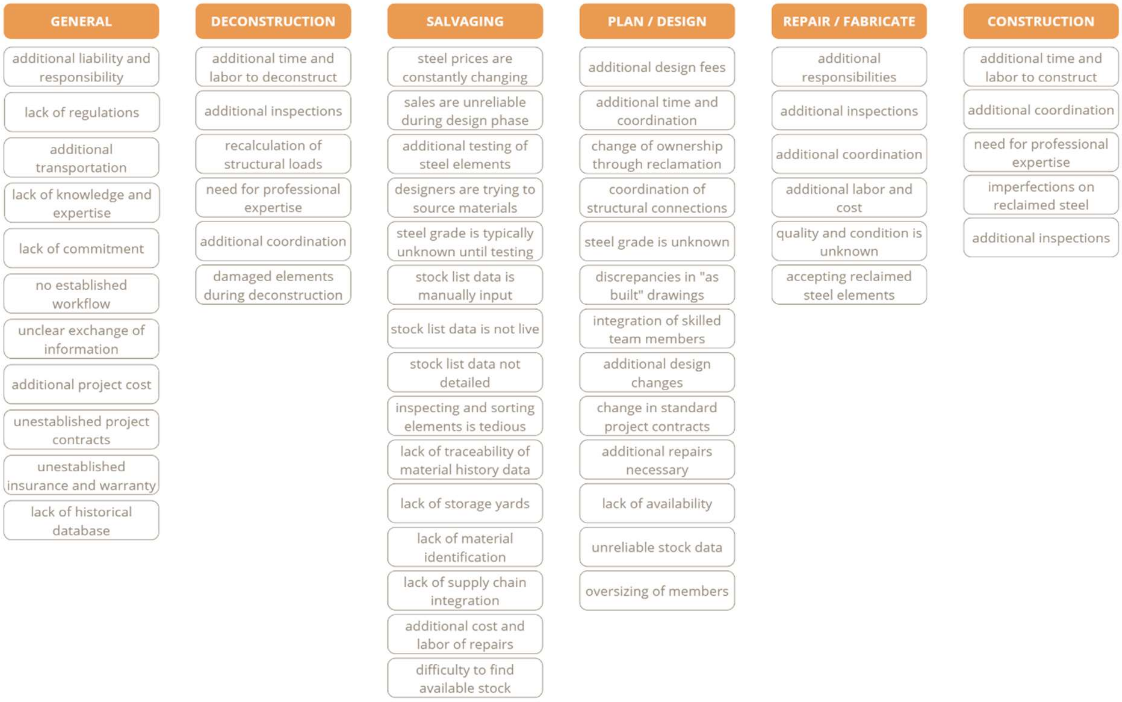

Figure 28: Challenges gathered from research categorized per project phase

2.2.1 GENERAL

This category comprises the challenges that do not fall within a single project phase but affect the overall project. Firstly, project stakeholders often exhibit reluctance towards embracing the idea of using reclaimed building components, perceiving them as inferior and more expensive. Additionally, the absence of a well-established workflow for deconstruction, salvage, design, and construction with reclaimed steel poses a challenge due to its uncommon practice. Furthermore, there is a lack of mechanisms for exchanging project workflow information and clarifying roles among stakeholders. The transportation of elements from the deconstruction site to various locations such as the stock yard, testing laboratories, fabrication plant, and construction site requires additional coordination, time, and cost, leading to uncertainty in project costs. This emphasizes the need for enhanced coordination strategies among stakeholders to effectively manage project complexity, time, and costs.

Legally, the challenges associated with reusing steel in construction necessitate appropriate project contracts to address liability and responsibility issues. These contracts should include insurance requirements, warranty provisions, and indemnification clauses to protect all parties from potential issues arising from the use of reused steel. Reclaimed steel introduces unique risks and uncertainties compared to new materials, requiring updated warranty and insurance coverage to address emerging liabilities. Moreover, the absence of established building codes and regulations for implementing reclaimed building components, specifically steel elements, in new structures poses a challenge. Compliance with existing steel regulations can be difficult when working with reclaimed steel, as there is a lack of historical data and reliable information necessitating testing to ensure compliance and obtain certifications.

Furthermore, the lack of economic incentives and legislative drivers hinders the adoption of reclaimed steel in construction projects. The volatile nature of the reclamation market contributes to significant fluctuations in the cost of reclaimed steel over time. Pricing reclaimed steel equivalent to new steel would undermine its value proposition, considering the additional coordination and effort required. Negotiation plays a crucial role in ensuring client satisfaction regarding the price of reclaimed steel. Sansom (2023) highlighted that stock companies most likely purchase reclaimed steel at a higher price than scrap steel but lower than new steel due to associated testing, transportation, storage, and refabrication costs.

These challenges emphasize the need for standardized regulations, economic incentives, and cost management strategies to support the integration of reclaimed steel in construction.

2.2.2 DECONSTRUCTION

The deconstruction phase is a new project stage that requires additional expertise, time, coordination, and labor cost for the project. The importance of this phase is to disassemble the structural framework to salvage the components without damaging them or hindering their quality. It is essential to have clear communication and coordination among the demolition contractor, engineer, and stock yard manager to ensure the quality of the salvaged elements. The deconstruction contractor must be knowledgeable about the different types of steel elements and their potential applications in the new project, which may require more time and effort. Thus, careful planning and organization are crucial in this stage to prevent any unnecessary delays or additional costs.

2.2.3 SALVAGING

Once the existing building elements are salvaged after deconstruction, they are transported to a stock yard for storage, marking the beginning of a challenging stage in the project.

Firstly, Batty (2023) highlighted that the change of ownership of steel poses more difficulties compared to reusing steel within the same project site. This complexity arises from the procurement process of reclaimed steel from various sources. A major concern is the lack of a steady supply and availability of reclaimed steel elements due to the common practice of demolishing buildings and disposing of materials in landfills rather than salvaging them. This uncertainty regarding available sources and fluctuating steel prices can lead to project delays and increased costs. Furthermore, a shortage of storage for salvaged components often necessitates longer transportation distances to reach the nearest stock yard.

The origin of reclaimed steel is frequently unknown, making it challenging to determine its history and properties. The process of sorting and recording information for reclaimed steel elements is complex and time-consuming. Batty (2023) also mentioned that stock lists provided by stock yards often lack detailed information, making it difficult to assess the condition and quality of the steel sections. Moreover, the absence of scan or 3D information further hampers understanding the specific characteristics and condition of the elements. The steel grade remains unknown until testing is conducted, leaving buyers at risk of purchasing reclaimed elements of questionable quality. Additionally, stock lists are not always up to date, leading to potential conflicts where selected beams may have already been purchased by others. Fishwick (2023) explained that the data on stock lists is manually inputted and updated on a monthly or bi-monthly basis, adding to the complexity. Clients must request the stock list, which is then provided by CST. If clients wish to reserve specific elements, they need to communicate their intentions to CST, who will update the stock list accordingly. Fishwick (2023) also mentioned another challenge stemming from designers attempting to source reclaimed material, despite not being responsible for the purchase, as contractors or steelwork fabricators typically handle procurement.

Testing reclaimed steel is crucial for fabricators to meet certification requirements, as reclaimed steel often lacks test certificates from mills. However, the testing occurs after the steel has been selected and purchased, leaving the properties and quality unknown prior to procurement. Consequently, testing becomes necessary, incurring potential costs of up to €350 per test according to Van Der Loop (2023). Fishwick (2023) explained that reclaimed steel must undergo testing to obtain the necessary test certificates required for CE marking the structure. Without these certificates, fabricators are unable to verify the properties of the material they are using. The independent test lab report issued by the stock company should provide the required information to satisfy the EN1090 standards and allow fabricators to have the necessary data for CE marking the steel structures. Batty (2023) further noted that the testing of steel elements occurs after the steel has been selected, purchased, and sent to the factory, leaving the properties and quality of the steel unknown prior to procurement. Due to the lack of information on the properties and quality of the reclaimed elements, this crucial data is not included in the stock lists. As a result, designers face difficulties in incorporating the reclaimed elements into their designs due to the inherent uncertainties.

Unreliable sales present another challenge, as designers may reserve beams, but it is ultimately the contractor or steelwork fabricator who typically purchases them during the construction phase, after the design phase has concluded. Moreover, the project design often undergoes multiple modifications during this phase, making the reservation or selection process of beams unreliable due to the extended time frame and changing requirements. Finally, the constantly fluctuating steel prices make the buying and selling of reclaimed steel a risky endeavor for both parties involved.

2.2.4 PLAN & DESIGN

In a typical project, the planning and design phase already involves multiple stakeholders coordinating to create precise construction drawings. However, incorporating the reuse of reclaimed elements only amplifies the level of complexity and coordination required for the project.

According to multiple sources, a significant obstacle is the need to adapt the design based on the availability of salvaged components, which requires extensive research and coordination to determine which elements can be reused and which need to be newly produced. This increased level of coordination may result in higher design fees. In addition, insufficient communication and a lack of accessible and shareable information further compound these challenges. No established project contract to define the responsibilities and liabilities of each stakeholder within the project team. Fishwick (2023) stated that current standard contracts do not entail this “new” process with reused building components. This process causes more liability to different parties.

Designing with stock elements without knowledge of their availability or cost can be challenging. More specifically, the steel grade is typically unknown prior to the testing of the reclaimed elements, which occurs post-purchase. Fishwick (2023) said that currently in the UK, all new structures being designed are mostly specified to be S355 grade, whereas most buildings that are being disassembled now would have a lower grade such as S275 or S235. However, Batty (2023) did mention that not all designs are steel grade dependent. If the structure is designed for deflection criteria, like beams, then the steel grade, or yield strength, is not critical, but if the design is for strength, like it would be for columns, then this information is necessary. Oversizing of structural elements can occur due to concerns about hindered performance, as there is no set code for calculating the use of reclaimed steel members with set risk factors.

Furthermore, material passports are currently being implemented on new projects to plan for its future circularity, however, based on interviews conducted with Madaster and BAMB it can be concluded that these platforms do not include data per element but instead, the entire assembled building. The results give you the percentage of deconstruction or circularity of the building, but it is not a database of traceable building elements to obtain history or structural information about a specific element in the building. This can hinder informed decision-making for utilizing reclaimed materials. Sansom (2023) added that these platforms include environmental information about the building as a whole but lack the level of detail that designers would need to make informed decisions for utilizing reclaimed materials.

Lastly, testing reclaimed elements for compliance with structural criteria and quality standards is time-consuming and costly, potentially leading to delays and additional expenses. With that said, purchased elements may also fail to meet requirements after testing, leading to further delays and costs. Additionally, designers mentioned that they experience uncertainty when reserving the steel elements during the design phase, as there are always a lot of design changes, and they are typically not the ones that confirm the purchase; the contractor typically does this per the project contract.

2.2.5 FABRICATION

During this project phase, the interviewees discussed several challenges, including the existing condition of reclaimed elements, which often necessitate additional labor and costs for repairs. Compounding the issue is the absence of a designated stakeholder responsible for conducting these repairs, further adding complexity to the project.

As discussed previously in Section 2.1. of fabrication, Smolders (2023) mentioned that CSM has not yet incorporated reclaimed steel in their projects due to the perceived lack of economic viability in bearing the additional labor and costs associated with repairing reclaimed sections. Smolders (2023) stated, "the time, resources, and labor that go into repairing reclaimed beams and adapting them to new designs is more costly.” Factors such as welded plates, existing bolt holes, and inconsistent paint contribute to the complexity of working with reclaimed steel. Smolders (2023) emphasized that if the reclaimed steel sections were in a condition resembling new steel, CSM would be more willing to incorporate them. However, the unknown quality and condition of reclaimed steel pose challenges, requiring additional coordination to inspect and repair before initiating the fabrication process for each section.

In line with this discussion, Fishwick (2023) explained that in the current UK context, fabricators expect stock companies to handle all necessary repairs before sending the steel elements to fabrication companies. Fabricators prefer not to undertake this work, as it deviates from the established standard fabrication workflow. Their focus is solely on fabricating the structure according to the provided shop drawings. However, CST and SIG mentioned that they are capable of performing minor repairs, such as cutting off edges, removing coatings, and straightening bent beams, to ensure that the elements meet the desired quality standards when sold.

Furthermore, Batty (2023) emphasized that while steel elements may not be physically "like new" in certain scenarios, they should be considered "like new" from a technical perspective. Repair work to make steel sections appear “new” should be avoided whenever possible, such as leaving existing bolt holes or welded plates and stiffeners that do not interfere with the new fabrication drawings.

Regarding the repairs that need to be made, the removal of coatings and straightening of bent sections are essential. Shot blasting, which is the most energy-intensive repair, is necessary to remove coatings as the presence of paint on top of an existing coating would void any warranty. Additional repairs should only be undertaken if they pose problems with the new fabrication drawings. For example, bolt holes within 100mm of a new bolt hole location can be sliced off or welded in, but existing bolt holes that do not compromise the structural integrity of the section can remain. In addition, stiffeners that do not hinder performance can also be retained. Any loose concrete on the steel elements must be removed to prevent explosions inside the furnace, although this would not be a concern if the element undergoes shot blasting.

Lastly, another challenge is the lack of established regulations regarding the provision of required certificates by steelwork fabricators when utilizing reclaimed steel.

2.2.6 CONSTRUCTION

Similar to the deconstruction phase, this project stage requires new expertise as well as may require additional labor cost and coordination time to assemble the structure. In addition, reclaimed steel elements can have some imperfections or slight defects, such as existing welds and bolt holes, paint or coatings, and may also not be perfectly straight, as seen in new steel elements. As a result, construction contractors need to conduct additional inspections and testing to ensure that these elements meet the required standards before utilizing them. Furthermore, any issues that arise during the process will require additional time and resources to address.

3 PROPOSED DESIGN WORKFLOW & STRATEGIES FOR STEEL REUSE

3.1 FOSTER CHANGE

The World Green Building Council's report, "Bringing Embodied Carbon Upfront" (2019) presents a "theory of change", in figure29, that highlights the interconnected actions required for a collaborative effort between supply and demand-side actors to achieve net zero embodied carbon in the building and construction sector. To foster change, collaboration and commitment from everyone within a project team is crucial, as well as communicating and raising awareness to prioritize circularity despite the additional complexities that this might bring. In addition, implementing innovative ideals will promote new practices and training for new skills and roles within the profession. Lastly, evolving governmental regulations are essential to encourage advancements towards an environmentally friendly building industry.

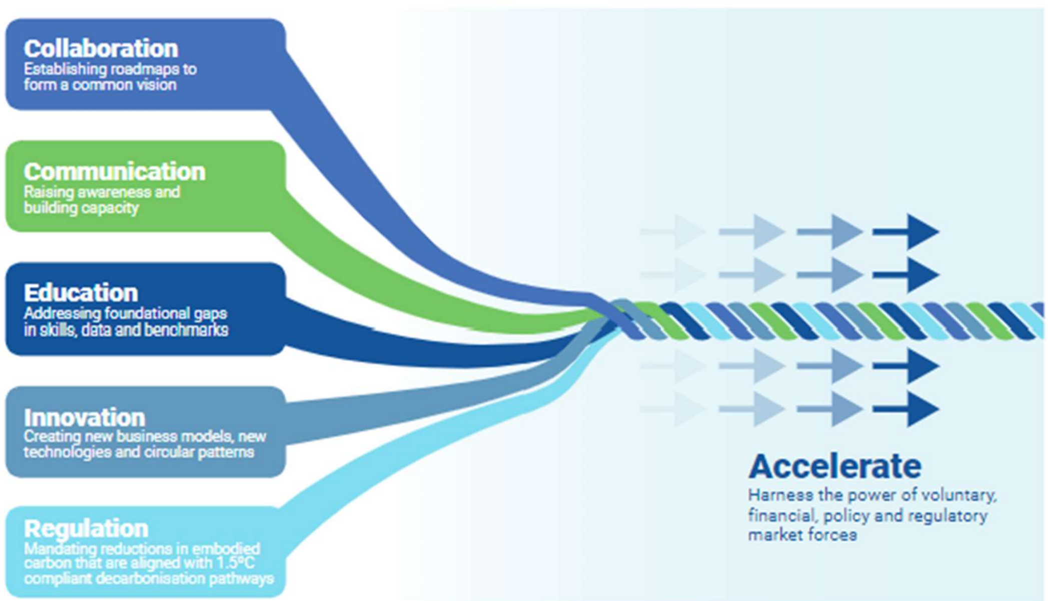

Figure 29: "Making Change Happen in our Sector" (World Building Council, 2019)

Governmental regulations can play a significant role in fostering change and promoting the reuse of building materials in several ways. Firstly, regulations can mandate that certain percentages of reused or recycled materials be used in new construction projects. For example, LEED and BREAM offers credits for projects that use a high percentage of recycled or reused materials. Secondly, regulations can incentivize the use of reclaimed materials through tax credits or other financial incentives. This can help offset the potentially higher costs associated with sourcing and utilizing reclaimed materials. Thirdly, regulations can require or encourage the development of standards and certifications for reclaimed materials. This can help ensure the quality and safety of reused materials, making them more appealing to architects, engineers, and builders. Lastly, regulations can encourage the development of circular economy models and practices. This can include supporting research and development of new technologies or promoting public-private partnerships to develop and implement circular economy practices. By creating an environment that supports and incentivizes the reuse of building materials, regulations can help foster a circular and sustainable built environment.

Apart from governmental regulations, project stakeholders also play a crucial role in driving change. One way designers and engineers can encourage the use of reclaimed steel in new projects is by educating clients, contractors, and fabricators about the benefits of reusing materials, such as reducing carbon emissions, saving resources, and potentially reducing costs. Designers and engineers can also highlight examples of successful projects that have incorporated reclaimed materials, and show how incorporating reclaimed steel can enhance the aesthetic value of a project. In order to address concerns from contractors and fabricators about increased work and time to coordinate, designers and engineers can propose strategies to streamline the process, such as developing a standardized system for evaluating the structural integrity of reclaimed steel, creating a digital inventory system that makes it easier to source reclaimed steel, and developing guidelines for integrating reclaimed steel into projects that are easy to follow. Additionally, designers and engineers can work collaboratively with contractors and fabricators to address any concerns and identify potential challenges early on in the process, so that they can be addressed and mitigated. This can help to build trust and foster a sense of shared responsibility among all stakeholders in the project, ultimately leading to a more successful outcome.

By addressing the challenges and opportunities discussed in the previous sections, the following section proposes a comprehensive design workflow aimed at facilitating and encouraging the integration of reclaimed steel in new construction projects, while also supporting circularity and sustainability goals.

3.2 PROPOSED DESIGN WORKFLOW

The proposed design workflow for steel reuse aims to provide a comprehensive framework for incorporating reclaimed steel in construction projects. Building upon the understanding gained from the analysis of business models, case studies, regulations, and current challenges, this workflow offers a systematic approach to facilitate the successful integration of reclaimed steel. By outlining this step-by-step process in figure 30, the aim is provide some guidance for project teams and emphasize an integrated design process to facilitate the exchange of information and enhance collaboration among the project stakeholders.

The steps involved in the process engage specialized deconstruction and construction contractors to ensure quality assurance and address discrepancies. In addition, the stockholder can also act as a project consultant to advice during the material selection process in the design phase. To facilitate an informed design process, the stock's digital inventory and BIM design models can be utilized as input data for the matching algorithm, which provides possible substitutions of reclaimed stock elements to incorporate into the design. This process is further explained in Chapter 4. Once the design stage is completed, the reserved stock elements ensure their availability. Upon finalizing the design and material selection, the stock elements can be purchased. Subsequently, these elements undergo testing, repairs, and fabrication to meet both project criteria and regulatory standards.

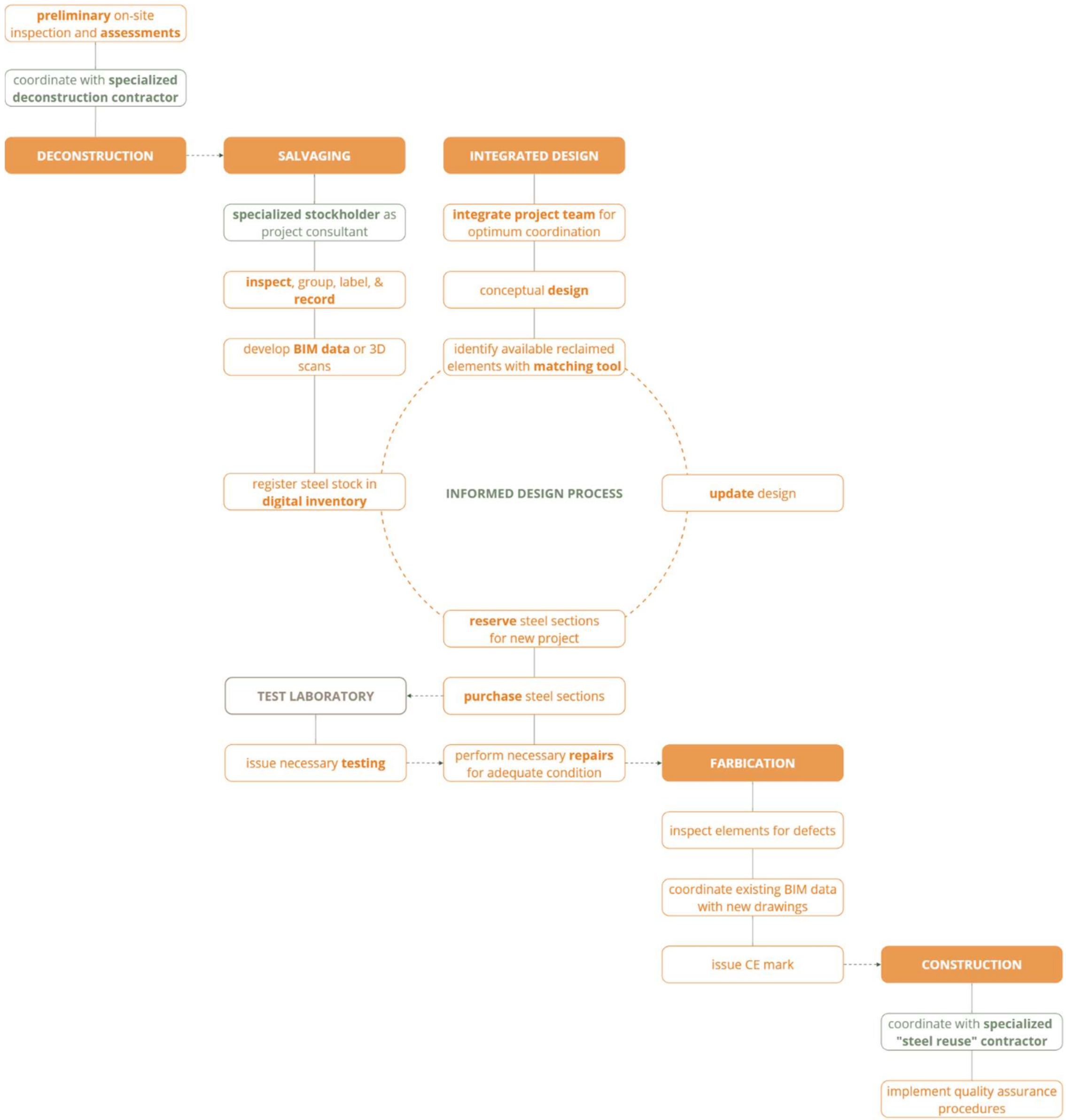

Figure 30: Proposed Workflow for incorporating reclaimed steel in new design projects

3.3 PROPOSED STRATEGIES PER PROJECT PHASE

Based on the research conducted in the previous chapter the following are potential opportunities to facilitate the reuse of reclaimed steel elements in new projects per the different project stages. These recommendations are in response to the current challenges stated in Section 2.2. where input was gathered from the conducted interviews during the research process.

3.3.1 GENERAL

Promoting Awareness and Education: It is important to educate project stakeholders about the benefits and value of using reclaimed building components. With that said, everyone in the project team should prioritize environmental factors and circularity strategies above the objective of completing the project as quickly and at the lowest possible cost. In addition, new team members need to be incorporated in projects with reclaimed steel as new expertise and skills are required. These would include a specialized disassembly contractor and construction contractor, a reusability consultant, a stockholder to act as an advisor, and a specialized steelwork fabricator.

Establishing Best Practices and Workflows: Developing standardized workflows for deconstruction, salvage, design, and construction with reclaimed steel can streamline the process and provide guidance to project teams. It is recommended for components should be reused close to the original location to reduce the emissions from transportation.

Enhancing Coordination and Communication: Effective coordination strategies and mechanisms for exchanging project workflow information are crucial.

Implementing Comprehensive Contracts: Project contracts must be updated to define clear roles and responsibilities among stakeholders. Additionally, these contracts should include insurance requirements, warranty provisions, and indemnification clauses that can protect all parties involved and mitigate potential risks.

Developing Building Codes and Regulations: Establishing specific building codes and regulations for reclaimed building components, including steel elements, can provide clarity and ensure compliance. Testing requirements should be outlined to guarantee the structural integrity and safety of reclaimed steel, enabling the issuance of certifications.

Following a Circular Framework: Additionally, the government could further incorporate regulations that align with the 10R’s framework to prioritize reuse, then remanufacture, then recycle, then disposing of the elements and for these chosen decisions to be backed up by written reasoning.

Creating Economic Incentives: Introducing economic incentives and legislative drivers can encourage the adoption of reclaimed steel in construction projects. These incentives can help offset the additional costs associated with testing, transportation, storage, and refabrication, making reclaimed steel a more financially viable option.

Public Source of Information: Finally, implementation should be monitored and progress communicated to disseminate information on successes, benefits, failures, and lessons learned.

3.3.2 DECONSTRUCTION

Plan for Disassembly: All demolition buildings should be planned for deconstruction and salvaging of structural elements and materials. This could be incentivized by governments by implementing a tax on disposing of elements at landfills.

Analyze Existing Data: During this phase it is important to analyze the "as-built" BIM model or drawings and label elements before disassembling them in order to maintain traceability of element information. Special attention must be given to the structural connections and fasteners, as understanding their configuration and functionality is vital for successful disassembly.

Involve Specialized Contractors: Engage contractors who possess the necessary expertise and specialize in deconstruction and salvage operations. Establish effective communication channels between the project team. Stockholder or reusability consultant may also provide advice during this process.

Define Instructions: Contractor should follow detailed instructions and guidelines pertaining to the project, including the specific requirements for disassembling and salvaging steel elements. This information should cover labeling procedures, preservation techniques, quality standards, and any specific instructions related to structural connections and fasteners.

Quality Assurance: Quality assurance measures must be implemented to ensure the salvaged steel components meet the required standards for reuse. This may involve inspections, quality checks, and documentation of the condition and characteristics of the salvaged elements.

Consideration of Time and Labor Cost: The additional time and labor costs associated with the deconstruction phase need to be recognized. Project planning should account for the extended duration and allocate sufficient resources to carry out the deconstruction activities effectively.

3.3.3 SALVAGING

Establish reclamation markets: These establishments provide a centralized and controlled environment for preserving salvaged steel and enhance the accessibility of reclaimed materials. The available markets also reduce the time and effort required to locate specific components and offer reassurance through trusted suppliers. They also foster a working relationship between designers, demolition and construction, and fabricators. Emphasizing the value of these reclamation markets will encourage their utilization in future design projects.

Stockholders as project consultants: Integrating stockholders as project consultants will provide access to valuable stock information, expertise, and advice. This will facilitate informed decision-making and seamless integration of reclaimed elements into the design process.

Data management of stock elements: To ensure proper data management, all known information of the steel structure – physical properties and connections - should be recorded during disassembly by the deconstruction contractor. Following, this documentation should be digitally combined with any existing drawings, mill test certificates, EPD's, or BIM data by the stockholder to ensure traceability. Fishwick (2023) said that CST currently provides data information of the elements when they are purchased. So, technically the engineer or designer could link the CST data to the new BIM design models. However, this has not been widely implemented by buyers or project teams.

Stockholder to issue initial hardness test to estimate steel grade: Unless any steel elements arriving to the stock yard have an existing sticker with the mill certification information, the steel grade is typically unknown. The steel grade is determined after the steel elements are sent to an external laboratory to be tested. However, there are simple and non-destructive hardness tests that can be performed, which consist of a probe that impacts the surface of the material and measures the rebound hardness. The rebound value obtained from the test is then correlated to the material's hardness, which can provide an estimation of its steel grade.

Perform necessary repairs: Based on the gathered challenges in Section 2.2.5, contractors and fabricators are reluctant to purchase steel elements that are in poor condition. Therefore, this proposal suggests that the stockholder undertakes the following repairs to ensure the steel elements meet the required condition standards: straightening bent beams, shot blasting to remove paint or coatings, and cutting off ends and welded plates. Both CST and SIG (2023) mentioned they can perform these repairs on site at the stock yard, however, it is not a standardized process. By ensuring that the steel elements are in good condition, the stockholder can effectively improve their market value, thereby increasing the likelihood of clients purchasing more reclaimed steel elements.

Management of digital inventory: Furthermore, stockholders should make the stock data accessible for material seekers as a digital inventory within an online market. Such inventory will not only enable users to search and retrieve reclaimed elements, but also allow stockholders to monitor stock levels, analyze usage patterns, forecast demand, and make informed decisions regarding procurement, production, and distribution. There are currently some examples of online platforms for material allocation such as: Opalis (*Opalis*, n.d.), Donorstaal (Swanenberg Ijzer Groep, n.d.), and Stad (*Stad*, n.d.). While these websites provide a digital stock inventory, the actual process to find the desired stock steel elements is nonetheless done manually. To allow buyers to visualize the quality and condition of the stock elements, the digital inventory should include BIM drawings or 3D scans, this will improve the reliability of reclaimed elements. This stock data would then serve as an input for a digital inventory interface and matching algorithm which were developed during this thesis and are further explained in Section 4.1.

Implement reservation system: As discussed in Section 2.2.3, stock companies face the challenge of designers utilizing the stock list for the design of a project, while the responsibility of purchasing stock elements typically falls on contractors (Fishwick, 2023). Moreover, the project team, whether designers or contractors, cannot rely on the availability of the stock elements initially considered, as they may have been purchased for other projects (Batty, 2023). To address these uncertainties and benefit both parties, a potential strategy is to implement a reservation system. This system would enable the project team to reserve steel elements from the stock list as needed during the design phase, with a monthly reservation fee and a maximum reservation period of 2 years. It would also provide stockholders with insight into the elements of high-demand, offering more certainty that reserved elements are likely to be purchased once the design phase concludes. Notably, both CST and SIG (2023) mentioned their provision of a purchase-back policy for acquiring steel elements at the end of a structure's life cycle. Determining the reservation fee price is beyond the scope of this research, as it requires further investigation due to the volatility of steel prices. This is further stated in Section 5.3.4.

3.3.4 PLAN & DESIGN

Integrated Project Team: It is critical that from the very beginning the entire *project team*[*] is involved in making important design decisions, as an *integrated project delivery method*[†]. As design is being developed, steel contractor shall coordinate closely with stockholder to reserve the reclaimed steel members needed and update as the design process is developed.

Involve specialized stakeholders: In addition, new specialist roles should be incorporated to enable a clear exchange of information and coordination responsibilities. This will require more time during the planning and design phase but will facilitate the process during the construction phase.

Plan Early: Decisions must be taken on early design phase and the overall process must be rethought from the design of new buildings to incorporate demountable connections, the traceability of project and element information, to how the buildings are put together and how they are demolished. This requires a change in the typical approach that designers, engineers, contractors, and builders are used to following. Needs a change in design strategy.

Willingness to Collaborate: Project team must be willing to coordinate additional challenges and the designer needs to be the leader of this push for circularity by educating the client, managing the team, proposing circularity as a primary goal and not a follow-up goal based on the budget or time frame. Commitment and willingness from the entire project team is necessary as this framework to reuse elements requires more coordination. Must also be open to rising challenges and willingness to solve them.

Design for Disassembly: New projects should be designed with modularity in mind to create adaptable, durable, and flexible steel structures. Furthermore, designing for disassembly must be implemented in order to accomplish a circular building industry. This means reducing welding connections and eliminating

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[*] Project Team – Refers to group of individuals assembled to work collectively in project. This may include project managers, architects, engineers, designers, contractors, subcontractors, consultants, and others involved in the planning, execution, and completion of the project (AIA, 1997).

[†]Integrated project delivery method - This project delivery approach combines individuals, systems, organizational structures, and methods to effectively utilize the skills and knowledge of all involved parties to optimize project results and maximize efficiency through all project phases (AIA, 2007).

the use of toxic coatings and paintings. Designers should proactively assess the future replacement and dismantling of building components, considering the building's lifespan and potential challenges during refurbishment and dismantling, to maximize the utilization of components and materials. The ease and cost of removing components from a building at the end of its life are important factors that determine the extent to which reuse and recycling can be achieved.

Plan for Future Circularity: Advocate for the inclusion of detailed information on material passports or similar platforms, specifically at the element level, to support informed decision-making regarding reclaimed materials.

Utilize Computational Tools: The utilization of computational tools in the design phase is of utmost importance. A matching algorithm, developed through computational advancements, plays a significant role in this process. By employing the algorithm, the oversizing of structural elements can be avoided by searching for an exact match on the profile and subsequently identifying a range of lengths that can be cut to the exact dimensions as specified in the design list. Furthermore, the combination of material passport data with the element's history enables the integration of comprehensive data information, enhancing the overall decision-making process.

Optimized Design Process: Several sources mentioned that design must be based on the availability of reclaimed elements. However, with the increase of disassembly in the construction industry there could be a vast amount of reclaimed elements that makes this easier. Additionally, the design process might be more complex when designing per availability. It may be simpler to design as normal and then utilize a computational tool to either optimize this matching process. This must be a balance between a design that is hindered because elements are not available or accepting to incorporate new steel elements where needed. This decision would be based on the project criteria and the client's objectives.

Plan for Discrepancies: Allocate additional time and cost for discrepancies. Adapt the design process to account for the unknown steel grade of reclaimed elements by considering different design criteria and performance factors.

3.3.5 FABRICATION

Establish Repair Responsibilities: Designate a specific stakeholder responsible for conducting repairs on reclaimed steel elements, ensuring clarity and accountability throughout the fabrication process.

Coordinate with Stock Companies: Collaborate closely with stock companies to handle necessary repairs before sending steel elements to fabricators, reducing the burden on fabricators and aligning with the standard fabrication workflow.

Prioritize Technical Condition: Consider reclaimed steel elements as "like new" from a technical perspective, avoiding unnecessary repairs that focus on the appearance rather than the functionality of the sections.

Focus on Essential Repairs: Perform essential repairs such as removing coatings, straightening bent sections, and addressing issues that directly affect the new fabrication drawings, while retaining elements that do not compromise structural integrity or performance.

Ensure Compliance with Regulations: Work towards establishing regulations that outline the requirements for steelwork fabricators when utilizing reclaimed steel, including the provision of necessary certificates to meet industry standards.

3.3.6 CONSTRUCTION

Enhanced Expertise and Coordination: Ensure that construction contractors possess the necessary expertise in working with reclaimed steel elements and coordinate closely with all stakeholders involved in the construction process. This includes clear communication channels and coordination to effectively assemble the structure.

Thorough Inspections and Testing: Conduct comprehensive inspections and testing of reclaimed steel elements to identify any imperfections or defects, such as existing welds, bolt holes, coatings, and straightness. This will help determine their quality and suitability for use in the construction project.

Quality Assurance Procedures: Implement robust quality assurance procedures to ensure that reclaimed steel elements meet the required standards and can safely integrate into the structure. This may involve additional testing, measurements, and documentation to verify their integrity and performance.

Timely Issue Resolution: Anticipate and address any issues that arise during the construction process promptly. This includes having contingency plans in place to handle unexpected challenges associated with reclaimed steel elements. Prompt resolution will help minimize delays and allocate resources efficiently.

Collaborative Problem-Solving: Foster collaboration between construction contractors, engineers, and other relevant stakeholders to collectively address any challenges encountered during the construction phase. Encourage open communication and proactive problem-solving to ensure smooth progress and successful integration of reclaimed steel.

3.4 FEEDBACK

This section incorporates feedback and insights obtained from follow-up interviews with industry professionals, during which the proposed workflow and strategies were discussed. The purpose was to assess the feasibility of implementing these approaches within the design process to enhance the reusability of steel elements.

Stock data: Fishwick (2023) highlighted that while 3D scans or BIM models would be an ideal solution, the current market size and profitability pose challenges to the viability of implementing such practices.

However, as the market for reclaimed steel grows and more individuals embrace steel reuse, there is potential for these services to become more feasible and valuable.

Stockholders as project consultants: According to Fishwick (2023), the active involvement of stockholders as consultants in design projects is highly valuable, and they could provide detailed stock data. However, the challenge remains with potential design changes that may arise later. Nonetheless, having more information is advantageous, and Fishwick does not anticipate any significant increase in liability.

Design guideline: Herman (2023), who was involved in the Mundo Lab LLN project that incorporated reclaimed steel elements, expressed that the design workflow presented in this thesis would have been immensely valuable as a guideline and a set of steps to follow during various project phases.

Reservation system: Batty (2023), Van Der Loop (2023), and Fishwick (2023) mentioned that incorporating such system to manage the allocation of stock elements would be beneficial for both the stockholders and the clients seeking the stee elements. Fishwick (2023) said that in terms of reservations and fees, it is reasonable to have defined time limits and breakpoints in the agreement that can be adjusted based on the specific nature of each project. This ensures clarity and flexibility in the allocation process.

However, this particular aspect may necessitate further investigation, especially when considering the financial complexities arising from the constant fluctuations in steel prices. This is mentioned in Section 5.3.4. According to Fishwick (2023), contracts that secure materials well in advance of their use can result in significant gains or losses, which would need to be shouldered by the buyer. In line with this, there are considerations raised by Van Der Loop (2023) regarding the use of deposits to secure materials. Issues arise from the fact that engineers and designers often lack the funds to purchase materials directly, as they are typically part of the contract awarded to the main contractor. This introduces disruptions to the normal business practices. Additionally, there are concerns regarding how individuals react when design changes occur, leading to the loss of fees. Linking the future price to steel price indexes could be a potential solution, although some customers may prefer to lock in prices early for contract price certainty.

Responsibility of repairs: The repairs should be a balanced responsibility between the stock companies and the fabrication companies. This can also be better communicated and coordinated within the project team if the stockholders and steel work fabricators are consultants. Ideally, the stock companies could make sure that after the steel elements have been purchased and tested, they can shot blast the elements to remove all paint and coatings. In addition, based on both stock companies interviewed (CST & SIG), they are able to perform straightening to minor bent elements as well as cut the ends to remove welded plates or concrete remains. Assuming the stock companies perform these repairs, the fabricator companies can take care of any bolt holes that need to be infilled, only if it is necessary per the shop drawings.

4 COMPUTATIONAL TOOL DEVELOPMENT FOR SEAMLESS DESIGN WITH RECLAIMED STEEL

4.1 OVERVIEW OF COMPUTATIONAL TOOL

This chapter elaborates on the development of a computational tool, consisting of a prototypical web interface and a matching algorithm, to facilitate the proposed design workflow to integrate reclaimed steel. The user interface prototype is a web platform that serves various types of users (in this case 2 user scenarios based on the research concluded from the research). The matching algorithm is comprised of excel data, a Grasshopper script to sort the data, and a Python script to match the lengths and optimize the matching selection. The matching is based on geometrical properties.

4.1.1 OBJECTIVES

The objective of the development of this computation tool and user interface is to facilitate the integration of reclaimed steel into the design process. As established in the proposed design workflow, the computational tool will enable an informed design process to facilitate the selection of reclaimed elements and optimize the design based on the results. This tool can serve as a final design check, but it can also be employed during the conceptual design process to guide the design and optimize the potential for reuse. In addition, the goal is to create a platform to facilitate the flow of information and coordination among two sets of users: the material suppliers and the material seekers, to make informed design decisions when utilizing reclaimed steel. This is further explained in Section 4.2.

Digital inventory: Based on the current challenges, in Section 2.2, one main challenge is the lack of publicly available stock data. For this reason, a digital inventory is proposed within the computational tool to provide a centralized and easily accessible repository of stock information. The inventory will allow users to search, retrieve and update information. The open access to this data will allow architects and engineers to make informed design decisions in the early stages of design in order to optimize the amount of reclaimed steel to be utilized in new projects.

Matching algorithm: to allow for the retrieval of stock information from the digital inventory a matching algorithm is developed to compare the list of design elements needed with those of a stock list. This tool will find the possible substitutions.

Lastly, the goal of developing this integrated computational tool is to align with the expectations of the different users by catering to the different needs, addressing the challenges, improving the workflows and promoting user engagement and adoption. This with the ultimate objective of facilitating the proposed design workflow when implementing reclaimed steel elements in new building designs.

4.1.2 CONSTRAINTS AND REQUIREMENTS

To ensure the effectiveness and functionality of these tools, it is crucial to take into account the constraints and requirements identified through the research process. These constraints and requirements serve as valuable insights that inform the design and functionality of the tools, ensuring they meet the specific needs and objectives of the users.

Web Interface: Firstly, the web platform should provide a user-friendly interface that allows users to navigate the platform seamlessly and efficiently upload, view, and search relevant data. In addition, the interface should enable real-time updates of the inventory data to ensure the availability and status of the reclaimed stock elements are accurately reflected. This will avoid outdated or misleading information. Another feature that should be implemented is a notification system to alert users about new stock listings, matches, or inquiries, and provide communication channels for material seekers and material providers to interact. Lastly, the interface should incorporate adjustable settings to allow for search and filter capabilities based on user needs and project criteria.

Matching Algorithm: In regards to the matching algorithm, the data formats should be standardized to ensure consistency and effectiveness. Lastly, the integration of these different platforms should be seamless to allow for efficient data exchange and user coordination during the project workflow.

4.2 USER CASE SCENARIOS

Prior to developing the computational tool, a user case scenario was conducted to identify the different users that will utilize this tool and the individual needs for each user. This is illustrated on Figure 31. Understanding the specific needs of the different users allows for the development of a tool that aligns with their expectations and addresses their challenges effectively. It ensures that the tool caters to their unique workflows and processes.

Furthermore, user case scenarios provide insights into the diverse roles and responsibilities of users involved in the process. This helps in tailoring the tool's functionality and interface to accommodate the specific requirements of different user groups, ensuring usability and adoption across the entire workflow.

By dividing the users into material providers and material seekers, it becomes easier to understand their distinct roles and responsibilities in the process of utilizing reclaimed materials, and tailor the computational tool to meet their specific needs and challenges.

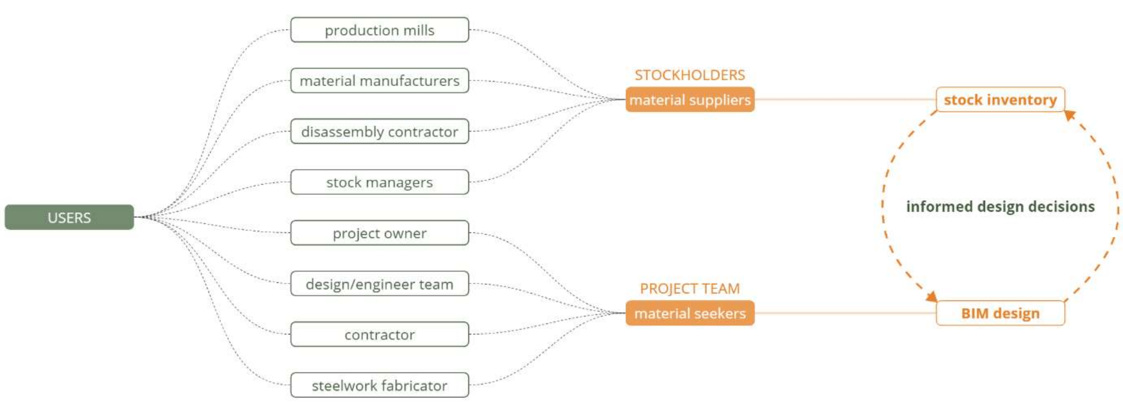


Figure 31: User case scenario diagram of potential users of the computational tool

4.2.1 MATERIAL SUPPLIERS

USER PROFILES

Production mills: are responsible for manufacturing new steel sections. They produce steel materials according to industry standards and specifications.

Material Manufacturers: specialize in producing materials from recycled or reclaimed sources. They transform reclaimed materials into usable products that meet quality and performance standards.

Disassembly contractors: specialize in dismantling buildings and structures to salvage reusable materials and may be a source of reclaimed steel.

Stock Managers: are responsible for managing and maintaining an inventory of reclaimed materials. They oversee the storage, organization, and tracking of available stock elements to ensure their accessibility and suitability for reuse.

USER NEEDS

The computational tool for material suppliers should include a search function that enables easy and efficient identification and location of available reclaimed steel materials. Additionally, the tool should provide the capability to upload and manage the inventory of reclaimed steel elements, ensuring effective organization and tracking. To ensure quality control, an automated system for tracking the supply chain and material certifications should be incorporated. Lastly, seamless integration with other management softwares as well as platforms for planning the disassembly process would enhance overall efficiency and effectiveness.

4.2.2 MATERIAL SEEKERS

USER PROFILES

Project owner: is the project initiator who establishes the project criteria and sets the sustainability and circularity goals.

Design/engineer team (architects, designers, engineers, and consultants): these professionals are responsible for the planning, design, and construction coordination of the project in alignment with the client's criteria.

Construction contractor or construction manager: is responsible for overseeing the execution of the designed project and managing the means and methods of the construction process. They are responsible for executing the project according to the design plans and specifications, including the procurement and installation of materials.

Steelwork fabricator: specializes in fabricating and assembling steel components based on the design specifications provided by the design/engineer team. They transform raw steel materials into finished elements that can be integrated into the construction project.

USER NEEDS

Material seekers utilizing this computational tool have specific needs to enhance their search for reclaimed steel materials. The tool should provide an intuitive interface with search and filtering functionalities, allowing users to easily locate materials that meet their project requirements, such as size, shape, and material properties. Additionally, the tool should offer automated calculations to assess the strength and performance characteristics of the reclaimed steel, enabling designers to make informed decisions. Integration with (BIM) software would facilitate seamless incorporation of the reclaimed steel into the design process. Finally, an efficient system for managing and tracking the delivery and installation of the materials on-site would streamline the construction workflow.

4.3 WEB INTERFACE

The development of a prototypical web platform serves as a proof of concept for facilitating interaction between material seekers and material providers designed to support the exchange of reclaimed steel materials for construction projects. To accommodate the different roles and responsibilities within the web platform, two sets of user profiles have been created. The first profile is for material seekers, which encompasses individuals from project teams who are searching for suitable materials. The second profile is for material providers, specifically the stockholders, who are the focus of this research and responsible for supplying the reclaimed steel materials. This distinction allows for tailored functionalities and interfaces based on the specific needs and objectives of each user group, as described in Section 4.2. This interface was developed as a strategy to be implemented within the proposed workflow of designing with reclaimed steel, as discussed in Section 3.2.

The web interface serves as a convenient one-stop platform, by providing access to the digital inventory and matching algorithm within a single interface, eliminating the need for users to navigate multiple programs or software to access relevant data and information. Through an intuitive and user-friendly interface, the platform enables material seekers to conveniently search for available materials that meet their project requirements, while allowing material providers to showcase their inventory and connect with potential customers.

It is important to note that this web platform prototype serves as a demonstration of the envisioned functionality and user experience, highlighting the potential benefits and possibilities that a fully functional website could offer in the future.

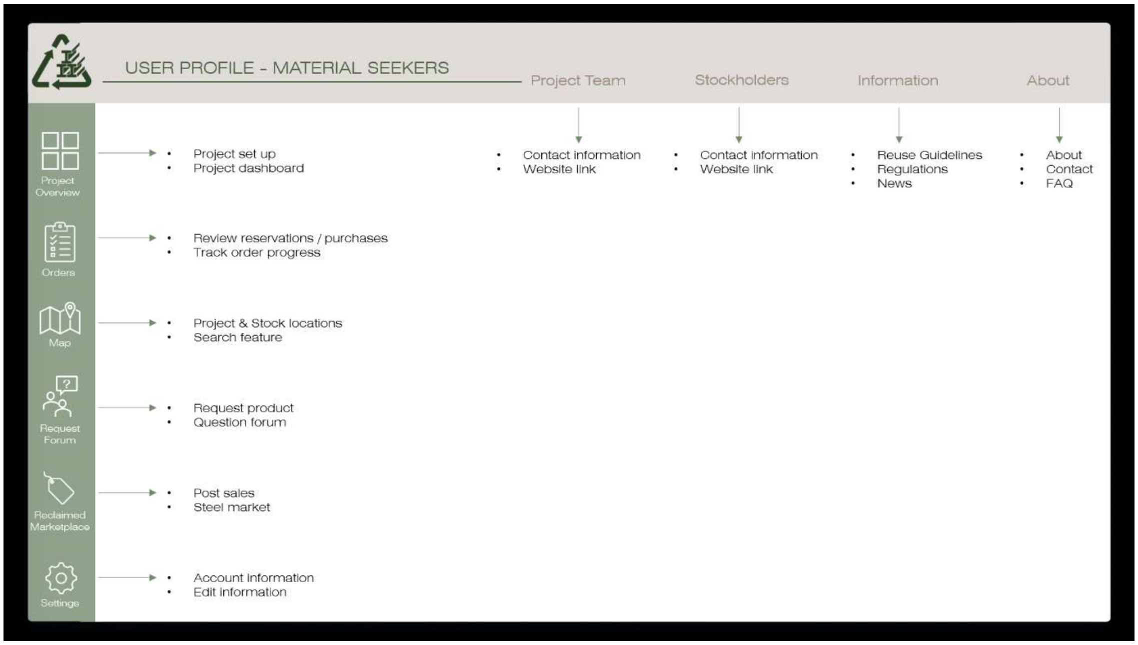


Figure 32: Web Platform Interface – Example of user profile for "material seekers"

WORKFLOW – USER INTERFACE

The development of a web platform involves the consideration of the workflow process as well as the flow of information to ensure an intuitive and efficient user experience. As mentioned above, the objective is to create a seamless interaction between the two user profiles that allows for interaction and exchange of data effectively. The workflow for the web platform is separated into Part 1 and Part 2. The first part involves the input within the interface prior to the stock matching process. Part 2 is the output result after the stock matching process and the available options or design choices that can be taken based on the user preferences.

The Part 1 workflow, in figure 33, illustrates the input information provided by the two sets of users. The stock companies provide their stock list data as well as the corresponding stock yard locations. This database becomes a public and digital stock inventory to facilitate the exposure of available stocks. The project team provides the project location as well as a design list. The project location helps in identifying the geographical context and potential steel stock sources within a given radius to reduce the time and effort required to locate suitable reclaimed steel elements and also manage the transportation emissions encountered by the delivery of these elements. The design list, on the other hand, represents the project design and structural criteria, outlining the specific requirements and specifications for the needed steel elements.

Finally, based on the search radius defined, the map will highlight the stock yards that fall within this radius and will compile the various stock lists into one stock list. This stock list, along with the design list, are then the inputs into the matching algorithm which will initiate the matching process, which is later described in Section 4.5.

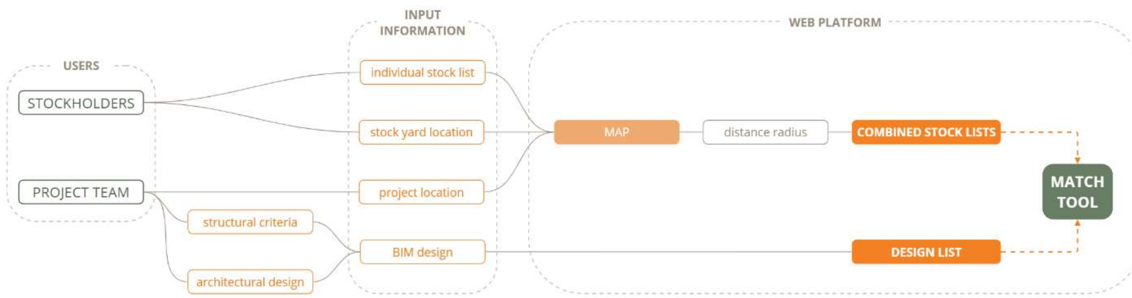


Figure 33: User Interface Workflow: PART 1 – Input parameters and user preferences

The Part 2 workflow, in figure 34, showcases the output results obtained after the matching process. These results consist of two lists: the list of matched elements and the list of remaining unmatched elements from the design list. The matched elements are those that can be replaced with reclaimed steel stock elements for the project, while the unmatched elements require newly manufactured steel elements to fulfill the project requirements. This information empowers the project team to make informed design decisions and explore the options outlined below.

For the list of matched elements the user can choose to reserve or purchase the elements within the web platform. When a user reserves an element, the corresponding stock company is notified to hold the element, while a purchase notification confirms and initiates the order process. In the context of conceptual design, designers and engineers using the interface would typically reserve elements to ensure their availability after the design phase. On the other hand, contractors or fabricators utilizing the interface would likely purchase the elements if the design phase has been completed and the elements are needed for fabrication and construction. The reservation or purchase of elements can be conveniently done directly through the web platform.

For the list of unmatched elements, the project team has several options to consider. One option is implementing beam splices, which involves connecting multiple shorter beams to create a longer beam that meets the desired length specified in the design list. To ensure even load distribution, structural stability, and integrity, the splicing technique follows the 2/3 and 1/3 rule, where the splice connection on a beam should be positioned at 2/3 of the span length. To utilize this option, the matching algorithm is rerun to specifically search for matched elements that can be combined to splice beams. This option is carried out after the initial matching process to optimize the number of matched results. However, implementing this option will require additional structural verification and coordination in connecting the spliced beams. Batty (2023), along with colleagues from HTS, are currently working on a stock matcher tool and described the implementation of splicing rules as an efficient solution to enhance the matching results.

Another option that the project team can take is uploading the list of unmatched elements in the "request forum" of the web platform. This section allows stock companies to get notified of the list of elements that are being searched for or are in high demand so that they may focus their search on those elements. If the elements are found, the stock companies will update their stock lists and then the project team will get notified when the initial unmatched elements are available.

Thirdly, the project team has the option to expand the distance radius around the project location within the project settings, allowing for a broader search of stock yards on the map. Additionally, during the conceptual design phase, the matching algorithm can be run through multiple iterations to compare the matching results, aiding the project team in identifying the optimal design for maximum steel element reuse. Ideally, design updates or changes should be made within a parametric model, enabling easy adjustment of parameters and the creation of efficient design options. These variations can then be used to re-run the matching algorithm multiple times, facilitating informed design decisions based on the updated matching results.

Lastly, the list of unmatched elements can be downloaded for the project team to utilize for purchase orders of newly manufactured steel.

This tool can serve as a final design check but can also be utilized throughout the conceptual design process to inform the design and maximize the reuse potential.

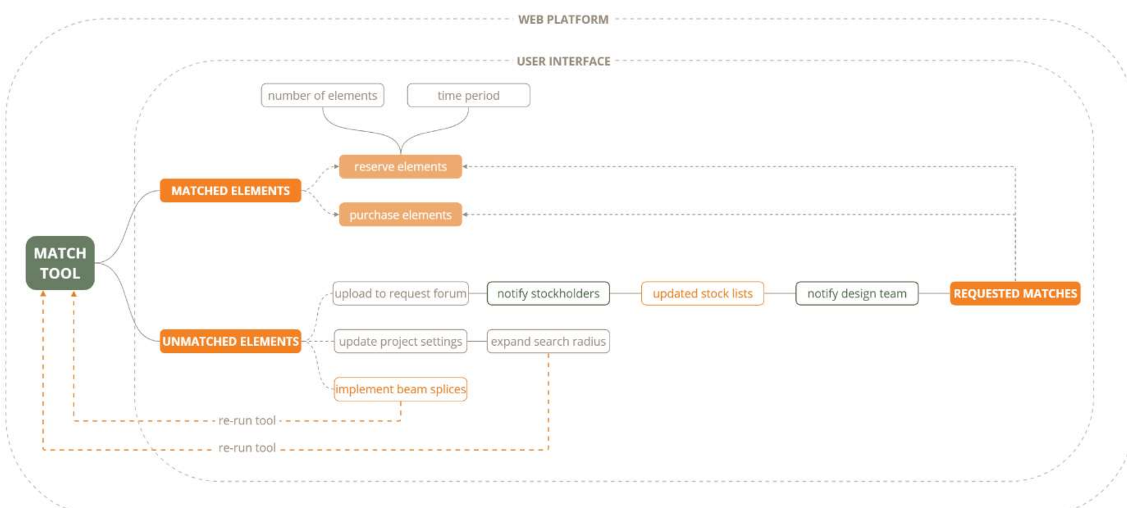


Figure 34: User Interface Workflow: PART 2 – Output results allowing for informed decisions to be taken by users

4.3.1 MAP

The map feature in the web platform is essential for various reasons. Firstly, it provides a visual representation of the stock yards and their locations, allowing material seekers to easily identify nearby options. This spatial information is valuable as it helps users assess the feasibility and logistics of sourcing materials from specific stock yards based on their proximity to the project site. By adding a search radius to the map, the project team can narrow down the search for stock lists within a specific distance from the project location. This functionality enhances efficiency by focusing the search on relevant stock yards, reducing the time and effort required to locate suitable reclaimed steel materials. Overall, the map feature enhances the user experience by providing a geospatial context, facilitating informed decision-making, and streamlining the search process for all material seekers.

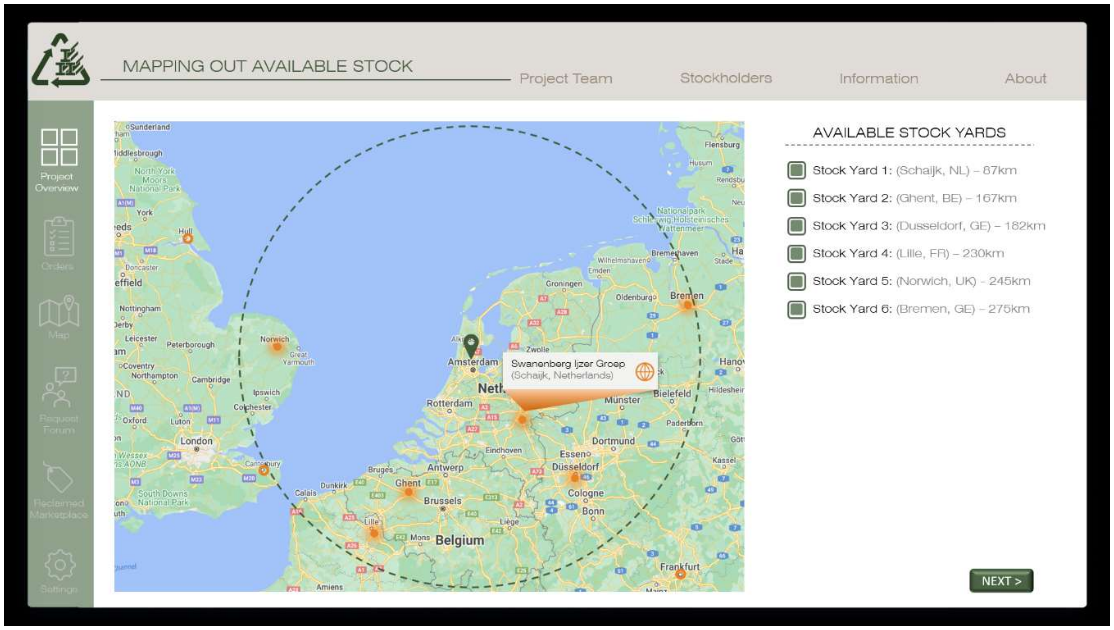


Figure 35: Web Platform – Map of available stocks specified by a distance radius search

4.3.2 PROJECT DASHBOARD

The web platform includes a dedicated *Project Dashboard*, for the material seeker interface, that empowers the project team to efficiently set up and manage their projects. Within this tab, users can enter vital information about the project, such as its location, function, and design phase end date. By inputting these details, the website leverages this data to streamline the subsequent steps of the process. One key feature of the *Project Dashboard* is the ability to specify a distance radius, enabling the platform to identify and select relevant stock yards located within the designated proximity. This radius parameter allows for targeted searches and facilitates the compilation of stock lists from multiple sources. Finally, the project setup is completed by uploading the design list of steel elements required for the project. By centralizing project information, this tab optimizes the workflow, ensuring that the project team can seamlessly move forward with the next stages of the material selection and matching process.

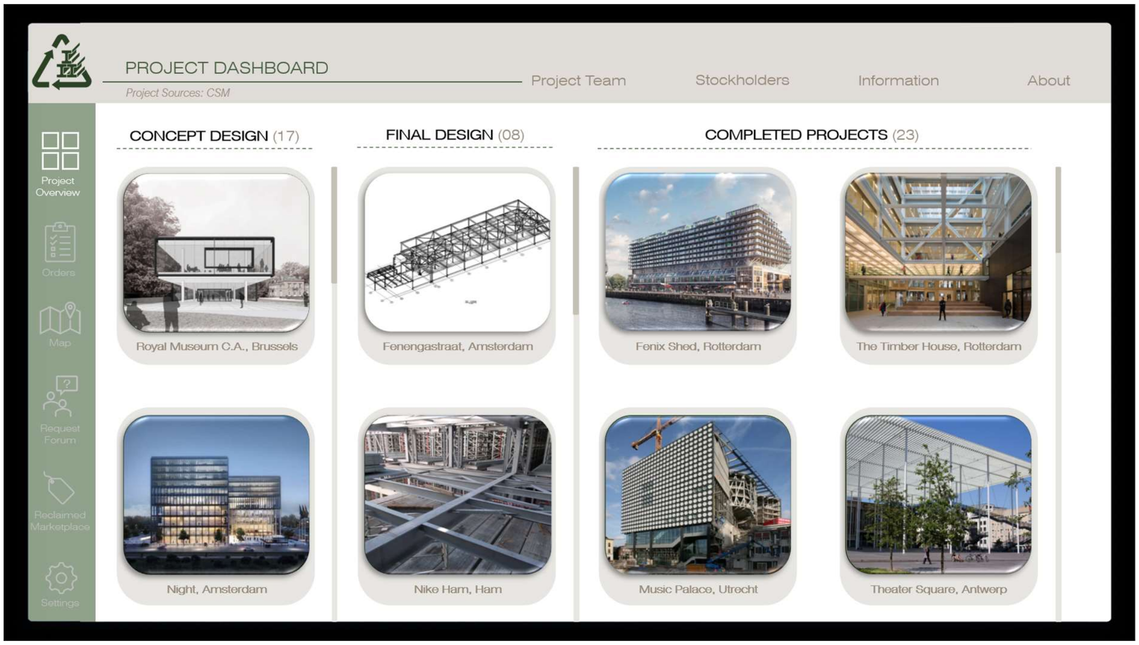


Figure 36: Web Platform – Overview of working or completed projects within the interface (images by CSM)

In addition, as shown in Figure 36, the *Project Dashboard* allows users to have access to all current and past projects. This stored database serves as a historical reference, allowing easy access to past project information, lessons learned, and patterns for informed decision making. This tab supports communication by providing a centralized server with up-to-date project status. Overall, it enhances project management, efficiency, and organizational effectiveness.

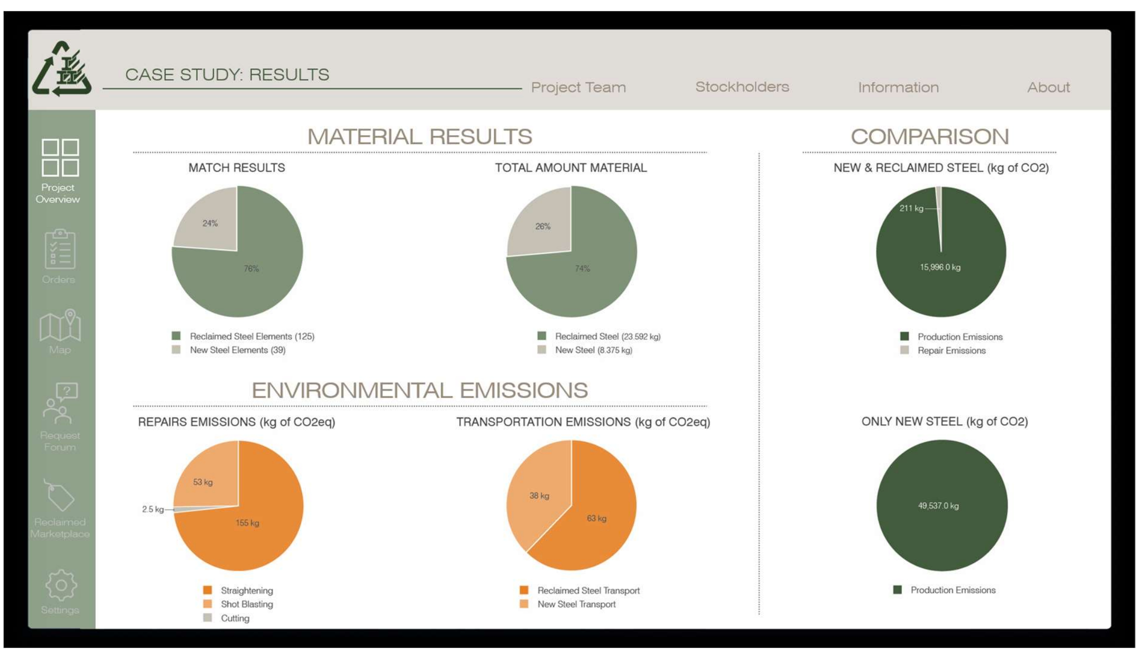


Figure 37: Web Interface - Project environemntal impact data based on results from the matching algorithm

The database plays a crucial role in facilitating performance evaluation, benchmarking, and strategic planning through the analysis of project metrics. Additionally, within each project, users have access to environmental impact data based on the results of the matching algorithm, as depicted in Figure 37. This data is essential for calculating the carbon footprint of the project and can also serve as a means to encourage the project team to make sustainable and responsible decisions.

4.3.3 RESERVATION SYSTEM

A reservation system within the web platform would address the challenges faced by stock companies and provide assurance to design users regarding the availability of matched stock elements. The reservation system would allow the project team to reserve steel elements from the stock list during the design phase. Users would pay a monthly reservation fee, ensuring material availability at the end of the design phase for a maximum reservation period of 2 years. This system would benefit both parties by offering more certainty for stockholders and enabling users to secure the desired elements.

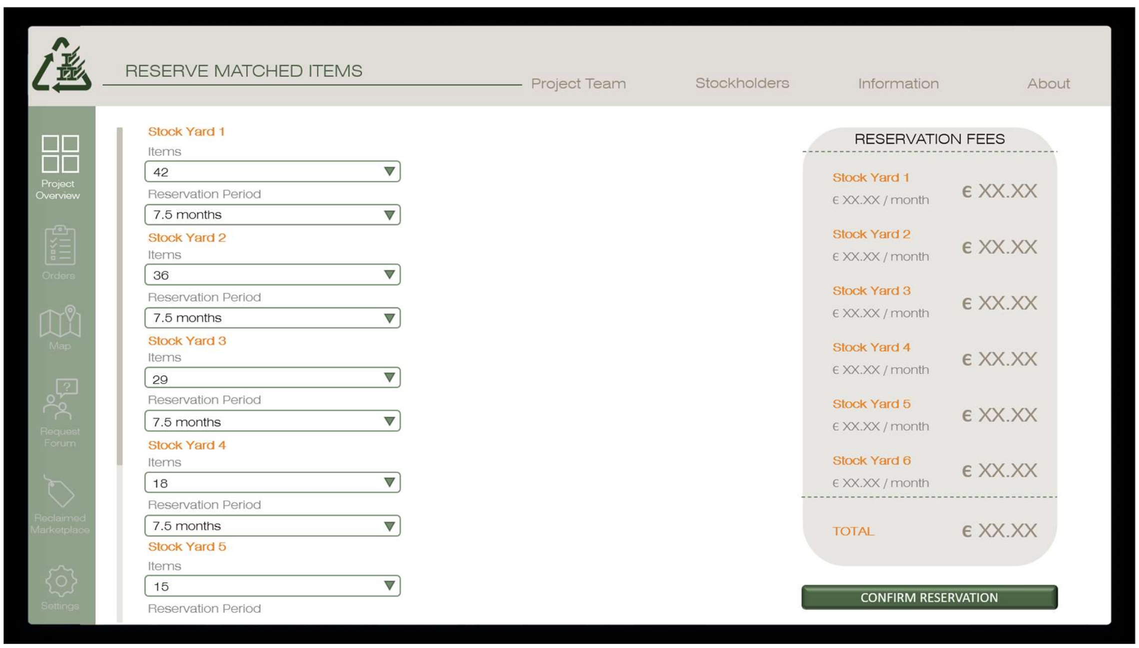


Figure 38: Web Platform - Reservation System of matched stock elements

4.3.4 REQUEST FORUM

The web platform incorporates a dedicated *Request Forum* tab, designed to facilitate seamless communication between the project team and stock companies. This feature serves multiple purposes and brings numerous benefits to the users. Firstly, the *Request Forum* allows the project team to submit specific product requests for the elements that were unmatched by the matching algorithm. Additionally, the *Request Forum* serves as an open forum for communication, enabling both the project team and stock companies to engage in discussions and exchange information. Users can leverage this forum to ask general questions, seek clarification on product details, or directly communicate with stock companies.

This interactive space fosters collaboration and enhances the overall user experience by promoting transparency, facilitating inquiries, and creating opportunities for direct engagement with suppliers.

This feature also provides a notification system to keep users informed of any updates or responses related to their product requests. When the project team uploads their unmatched list, the stock companies will get notified of the elements that are requested and in high demand so that they are able to search for those elements specifically. Once the stock companies make updates to their stock lists, the project team users will get notified when there are new responses or updates to stock lists that match their requirements. These notifications are referred to as “a call to action” as it will then prompt the project team to review the updated stock lists within the matching algorithm to verify the list of matched elements. These notifications ensure that users stay informed in real-time, allowing them to promptly review and assess the available options. This notification feature adds an extra layer of convenience and responsiveness, ensuring that users remain engaged and connected throughout the material selection process.

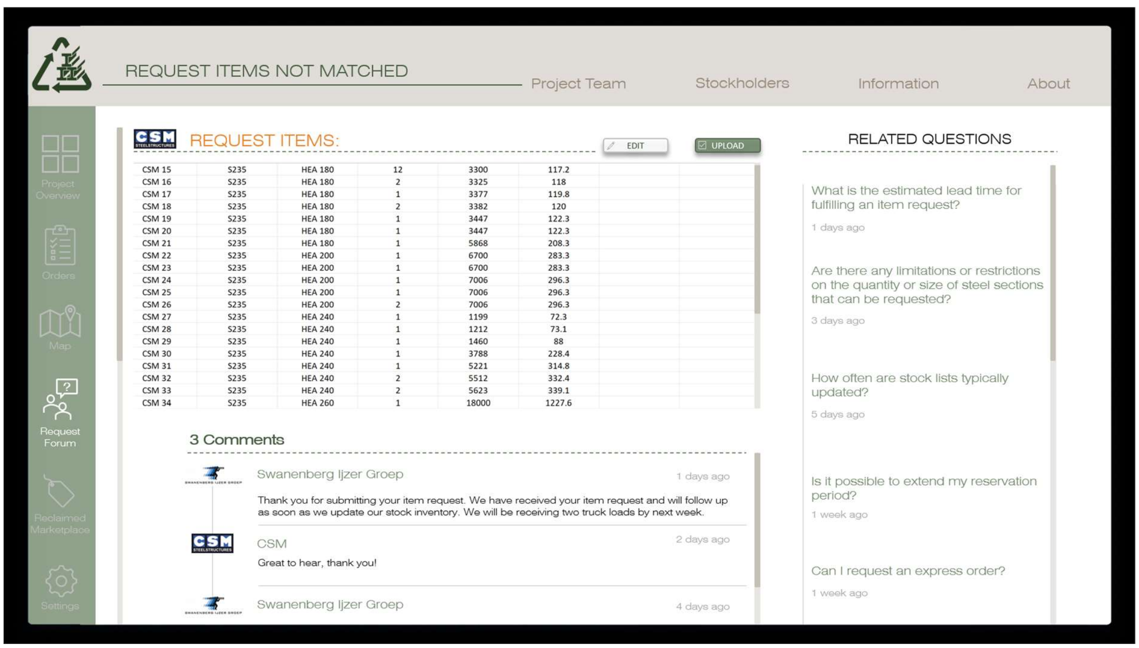


Figure 39: Web Platform - Request Forum where users can effectively communicate and request information

4.3.5 RECLAIMED MARKETPLACE

The *Marketplace* feature of the web platform serves as a dynamic platform for stock companies, connecting them with potential sellers of steel products. This feature enables stock companies to receive notifications when steel products become available for purchase, including components from building owners undergoing deconstruction and disassembly contractors looking to sell steel elements. In addition, stock companies may also seek "D-classed" or "off-grade" steel from production mills, which encompasses elements that were either over-ordered or did not meet the requirements for the intended use due to defects. Including production mills expands the range of options available to cater to the specific needs and preferences of stock companies in procuring steel for construction projects, as highlighted by Van Der Loop (2023).

Once notified, stock companies can actively engage with sellers, manage product negotiations, and facilitate the purchase process. This marketplace feature streamlines the process of acquiring reclaimed steel elements, enabling efficient and direct communication between sellers and stock companies. By facilitating these interactions, the web platform promotes the circular economy by encouraging the reuse and repurposing of steel materials, fostering sustainability within the construction industry.

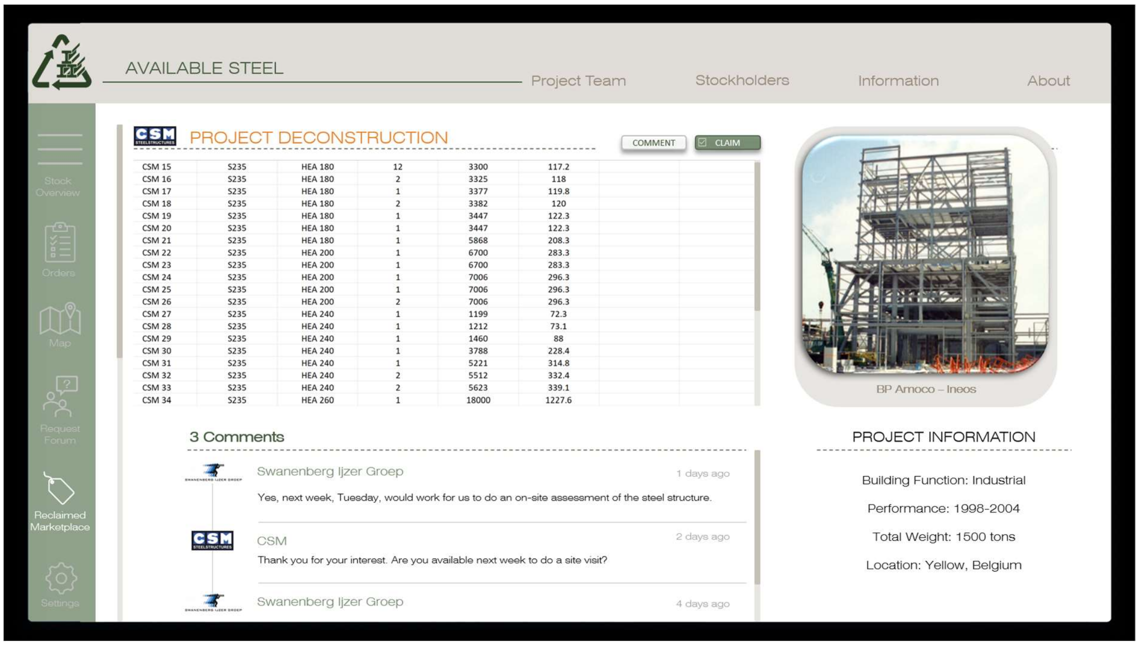


Figure 40: Web Interface - marketplace for available steel for deconstruction

4.3.6 STOCK LISTS – DIGITAL INVENTORY

The web platform incorporates a dedicated *Stock List Inventory* tab exclusively designed for material suppliers, enabling them to upload and manage their stock information. This feature provides a user-friendly template that ensures consistent and structured data entry, facilitating effective utilization by the matching algorithm. Stock companies can input details such as steel element dimensions, material properties, availability status, and location. By adhering to the predefined template, the stock list data becomes easily readable and searchable by the matching algorithm, enhancing the accuracy and efficiency of the material matching process. This standardized approach enhances the inventory management process for stock companies, allowing them to effectively showcase their available reclaimed steel elements to potential buyers.

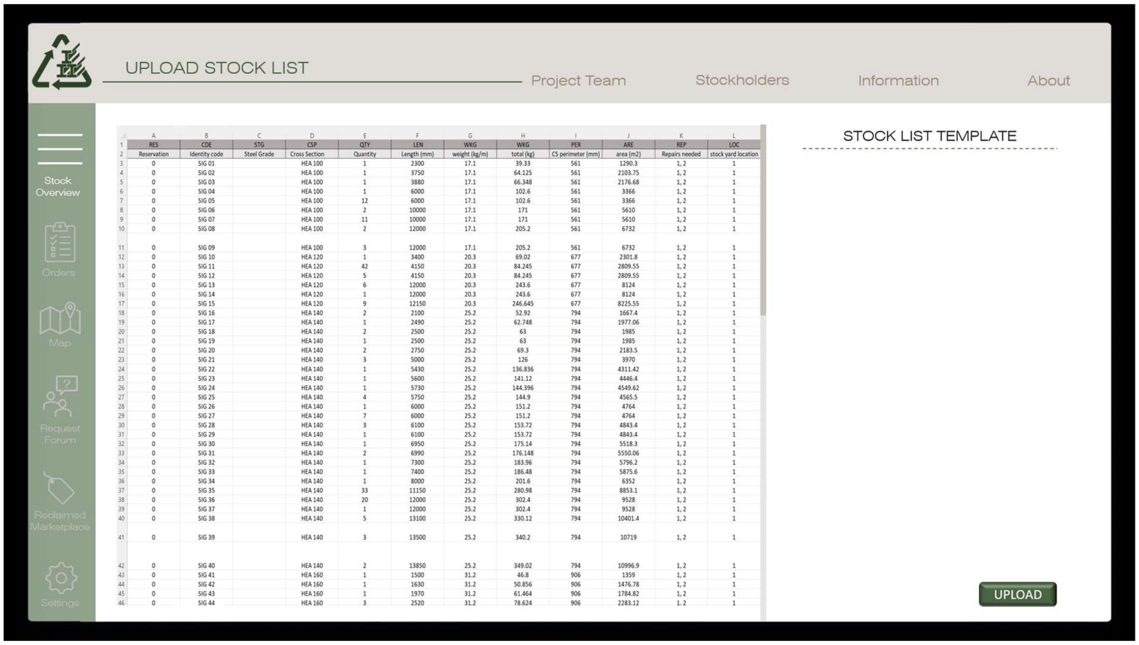


Figure 41: Web Platform - Stock List input for digital stock inventory overview

4.4 EXCEL DATA

Excel is an ideal tool due to its flexibility, data manipulation capabilities, and data visualization options. It allows for easy sorting, filtering, and organizing of data, while also providing functions and formulas for efficient calculations and analysis. With Excel, users can effectively manage and analyze stock list data, making it a convenient and versatile choice for stock list management.

4.4.1 STOCK LIST CASE STUDIES

Both stock companies interviewed, CST and SIG, provided their most recent stock lists to be utilized for this thesis project. CST mentioned that they have an internal software program where they store stock data and then they export it as an Excel spreadsheet; this was not specified by SIG.

Cleveland Steel Tubes:

	A	B	C	D	F	G	H	I	J	K	L	M	N
1	RESERVATION												
2		NUM	CDE	PRO	LO1	CHO		ASP		EXT		RVE	
3		Beam No.	P.O. No.	Section	Length	Quality		Condition		Ends		Coating	
4	Reserved but unsold	SB00714	502006	UB35617145	6400	4	SECONDHAND	8	PAINT REQUIRES REMOVAL	1	PLAIN	3	PAINTED
5		$SB01153	501972	PFC20021060	6400	4	SECONDHAND	7	PAINT REQUIRES REPAIR	0	NO INPUT	3	PAINTED
6	Reserved but unsold	$SB01277	502026	UB610229101	10100	4	SECONDHAND	7	PAINT REQUIRES REPAIR	6	FLAMECUT	3	PAINTED
7		CSB00679	501973	UB25410228	11200	1	1ST CHOICE WITH CERTS	4	HEAVY PITTING	1	PLAIN	0	NOINPUT
8		71599	501972	UC20320346	9500	4	SECONDHAND	6	PAINT IN GOOD ORDER	1	PLAIN	3	PAINTED
9		71600	501972	UC20320346	7370	4	SECONDHAND	6	PAINT IN GOOD ORDER	1	PLAIN	3	PAINTED
10		71601	501972	UC20320346	9500	4	SECONDHAND	6	PAINT IN GOOD ORDER	1	PLAIN	3	PAINTED

Figure 42: CST Internal Stock List - Part 1 (CST, 2023)

Column A is to note items reserved. Column B defines the unique number per element assigned by CST. Column C refers to the purchase order number from the purchase contract. Column D is the profile section, where column F defines the length of the element and column G the quantity of that element. Column H refers to the life cycle of the element. The quality and condition are noted in columns I through N.

O	P	Q	R	S	T	U	V	Y	Z	AD	AE	AF	AP
DE1		DE2		DE3		NUA		POS	NBR	ORI	PDS	LIG	D99
Defect1		Defect2		Defect3		Grade		S.O Item	No Of Bea		Weight	P.O. Item	Defect Text
6	HOLES	0	NO DEFECT	0	NO DEFECT	INC	UNKNOWN	0	1		288	1	HOLES LENGTH OF BEAM
2	ATTACHMENTS	6	HOLES	0	NO DEFECT	INC	UNKNOWN	0	1		362.24	5	PLATES ON FLANGE
1	BENT	2	ATTACHMENTS	0	NO DEFECT	INC	UNKNOWN	0	1		1022.12	1	
0	NO DEFECT	0	NO DEFECT	0	NO DEFECT	355JR	S355JR-E36.2-5	0	1		316.96	5	
6	HOLES	0	NO DEFECT	0	NO DEFECT	INC	UNKNOWN	0	1		437.95	2	4.6M 2 HOLES 4.6M
0	NO DEFECT	0	NO DEFECT	0	NO DEFECT	INC	UNKNOWN	0	1		339.757	2	3.6M 2HOLES 3.6M
6	HOLES	0	NO DEFECT	0	NO DEFECT	INC	UNKNOWN	0	1		437.95	2	4.6M 2HOLES 4.6M

Figure 43: CST Internal Stock List - Part 2 (CST, 2023)

Continuing with the Excel spreadsheet, columns O to T as well as AP include information about defects. Columns U and V will include the steel grade if there is a test certification completed, otherwise it will state "unknown." The information of columns Y, Z, AD, and AF were not recalled by Fishwick (2023) during the conversation, but he stated they are not critical columns. Lastly, the individual section weight is listed in column AE.

Swanenberg Ijzer Groep:

	A	B	C	D	E	F	G	H	I	J
1	Article Code	Quantity	Weight	Length	Max Length	Quality	Shots	Location	Remarks	Exclude reporting
2										
3	HEA 100	1	17.1	2300		G	N	SCH-VAK 14	rode verf	
4	HEA 100	1	17.1	3750		O	N	SCH-GZ	langs snijplaats	
5	HEA 100	1	17.1	3880		N	N	SCH-VAK 10		
6	HEA 100	1	17.1	6000		G	N	SCH-VAK 11	blauwe kop S355G11	
7	HEA 100	12	17.1	6000		O	N	SCH-VAK 14	min S235 zonder cert (Kldrs paar kromme bij)	
8	HEA 100	2	17.1	10000		O	N	SCH-VAK 14	gestraald + gemenied, netjes	
9	HEA 100	11	17.1	10000		N	N	SCH-VAK 14	nieuwe balk, min s235 zonder cert / Stolk Recycl.	
10	HEA 100	2	17.1	12000		O	N	SCH-VAK 11	blauwe kop S355G11	

Figure 44: SIG Internal Stock List (SIG, 2023)

The stock list provided by SIG contains less information than the CST stock list, but still contains the necessary inputs for the matching algorithm. Column A contains the article code which represents the cross-section type, column B states the quantity of the elements.

The stock list provided by CST contains more information than SIG as shown and described on the figures above. However, CST's stock list is mostly composed of steel pipes, as that is mainly their focus. Their stock list only contains 16 H profiles of the same cross section and lengths, while SIG's stock list contains 3562 rows of data regarding H, I, and U profiles. For this reason, SIG's stock list data was utilized in the development of the matching algorithm further discussed below in Section 4.5.

4.4.2 PROPOSED STOCK LIST TEMPLATE

In order for the Grasshopper script to read the multiple excel data sheets, a stock list template was developed to allow for a standardized level of information needed from each stock company to inform the project team. Figure 45 below illustrates the utilization of information, where the cross-section types, quantity and length are the inputs that will be compared against a design list to find ideal match results.

The steel grade will not be verified until the elements are purchased and then sent for testing. However, stockholders can perform a non-destructive hardness test to estimate this value which will also serve as input in the matching process but will state that the steel grade still needs to be verified through an official test certificate. The ID Code will facilitate the recalling of the row data as this includes the data multiplied by the quantity data, which is further explained below. Furthermore, to calculate the repair CO2 emissions the geometrical properties of the element will be multiplied by the estimated energy consumption of each repair. The transport CO2 emissions will be obtained based on the number of elements, which will result in the number of trucks, and the distance from the stock yard to the project site. This is further explained in Section 4.7.

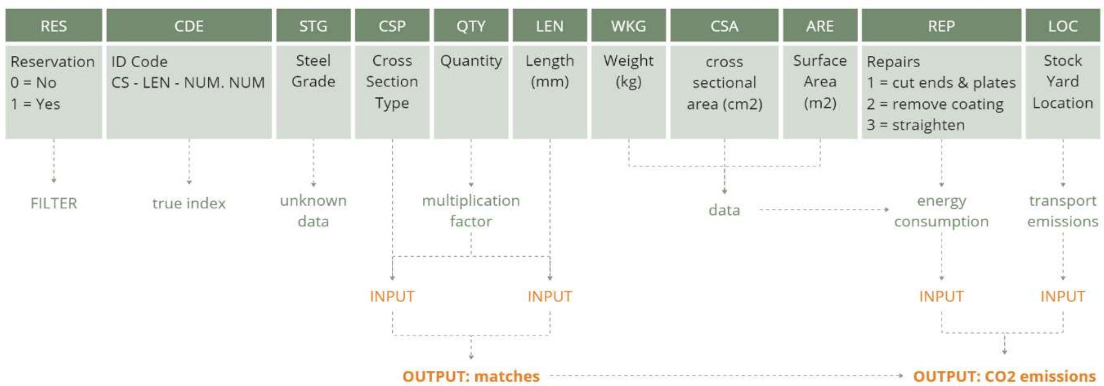


Figure 45: Stock list template to obtain matched results within matching algorithm

Based on the abovementioned diagram, Figure 46 is the final Excel spreadsheet that was input into the Grasshopper script for the matching algorithm. The data obtained from the SIG stock list case studies include the cross-section type, quantity, length, and weight. The remaining columns were added as proof of concept.

	A	B	C	D	E	F	G	H	I	J	K	L
1	RES	CDE	STG	CSP	QTY	LEN	WKG	WKG	PER	ARE	REP	LOC
2	Reservation	Identity code	Steel Grade	Cross Section	Quantity	Length (mm)	weight (kg/m)	total (kg)	CS area (cm2)	area (m2)	Repairs needed	stock yard location
3	0	SIG 01		HEA 100	1	2300	17.1	39.33	21.2	121.9	1, 2	1
4	0	SIG 02		HEA 100	1	3750	17.1	64.125	21.2	198.75	1, 2	1
5	0	SIG 03		HEA 100	1	3880	17.1	66.348	21.2	205.64	1, 2	1
6	0	SIG 04		HEA 100	1	6000	17.1	102.6	21.2	318	1, 2	1
7	0	SIG 05		HEA 100	12	6000	17.1	102.6	21.2	318	1, 2	1
8	0	SIG 06		HEA 100	2	10000	17.1	171	21.2	530	1, 2	1
9	0	SIG 07		HEA 100	11	10000	17.1	171	21.2	530	1, 2	1
10	0	SIG 08		HEA 100	2	12000	17.1	205.2	21.2	636	1, 2	1

Figure 46: Utilized Stock List Data (own spreadsheet with SIG data)

4.5 DESIGN CASE STUDY

CSM provided a design case study of a project they are currently working on, shown in figure 47. The scope of the project is a simple rooftop construction on top of an existing office building located on Willem Fenengastraat, Amsterdam.

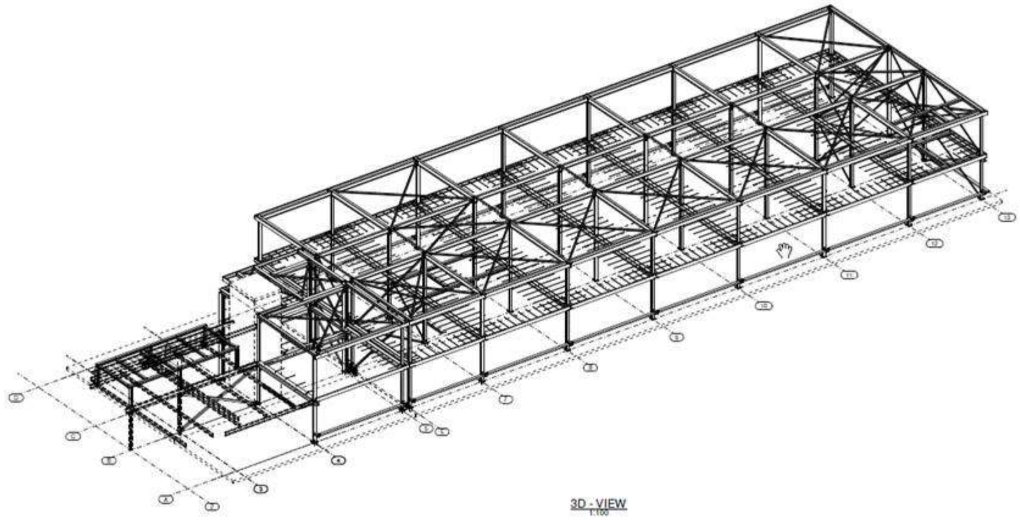


Figure 47: Design Case Study provided by CSM (CSM, 2023)

Following, the BIM data is imported to Tekla Structures as an IFC file. Within Tekla Structures the material list, comprising the required structural steel elements for the project, was then generated based on this imported model. This material list includes the profile and length of the steel sections as well as the corresponding connecting plates. This list is typically sent to production mills as a purchase order to order new steel sections. However, this material list will be utilized to find reclaimed steel within various stock yards, as a first option before ordering new steel sections. By leveraging the capabilities of Tekla Structures and its compatibility with BIM data, the process enabled efficient data extraction, accurate material list compilation, and seamless integration with the matching algorithm, contributing to the overall effectiveness of the design workflow.

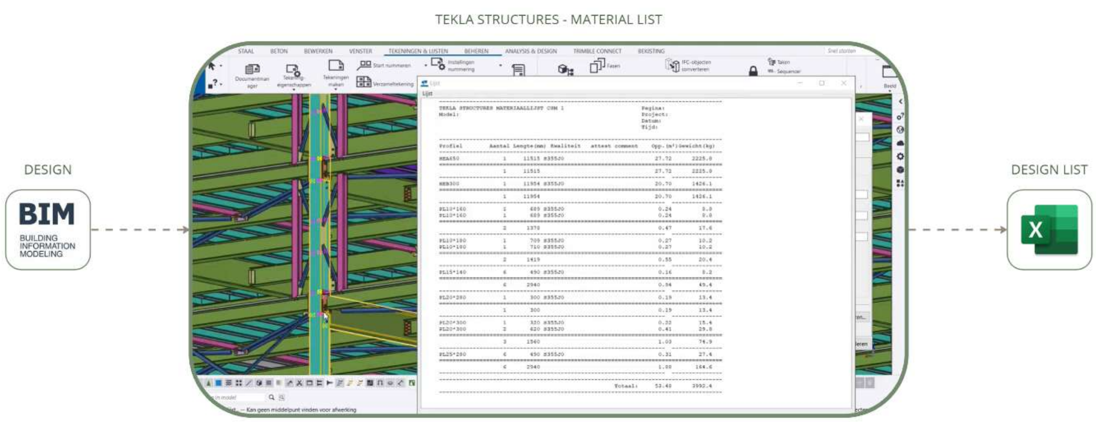


Figure 48: Workflow to Obtain Design List

CSM provided the Tekla Structures file for this case study project, shown on Figure 48, where the material list was extracted into an Excel spreadsheet and formatted to match the template of the stock list. This was important as the objective is to compare column data within the matching algorithm in order to find the matches between the design list and the stock list. Figure 49 below displays the final Excel spreadsheet that was input as the design list into the Grasshopper script.

	B	C	D	E	F	G	H
1	CDE	STG	CSP	QTY	LEN	WKG	ARE
2	Identity code	Steel Grade	Cross Section	Quantity	Length mm	total (kg)	surface area m2
3	CSM 01	S235	HEA 140	18	530	13.1	
4	CSM 02	S235	HEA 180	2	1869	66.3	
5	CSM 03	S235	HEA 180	1	3000	106.5	
6	CSM 04	S235	HEA 180	12	3012	106.9	
7	CSM 05	S235	HEA 180	2	3050	108.3	
8	CSM 06	S235	HEA 180	2	3070	109	
9	CSM 07	S235	HEA 180	6	3077	109.2	
10	CSM 08	S235	HEA 180	6	3077	109.2	

Figure 49: Utilized Design List Data (own spreadsheet with CSM data)

4.6 MATCHING ALGORITHM - GRASSHOPPER

Grasshopper is a Rhino3D plugin that allows for seamless data integration between Excel spreadsheets and programming components. This program was utilized for the development of the matching algorithm as it can easily import and manipulate Excel data and enable direct access to the information that needs to be processed. With its visual programming interface, one can create algorithms and workflows to sort and match data according to parametrized requirements.

4.6.1 PROCESS

Firstly, the stock list and design list are imported from their respective excel spreadsheets into Grasshopper. The following workflow diagrams represent the multiple steps that were performed within the Grasshopper script. The color key below was utilized for clear interpretation of the workflow diagrams.

Key:

GH WORKFLOW PART 1

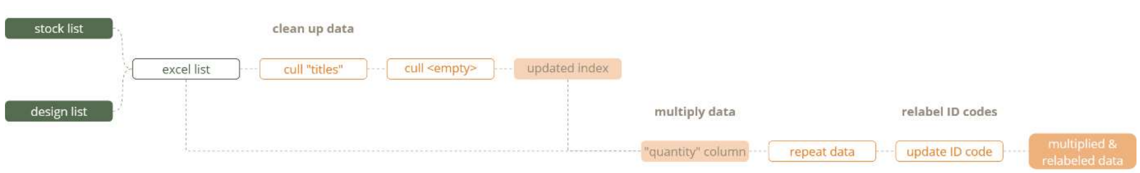


Figure 50: GH Workflow Part 1 – clean up and organize data for proper data structure

As displayed in Figure 50, to clean the data, any <empty> vales are culled from both lists to avoid empty indexes. The next step is to multiply the data by the quantity column (4) of the excel lists. This is necessary in order to have an individual index and unique ID code for each steel element. Once the indexes are multiplied by the quantity, the ID codes (1) are renumbered to include a ".0" value and incremented for identical elements resulting from the multiplied quantity. This is done so that each element has a unique ID code which will make it easier to search and call in the script later in the process.

GH WORKFLOW PART 2

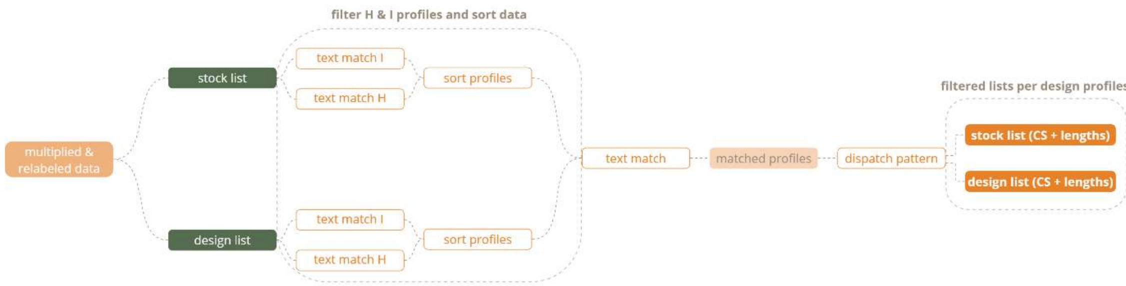


Figure 51: GH Workflow Part 2 – filtering lists per design profiles to reduce data amount

Furthermore, the case study stock list and design list include multiple types of section profiles. However, the scope of the thesis is only H & I steel profiles. For this reason, the cross section profile column (3) is filtered to retain only profiles starting with the letters "H" and "I," while removing other profile types from the lists. With the filtered lists of H & I section profiles, the subsequent step involves grouping the respective lengths per individual profile type. This is shown on the workflow in figure 51.

4.7 MATCHING ALGORITHM - PYTHON

The GHPython component is a Python interpreter within the Grasshopper tool, allowing for seamless integration between both programs. Python, a compatible coding language, was utilized in the development of the matching algorithm because it offers the ability to manipulate data, develop algorithms, and conveniently operate within the Grasshopper interface.

In this case, Python is employed to iterate through the design and stock lengths, comparing and matching them based on predefined conditions. By employing a combination of sorting techniques and conditional statements, the script efficiently matches design lengths to stock lengths, considering both the optimal utilization of available materials and the specific requirements of the design. This approach ensures that the matching process is effective, contributing to improved efficiency and reduced waste in the construction workflow. Figure 52 illustrates the workflow.

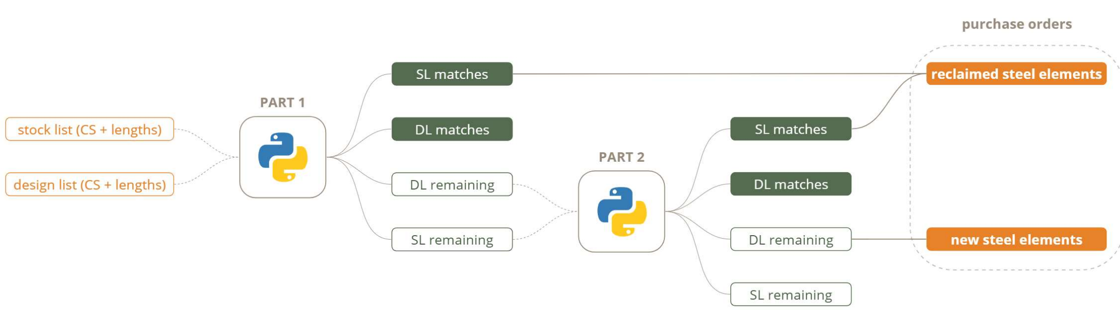


Figure 52: Python Workflow – Matching algorithm part ! & 2 to maximize matching results

4.7.1 PART 1 – INITIAL MATCHING

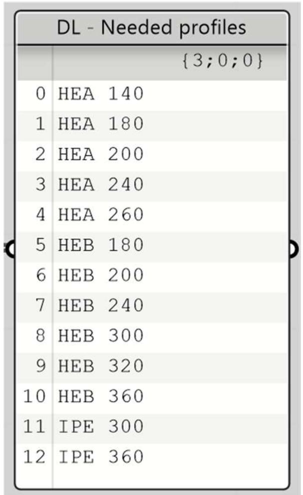


Figure 53: Needed profiles per design list case study

Data matching in Grasshopper and Python involves comparing and matching data from different lists or data sets based on specific criteria. In the context of the script, the goal is to match design lengths with available stock lengths. To achieve this, the design lengths are sorted in descending order, from big to small, ensuring that larger elements are matched first. This order prioritizes finding matches for the biggest design elements, optimizing the use of available stock materials. On the other hand, the stock list lengths need to be sorted in ascending order, from small to big. This arrangement allows the script to consider the smallest possible scenario when searching for matches. By starting with the smallest available stock lengths, it maximizes the utilization of stock materials and minimizes waste. The Python script has several nested loops, which are organized in tree data format where the separate branches represent the different lists determined by the different cross section types as illustrated in Figure 53.

The loops were set up this way so that each cross-section type is searched separately, and the matching results are separated per profile type. Furthermore, two copies of the stock list were created. The `tempLengthSL` list will be the list that is utilized to remove the matched values, so they are not selected multiple times. This was done to not delete any data from the original stock list. The second copy, `IndexsearchSL`, is utilized to find the correct index of the elements that matched, as these indexes are removed from the `tempLengthSL` list. In Grasshopper, when indexes of values are retrieved, the first index will always be selected if there are multiple identical values. For this reason, the matched items will be overridden with a `TRUE` value to avoid the retrieval of the same indexes. So, the `tempLengthSL` list keeps track of the available items and `IndexsearchSL` keeps track of the booked indexes and saves them within the list of results.

To optimize the matching process and minimize material waste, the algorithm employs multiple nested if-else statements and loops. These statements determine the matches between the design list (DL) and stock list (SL) by considering the length requirements and potential cut-off elements from the stock list. Initially, the script searches for exact matches. If no exact match is found, it proceeds to search for SL lengths within a range that is 10% longer than DL lengths. If still no match is found, it expands the search range to 20% and then 30% longer lengths. According to Batty (2023), who was interviewed, it is more efficient to use new steel if no suitable match is found after the 30% loop, as wasting more than 30% of reclaimed steel becomes less viable. This recommendation is based on studies conducted by HTS and Elliot Wood on the utilization of reclaimed steel in new projects. Batty suggests integrating the loops in increments of 10, 20, and 30 as any values lower than this would be overly restrictive and yield limited results.

Within the Python script, when an exact match is found, the corresponding index is stored in the results list, allowing for easy retrieval of data from the original input lists. Additionally, the type of match (exact, 10%, 20%, or 30%) is recorded to calculate the match efficiency. Moreover, the script captures the linear waste resulting from cut-off elements. This waste data is divided into two separate lists: one for lengths less than 500mm, which will be classified as scrap steel for recycling, and another for lengths greater than or equal to 500mm. The latter list could be reintegrated into the stock lists with new indexes, making the elements available for future matching.

This operation was able to find 65 matched results from the DL utilizing 65 stock elements.

4.7.2 PART 2 – IMPLEMENTING DIVISION OF ELEMENTS

To increase the reuse potential of the matching algorithm, an additional Python script was implemented to include the possibility of dividing larger stock elements into various design elements. For example, taking a SL item with length of 2.0m to be cut into two DL items of 1.0m in length. Initially, the script was set up to find exact duplicates in groups of 2's, 3's, or 4's. These duplicates were then added and then that total addition was searched for in the SL from an exact length and up to 30% increased length range. However, this scenario still presented limitations of possible matches as it will only analyze the duplicate or repeating values.

For this reason, the script was modified to search for combinations and not exact duplicates in the DL. For example, taking a SL item with length of 2.0m to be cut into two DL items with lengths 1.2m and 0.8m. This way a larger range of values are considered for the matching process. This process entailed adding a definition to find the closest combinations. This definition compares multiple values (in this case from the DL) and will match the combination to a target value (in this case from the SL). To generate various possible combinations the range was set from 1 to 10 which defines the length of combinations and allows up to 9 numerical values to be added to equal a target value . This range was cut off at 9 combinations to effectively manage the trade-off between the possible number of cuts of a SL element and the computational effort required to run the operations efficiently.

The script first checks for an exact match. If the sum of any combination equals a target value, it will notify that an exact match was found and will break out of the loop. If no exact match is found, it will run through the 9 combinations, add them, and then select the closest sum to the target value. This is done to ensure the optimum combination is selected and cut off waste is minimized. The target value includes a 30% length increase range to allow for cut-offs when the lengths of the DL are not an exact match with those of the SL. Once the combination with the closest sum is found, the operation breaks out of the loop and saves the matched indices in a new list which results in the final outputs of the script. The output list is maintained sorted into tree data with the 12 branches that define the different cross section types from the DL, as illustrated in figure 53. The format of the data structure ensures accurate matches of elements based on the previously stated matching criteria.

This operation was able to find an additional 62 matched results from the DL utilizing 21 stock elements.

4.7.3 PART 3 – IMPLEMENTING 2/3 & 1/3 SPLICING OF ELEMENTS (FURTHER DEVELOPMENT)

To enhance the reuse potential of the matching algorithm, the splicing rule of 2/3 and 1/3 could be implemented within the Python script. This rule allows for the combination of shorter beams to create longer beams that meet the desired length from the remaining design list elements. The implementation process follows a similar approach to the other scripts.

The first step is to divide the lengths of the remaining design list elements into 2/3 and 1/3 lengths, resulting in two separate lists. The script then runs loops within each different cross-section type to search for exact matches or matches with up to a 30% increase in length from these two lists. By applying this splicing rule, the algorithm expands the possibilities for finding suitable matches by considering combinations of shorter beams. This increases the likelihood of finding compatible reclaimed steel elements that can fulfill the required length criteria specified in the design list. This concept is further discussed in Section 5.3 as a topic for further research as it would provide some technical implications that would require additional structural analysis and coordination.

4.8 RESULTS OF DESIGN CASE STUDY

In this section, the focus is on quantifying emissions specifically related to transportation and repairs within the project's environmental impact. The goal is to measure and assess the amount of emissions generated during these activities to understand their environmental implications.

4.8.1 ENVIRONMENTAL QUANTIFICATION OF EMISSIONS: TRANSPORTATION

The calculation of GHG emissions due to transportation considers the type of vehicles used, their maximum load capacity, their fuel consumption, and the distance traveled. It is important to note the distance route that is calculated for the reclaimed elements is from the stock yard to the project site and for the new elements is from the production mill to the project site.

In the case of transporting reclaimed elements from the stock yard to the project site, the theoretical setup assumes the following stops: The design case study project site is located in Amsterdam (NL). The fabrication company, CSM, chosen for the project is situated in Hamonterweg (BE). The stock yard selected is Swanenberg Ijzer Groep, located in Spijksedijk (NL), and the testing laboratory utilized is Element Materials Technology, located in Breda (NL). As for the transport of new steel elements from the production mill to the project site, an estimated distance of 100 km was calculated from the production mill to CSM in Hamonterweg (BE) to be fabricated before being transported to the project site in Amsterdam (NL).

The truck information was provided by Swanenberg Ijzer Groep and is the following:

- Type of truck: Semi-trailer tractor
- Type of fuel: diesel
- Diesel emission class: 6
- Maximum load capacity: 27 tons

Figure 54 presented below provides a visual representation of the methodology used to calculate transportation emissions. The process involved dividing the total weight of the steel elements by the maximum capacity of the trucks, which in this case was 27 tons, to determine the number of trucks required for transportation. The transportation distance was then multiplied by the CO_2 emission factor of 0.166 $kgCO_2eq$ (NMD, 2023). This result was further multiplied by the number of trucks to obtain the CO_2 emissions per ton per kilometer per truck.

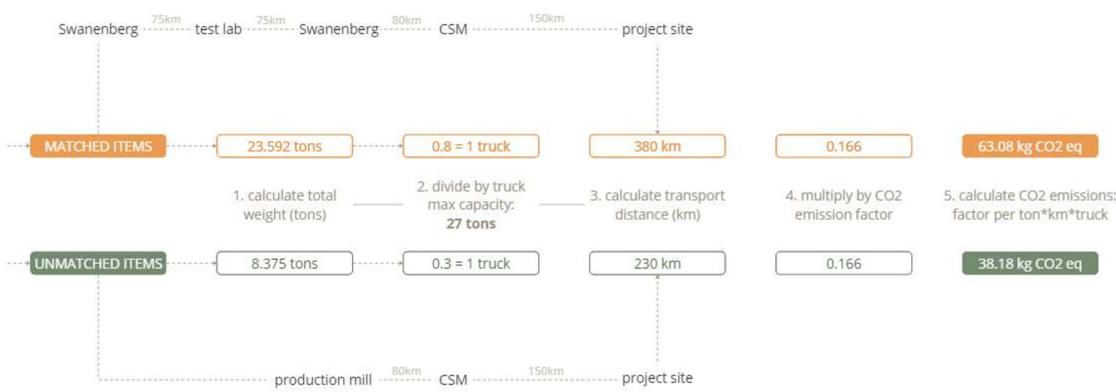


Figure 54: Quantifying emissions for transportation of new and reclaimed elements

It is important to acknowledge that fuel consumption rates and emission factors can vary based on factors such as the truck's model, age, load conditions, and driving conditions. Therefore, utilizing specific data for the truck used in transportation would yield a more precise estimation.

4.8.2 ENVIRONMENTAL QUANTIFICATION OF EMISSIONS: REPAIRS OF RECLAIMED ELEMENTS

Quantifying the CO_2 emissions of repairing reclaimed beams is important to understand the environmental impact of the repair process and ensure it aligns with the sustainability benefits of using reclaimed materials. It allows for carbon footprint analysis, informs decision making, and supports accurate sustainability reporting. By quantifying emissions, project teams can minimize environmental impact and make informed material choices.

Figure 55: workflow process to calculate repair emissions

The workflow shown in Figure 56 illustrates the calculations involved in determining the energy consumption associated with specific repair processes, namely straightening, cutting, and shot blasting. These steps are explained in more detail below. Once the energy consumption in kilowatt-hours (kWh) is calculated for each repair process across the 125 matched reclaimed stock elements, the total energy consumption in kWh is then multiplied by the emission factor for electricity generation in the Netherlands. This multiplication allows for the calculation of the total amount of carbon dioxide equivalent (CO2eq) emissions in kilograms.

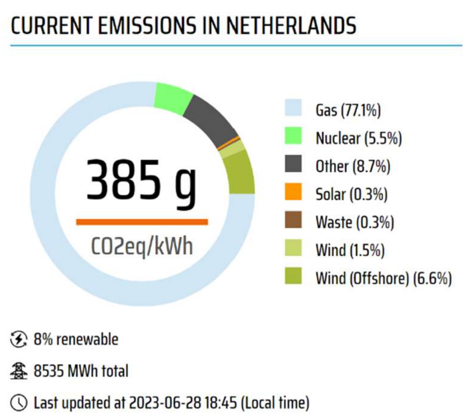


Figure 56: Current emission factor for electricity generation in the Netherlands (ENTSO-E Vision A Power System for a Carbon Neutral Europe, 2022)

Figure 55 provides the emission factor for electricity generation in the Netherlands, obtained from the energy production database of the European Association for the Cooperation of Transmission System Operators for Electricity (ENTSO-E) (*ENTSO-E Vision A Power System for a Carbon Neutral Europe*, 2022). This emission factor is used to calculate the energy consumption and subsequent CO2 emissions associated with the repairs, as measured in kilowatt-hours (kWh) of energy. It's important to mention that the emission factor is subject to change depending on the mix of power sources used at any given time. For instance, the energy generated by wind turbines would vary on a windy day. Nevertheless, this specific emission factor serves as an illustrative example for calculating the emitted CO2.

STRAIGHTENING

Straightening a bent steel beam typically requires approximately 0.3 kilowatt-hours (kWh) of energy when performed at a speed of 6.7 meters per minute (Senlisweld, 2023). The computational process depicted in Figure 57 showcases the workflow based on an assumption that 30% of the steel beams will require straightening repairs. Taking into account the specifications of the machinery, the total energy consumption in kilowatt-hours (kWh) for straightening 30% of the steel beams amounts to 404.3 kWh.

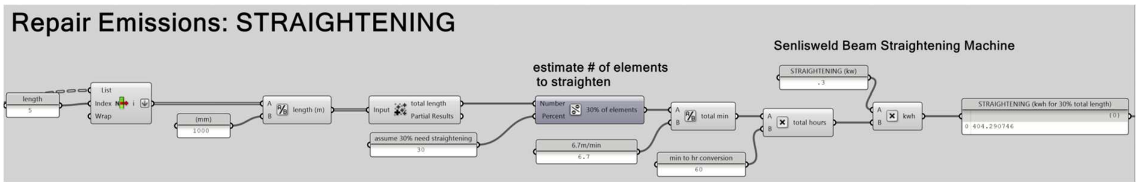


Figure 57: calculation of co2 emissions for straightening repairs (assuming 30% of sections need to be straightened)

CUTTING

Cutting off the ends of steel sections or cutting the sections to the desired length typically requires approximately 2.3 kilowatt-hours (kWh) of energy per linear meter of cutting length using a CNC drill saw machine (Voortman Steel Machinery, 2023). Figure 58 illustrates the calculation process for determining the number of cuts based on the matching iterations. In the first part of the matching algorithm, it was determined that 59 elements needed to be cut to the exact length as they fell within the 10-30% range of increased length. For the second part of the matching algorithm, the number of cuts was calculated among the combined number of elements. This value was then multiplied by the average cross-section height to estimate the linear length of cuts. Taking into account the specifications of the machinery, the total energy consumption in kilowatt-hours (kWh) for cutting the steel sections to the desired lengths amounts to 6.6 kWh.

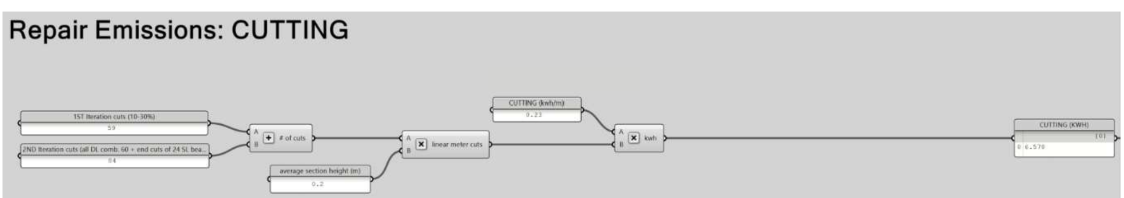


Figure 58: calculation of co2 emissions for cutting steel sections

SHOT BLASTING

Shot blasting steel sections to remove paint or coatings typically involves an energy consumption of approximately 2.3 kilowatt-hours (kWh) per square meter of surface area treated. To calculate the energy consumption for shot blasting, the average cross-section of the steel sections was used to determine the perimeter. This perimeter value was then multiplied by the length of each reclaimed element, assuming that all elements would require coatings and paint removal. Figure 59 provides a detailed description of the calculation process, resulting in a total energy consumption of 138.4 kWh for this repair.

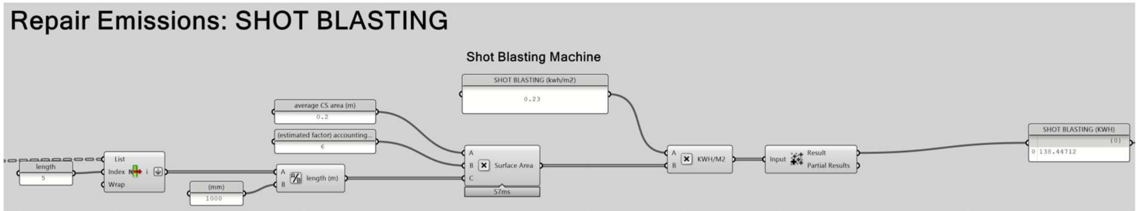


Figure 59: calculation of co2 emissions for shot blasting repairs

ENVIRONMENTAL QUANTIFICATION OF EMISSIONS

Based on the calculations mentioned earlier and considering the emission factors, Figure 60 presented below demonstrates the final estimation of the carbon dioxide equivalent (CO2eq) in kilograms for the repairs and transportation associated with the 125 reclaimed steel elements.

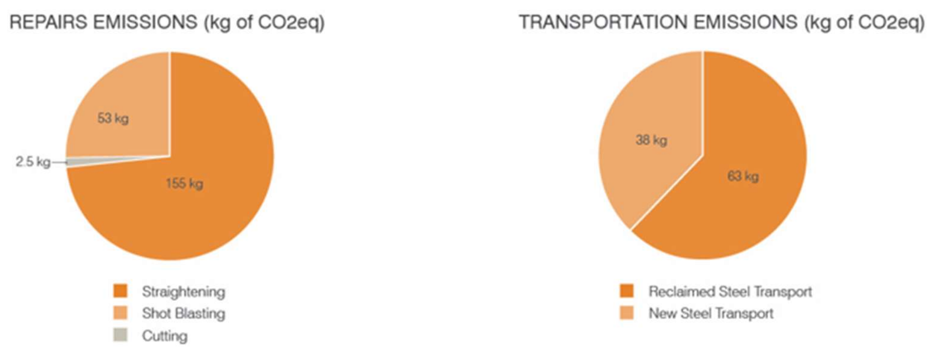


Figure 60: Final calculations of kg of CO2eq emissions

4.8.3 COMPARISON BETWEEN RECLAIMED STEEL AND NEW STEEL

This section presents a comparison between utilizing solely new steel and combining reclaimed steel with new steel in the case study project. The matching algorithm identified and matched 125 elements from the reclaimed stock, which means these elements would only incur emissions from the repair process. The remaining 39 steel sections were new and accounted for emissions from the production of virgin steel, based on the emission factor provided by the World Steel Association. According to the association's 2022 statistics, the production of each ton of steel emits 1.91 tons of CO2. The pie charts in Figure 61 visually depict the comparison, showing that utilizing 164 new steel sections would result in 49.5 tons of CO2 emissions from production alone. In contrast, the combined production emissions from the 39 new steel elements and the repair process of the 125 reclaimed steel elements amount to 16.2 tons of CO2. Therefore, the comparison reveals a significant 68% reduction in CO2 emissions by incorporating 125 reclaimed steel elements in the project.

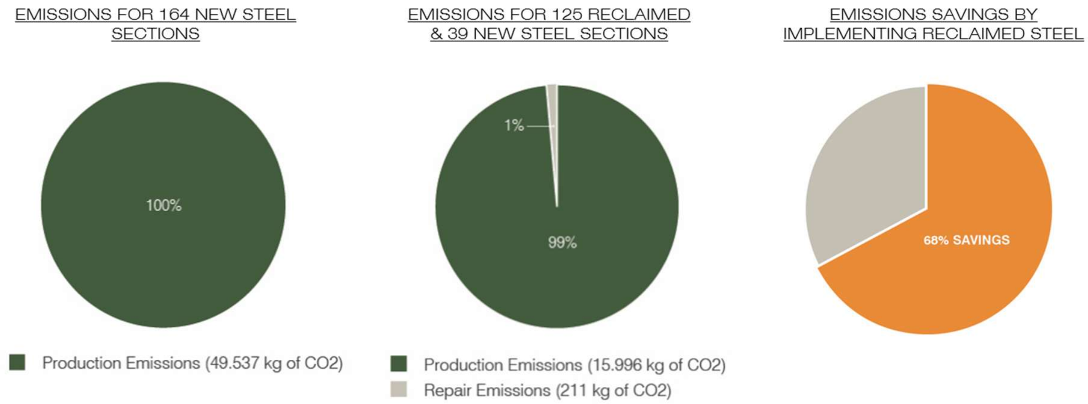


Figure 61: CO2 emission comparison between utilizing only new steel sections vs. matched results of 125 reclaimed steel sections and 39 new steel sections

4.8.4 LOGISTICAL SAVINGS OF TIME AND LABOR

The computational tool, in conjunction with the matching algorithm, revolutionizes the steel reuse process by offering significant time and labor savings. Traditionally, manually searching and matching reclaimed steel elements for a project could take weeks or even months, involving extensive coordination and labor-intensive efforts. In an interview with Julien Wilem (2023), the project manager of the Mundo Lab LLN project, he experienced delays in the matching process and testing certification. Initially, he anticipated it would take a maximum of two weeks, but it ended up taking a total of two months. Focusing solely on the matching process, Julien spent three weeks conducting the manual search, which translates to a substantial cost in terms of labor. Considering the average hourly rate for a project manager ranging from $50 to $70 per hour, the manual labor cost amounted to approximately $6,000 to $8,400.

However, with the matching algorithm, this task can be completed within a remarkably shorter timeframe. Assuming the design list and stock list are input into the matching algorithm, the total matching process should take less than an hour. This represents a remarkable 96 to 99% savings in both time and labor cost.

By automating the inventory retrieval, comparison, and identification of suitable reclaimed steel sections based on project requirements, the tool eliminates the need for time-consuming manual searches. This streamlined matching process significantly reduces the labor and effort required, enabling project teams to expedite the selection and procurement of reclaimed steel, ultimately accelerating project timelines, and increasing overall efficiency.

4.9 POTENTIAL OF COMPUTATIONAL TOOL DURING CONCEPTUAL DESIGN

During the conceptual design phase, the utilization of the computational tool and matching algorithm offers valuable insights for making informed design decisions and maximizing the potential for steel reuse. By incorporating a parametric model within the tool, the design and engineering team benefit from increased flexibility and ease of implementing design changes. The integration of the matching algorithm within the parametric model enables designers to efficiently explore various design iterations while considering the feasibility of incorporating reclaimed steel elements. Real-time feedback and recommendations provided by the computational tool based on the matching algorithm help designers assess the viability and impact of using reclaimed steel. Additionally, as depicted in figure 62, the tool also provides environmental data, such as the carbon footprint associated with repairs and the production emissions of new steel elements. This information empowers designers to evaluate the sustainability implications of different design choices and prioritize the use of reclaimed steel, taking into account both environmental benefits and project requirements. By engaging in this iterative process, designers can make well-informed decisions by considering factors such as structural performance and environmental impact, ultimately driving sustainable design outcomes.

In the figure provided below, a comparison is made between two design options. The parametric sliders highlighted in orange represent the "changing values" that can be adjusted. These values are modified to evaluate which option yields a higher matching percentage with reclaimed elements, using the stock data from the matching algorithm. Design option 2, characterized by a grid size of 3.2x3.6m and a height of 3.2m, achieved a matching percentage of 69% with reclaimed steel elements. On the other hand, design option 1 resulted in 59% matches. Based on this analysis, design option 2 was selected as the optimal choice between these two iterations, considering its higher compatibility with reclaimed steel elements.

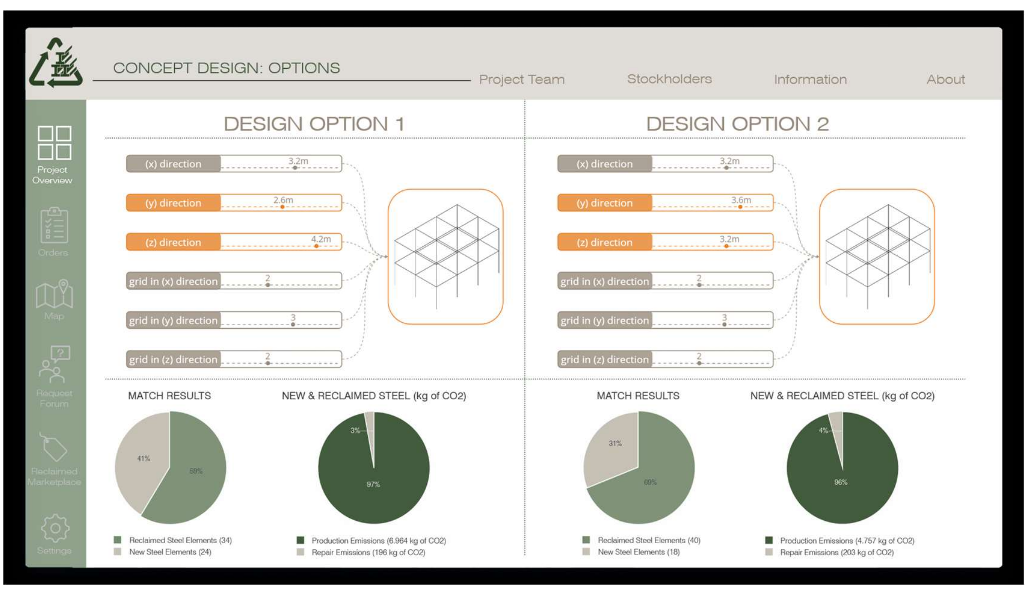


Figure 62: Web Interface - Comparing various design options in concept design phase

To provide a detailed understanding of the process, the workflow diagram in Figure 63 is presented. The entire workflow takes place within Grasshopper, ensuring a seamless experience and eliminating the need for data import and export between different software. The first step involves creating the parametric model using sliders within Grasshopper, although integration with other BIM plug-ins like Tekla Structures is also feasible. The choice of parametric modeling software depends on the project team's preferences. Since CSM, the design case study provider, uses Tekla Structures, this diagram demonstrates how the model can be viewed within the Grasshopper plug-in for enhanced integration.

Following, the parametric model is connected to Karamba 3D for structural verification, where the structural loads and other structural criteria are input. The Cross Section Range Selector is then utilized, loading different families of profiles such as HEA, HEB, and IPE. Then, the Cross Section Optimizer determines the optimal profiles required for the project based on the input span and structural load. These results provide the necessary cross-section types and lengths for the design.

The resulting output from the Cross Section Optimizer is the design list, which serves as the input for the matching algorithm. This algorithm compares the design list with the available stock elements and generates matching results, identifying which elements from the stock list are suitable for the project. In addition to the matching results, the algorithm also provides environmental impact data, as described in Section 4.8. This data equips the design team with valuable information regarding the environmental implications of their design choices. By considering these environmental factors, such as minimizing the carbon footprint and promoting material circularity, the design team can make informed decisions to ensure sustainable practices and optimize the overall design outcome.

Finally, an optimization tool like Galapagos can be introduced to further refine the design. This tool can be used to maximize the number of matched results or minimize the carbon footprint, optimizing the overall design outcome.

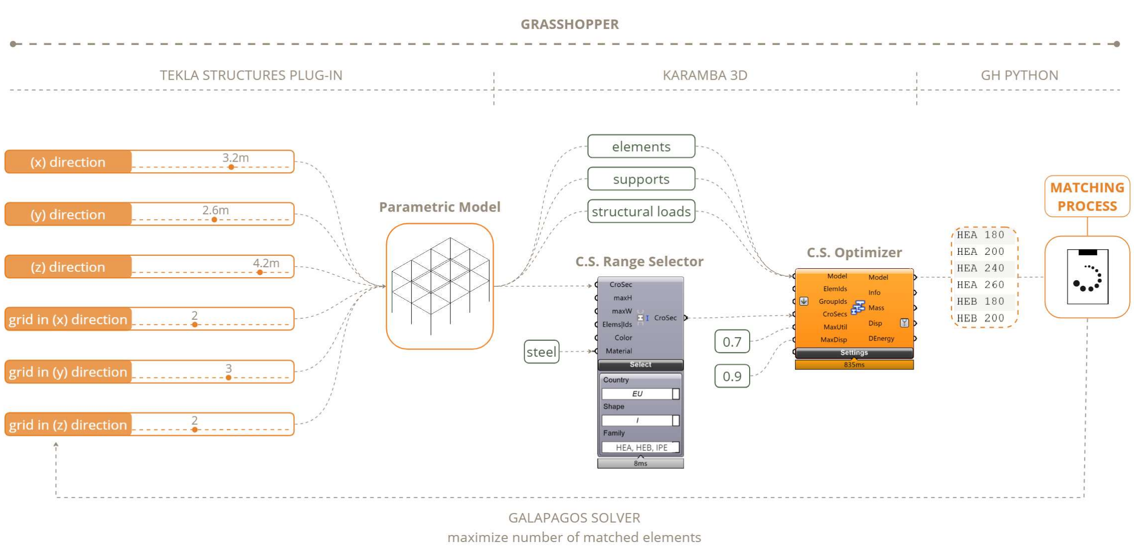


Figure 63: Parametric model workflow with integrated optimization tools

5 CONCLUSION

5.1 CONCLUSION

In conclusion, this thesis project has explored the topic of steel reuse in the construction industry and proposed a comprehensive approach to enhance its implementation.

5.1.1 CONDUCTED INTERVIEWS

The interviews conducted with industry professionals proved to be invaluable in providing insights and firsthand perspectives on the topic of reusing steel in the building industry. Through these interviews, a comprehensive understanding of the process and flow of information across the value chain was gained, providing awareness on the practical challenges and opportunities associated with steel reuse. Follow-up interviews were particularly valuable in shaping the proposed design workflow and guiding the development of effective strategies and solutions. By including professionals from various roles within the construction industry, such as computational designers, structural engineers, project architects, steel contractors, stock companies, sustainability consultants, material passport advisors, and academic researchers from different regions in Europe, ensured a comprehensive and multi-faceted perspective contributing to the relevance and applicability of the research findings. The accuracy and reliability of the information gathered through the interviews was ensured by allowing the interviewees to review their post-interview reports, demonstrating the rigorous approach taken to maintain the integrity of the collected data.

5.1.2 MAIN FINDINGS

This research explored circularity in the built environment by focusing on the reusability of structural steel profiles in new architectural projects. Different state of the art applications where reviewed to gather the following findings:

- The concept of urban mining shows potential to help determine in the future the availability of materials in existing buildings and estimate when this could become available.
- Material passports provide environmental data and percentage of demountability for overall building design, but do not allow individual material traceability nor provide structural data. However, there are opportunities to implement material passport data along with BIM information and material test certificates to ensure the completeness of information and traceability of building components.
- Designing for disassembly will ensure that steel elements can be disassembled without causing damage and preserve their integrity for future reuse, expanding their lifespan. While modularity enhances the flexibility to adapt reclaimed elements in future applications. However, implementing these practices should include the development of disassembly plans to provide a detailed roadmap for the efficient and safe dismantling of the structure.
- The development of the first Environmental Product Declaration (EPD) for reclaimed steel along with life cycle assessment tools provide users with the necessary environmental data to make informed design decisions when selecting materials for projects.

Furthermore, the research examined three distinct business models of reuse, with a primary focus on the reclamation market. The analysis of project case studies shed light on the encountered challenges and valuable lessons learned throughout the process. Additionally, the study explored computational tools developed to streamline the integration of reclaimed steel, showcasing their potential to reduce time and labor through programming assistance. Based on the analysis, it was found that specifying a length range of greater than or equal to is crucial for the matching algorithm to identify the closest option, even if it is not an exact match, and subsequently implement the cutting of steel elements to the desired length. This approach enhances matching results and minimizes waste by identifying the optimal option closest to the required length. Another notable finding was the importance of providing a single interface to ensure user-friendliness, as navigating between multiple software tools for data import and export can be challenging. These findings played a pivotal role in shaping the objective of the proposed computational tool, which aims to facilitate information exchange, enhance coordination, and foster collaboration among various project stakeholders to enable informed design decisions when utilizing reclaimed steel.

In addition to exploring these applications, the research delved into the existing regulations that govern the utilization of reclaimed steel in construction projects. This investigation uncovered a dearth of standardized guidelines and requirements pertaining to the assessment of suitability, structural integrity, and quality assurance of second-hand steel sections. However, promising advancements were identified, such as the Publication P427 Structural Steel Reuse by SCI and the Model Specification for the Purchase of Reclaimed Steel by BCSA in the UK, both of which offer guidelines for the evaluation and re-certification of reclaimed steel.

By synthesizing the data collected from interviews, literature reviews, and project case studies, a comprehensive compilation of challenges associated with steel reuse was created. These challenges were then categorized according to the different phases of a project: deconstruction, salvaging, planning and design, repair and fabrication, and construction. It was crucial to recognize that these challenges may be perceived differently depending on the various stakeholder roles and project phases involved. Furthermore, the research aimed to develop a clear understanding of the current workflow process for implementing reclaimed steel in projects. However, it was evident that this process was far from linear, given the absence of well-established procedures, standards, and mechanisms for tracing information related to reclaimed building components.

Collectively, these findings laid the groundwork for proposing a design workflow and a computational tool that aim to address the gaps identified in the research.

5.1.3 PROPOSED DESIGN WORKFLOW AND STRATEGIES

The proposed design workflow and strategies outlined in this research offer a systematic approach to promoting the reuse of steel elements in construction projects. The process begins with engaging a specialized deconstruction contractor to ensure a careful and efficient dismantling of existing structures. The involvement of a stockholder as a consultant, providing stock data and BIM drawings, enhances coordination during the salvaging stage. A key component of the workflow is the utilization of a digital inventory and a matching algorithm, integrated within a web interface, which facilitates the identification and selection of suitable stock elements for the design. By involving the entire project team during the integrated design stage, input from various stakeholders is received, fostering collaboration and informed decision-making. Another strategy implemented is a reservation system where users can reserve or purchase the matched stock items to provide assurance of availability for both stockholders and the project team. Once the stock elements are purchased, the stock company is responsible for managing the testing process to ensure the elements meet regulatory criteria. Additionally, it is recommended for stockholders to address necessary repairs (such as straightening beams, cutting off ends and plates, and shot blasting to remove coatings) to ensure the steel elements are in satisfactory condition according to standards. The fabrication process follows shop drawings and concludes with the certification of the steel structure with a CE mark, affirming its fitness for purpose. Lastly, to maintain quality assurance and address any discrepancies, it is recommended to engage a specialized contractor during the construction phase. This ensures that the reused steel elements are successfully integrated into the project while meeting the necessary standards.

Overall, this proposed design workflow and the incorporation of strategies involving specialized contractors, digital inventories, matching algorithms, and collaborative decision-making processes contribute to a more streamlined and effective approach to reusing steel elements in construction.

Feedback from follow-up interviews reinforces the efficacy and practicality of the proposed design workflow and strategies. Fishwick (2023) highlights the value of stockholders as project consultants, providing detailed stock data, and believes that potential design changes can be managed without significant increases in liability. Herman (2023) expresses the immense value of the proposed design workflow as a guideline throughout various project phases. Batty (2023), Van Der Loop (2023), and Fishwick (2023) acknowledge the benefits of a reservation system to manage the allocation of stock elements, ensuring clarity and flexibility. Additionally, the responsibility of repairs can be balanced between stock and fabrication companies, with coordination facilitated through the involvement of stockholders and fabricators as consultants within the project team. The positive feedback from follow-up interviews further supports the efficacy and practicality of the proposed design workflow and strategies for promoting the reuse of steel elements in construction projects.

5.1.4 PROPOSED COMPUTATIONAL TOOL

The developed computational tool compiled of a digital stock inventory and matching algorithm within a web interface, provides a user-friendly platform for managing reclaimed steel in building projects. By addressing the challenge of limited stock data availability, the digital inventory provides a centralized repository of stock information, accessible to the different stakeholders involved in a project. The matching algorithm compares a list of design elements with the available stock lists, which results in potential substitutions to optimize the utilization of reclaimed steel. Ultimately, this computational tool supports and enhances the proposed design workflow, enabling seamless implementation of reclaimed steel elements in new building designs.

SET UP OF DESIGN CASE STUDY AND INPUT DATA

CSM, the company providing the design case study, is currently working on a rooftop construction project on an existing office building located in Amsterdam. The project's BIM data was imported into Tekla Structures as an IFC file, and the material list, consisting of the required structural steel elements and connecting plates, was generated based on this imported model. Typically, this material list would be sent as a purchase order to order new steel sections from production mills. However, in this case study, the material list is utilized as the design list for the matching algorithm. In addition, the case study setup involves two stock companies, CST and SIG, who provided their most recent stock lists for utilization in the matching algorithm. To enable the Grasshopper script to read multiple Excel data sheets, a stock list template was developed to establish a standardized level of information required from each stock company for the project, and the design list was adjusted to align with this template.

WEB INTERFACE

The web interface of the developed computational tool encompasses several essential features that enhance the management and utilization by users. The *Map* feature provides a visual representation of stock yards and their locations, facilitating easy identification of nearby options and streamlining the search process. The *Project Dashboard* empowers project teams to efficiently set up and manage projects by centralizing project information and integrating it with stock yard data. The *Request Forum* fosters seamless communication between project teams and stock companies, consolidating product requests and promoting collaboration. The *Notification System* keeps users informed of updates and responses related to their requests, ensuring real-time engagement. The Marketplace feature connects stock companies with potential sellers, expanding the range of available steel materials and promoting sustainability. Lastly, the *Stock List Inventory* tab enables material suppliers to upload and manage their stock information in a structured and user-friendly manner. Together, these features create a comprehensive and user-centric web platform that optimizes the material selection and matching process, and fosters collaboration among stakeholders.

MATCHING ALGORITHM

The matching algorithm developed for the computational tool utilizes the GHPython component within the Grasshopper, enabling efficient data manipulation, algorithm development, and convenient operation within the interface. The algorithm employs a combination of sorting techniques, conditional statements, and nested loops to match design lengths with available stock lengths based on predefined conditions. It optimizes the utilization of materials while considering the specific requirements of the design, contributing to improved efficiency and reduced waste in the workflow. The algorithm is structured in a tree data format, with separate branches representing different cross-section types. It iterates through the design and stock lengths, searching for matches and distinguishes between exact matches and matches within specific percentage ranges, accommodating different tolerances for length discrepancies.

To further enhance the reuse potential, an additional Python script was implemented to enable the division of larger stock elements into multiple design elements. It searches for combinations of lengths in the design list that closely match the target value derived from the stock list. By considering various combinations, the algorithm expands the range of possible matches and minimizes material waste. The algorithm also captures data on linear waste resulting from cut-off elements. Waste lengths less than 500mm are classified as scrap steel for recycling, while lengths greater than or equal to 500mm can be reintegrated into the stock lists for future matching.

The implementation of the splicing rule of 2/3 and 1/3 within the Python script represents a valuable enhancement to the matching algorithm, that would result in increased matching results. This approach would enable the creation of longer beams by combining shorter ones, effectively fulfilling the desired length criteria outlined in the design list. The inclusion of the splicing option would occur after the initial matching process, encompassing part 1 and part 2, to provide the project team with an additional option to implement beam splicing and possibly find additional matched results. This sequential approach would require additional coordination of connection design and structural verification involved in beam splicing. By carefully analyzing the technical implications, the splicing process can optimize the matched results while ensuring structural integrity of the steel structure.

Overall, the matching algorithm enhances the computational tool's ability to efficiently match design requirements with available stock materials, optimizing resource utilization, and streamlines the material selection process.

5.1.5 RESULTS

The initial matching algorithm successfully identifies 65 matched results from the design list utilizing 65 stock elements. Additionally, the inclusion of the combination-matching algorithm allows for an additional 62 matched results from the design list utilizing 21 stock elements. It can be assumed that if the third script to implement splicing of 2/3 and 1/3 length matches, would be added, the matching results would increase.

In addition, the Grasshopper script concludes by calculating the carbon emissions associated with transportation and repairs of the reclaimed steel elements. The transportation emissions are determined based on the case study's transportation distance and the number of trucks required, considering their maximum load capacity. The repair emissions are estimated based on the energy consumption associated with repairing the reclaimed stock elements to satisfactory conditions and then cut to the necessary lengths. Furthermore, these emissions are compared to those generated by the production of new steel, allowing users to assess the emission savings achieved through steel reuse in projects. This data enables users to accurately quantify the environmental benefits of using circular steel elements instead of virgin steel.

Another significant finding is the logistical savings in terms of time and labor resulting from the developed workflow and computational tool presented in this thesis. Quantifying these savings is challenging, as the initial hours spent contacting and searching for stock companies, as well as manually matching stock elements to project requirements, can vary across projects. However, it is important to note that utilizing the web platform, which consolidates various stock lists within a specific radius, uploading the design list to initiate the matching algorithm, and waiting for the results can be completed in a matter of minutes, streamlining the process, and reducing the required time and labor efforts. The utilization of this application has the potential to be an invaluable resource for engineers when it comes to persuading clients and decision makers about the advantages of reuse. It can effectively demonstrate the benefits of incorporating circular components into a structural steel design, thus encouraging their adoption.

5.2 DISCUSSION

5.2.1 RESEARCH QUESTION

"How to facilitate the design process when integrating reclaimed steel structural profiles for new construction with the use of computational tools?"

The research question was effectively addressed through a multi-faceted approach. The project recognized the challenges and limitations associated with integrating reclaimed steel and identified the need for a more streamlined and efficient design process. The use of computational tools emerged as a potential solution to facilitate this process. Through the development and implementation of the proposed design workflow and computational tool, the project aimed to facilitate the design process by streamlining the integration of reclaimed steel. By leveraging computational tools and digital data, the project sought to improve efficiency, reduce errors, and promote more sustainable construction practices.

5.2.2 SUB QUESTIONS

What are the current limitations of reusing steel structural components, more specifically H and I steel sections?

To summarize some of the main limitations of reusing steel sections from buildings are structural fatigue or plasticity, signs of corrosion damage, finishing coatings with hazardous materials, and the existing structural connections.

What is the current process of analyzing and evaluating the structural integrity of reclaimed steel sections?

The research entailed looking at what building regulations are currently enforcing. With that said, the Steel Construction Institute, which is a global organization, published in 2019 the following assessment process for reusing steel (P427). Where preliminary inspections are done on site – then the material is taken to a stock yard where it should be properly labeled, grouped, and tested – and then taken to factory for repairs and remanufacturing – and then to fabrication to be CE marked according to code.

What are the current challenges in the different project phases, in terms of project coordination, to integrate reclaimed steel sections?

The third sub-question explored the current challenges faced in different project phases, particularly in terms of project coordination, when integrating reclaimed steel sections. Through interviews with industry professionals and the analysis of project case studies, the project identified the coordination challenges and workflow inefficiencies that hinder the successful integration of reclaimed steel. The proposed design workflow addressed these challenges per each project phase by providing a structured approach to streamline project coordination and improve communication among project stakeholders.

How can computational tools and digital data help to better integrate the available reclaimed steel sections in new construction?

The fourth sub-question examined how computational tools and digital data can enhance the integration of available reclaimed steel sections in new construction. The project developed a computational tool comprising an interface with a digital inventory and matching algorithm, which will enable engineers and designers to assess the suitability of reclaimed steel sections and make informed design decisions. The tool utilized digital data to facilitate the selection and substitution of reclaimed steel sections, thereby improving the integration process and promoting resource efficiency. Another objective was to enhance the communication and collaboration between material seekers and material providers.

5.3 FURTHER RESEARCH

Updated regulations or guidelines: A potential further research topic could involve examining and analyzing the updated P427 regulations, scheduled to be released in June 2023, and exploring the implications and impact of these revised regulations on the reuse of structural steel. Additionally, investigating the forthcoming publication in June 2023, titled "Circular Economy and Reuse: Guidance for Designers," could provide valuable insights into incorporating circular economy principles and design strategies for promoting the reuse of building materials, including steel, in construction projects.

AI tools: Further research should focus on leveraging AI technology to automate the calculation of steel quantity in existing buildings, generate accurate drawings and BIM data, improve data tracking and database management, and enable AI-driven structural analysis for reclaimed steel elements. These advancements have the potential to enhance efficiency, accuracy, and decision-making in steel reuse and urban mining practices.

Financial complexity of steel: While financial complexities and fluctuating steel prices pose challenges, potential solutions such as linking prices to steel price indexes are considered.

Integrate reclaimed element data with material passport information: Further research could focus on exploring the potential benefits and challenges of integrating material passports with BIM data and test certificates to create a comprehensive database of information. This approach could enhance the identification and traceability of individual material elements throughout their lifecycle, providing a more holistic understanding of their origin, characteristics, and performance. Investigating the technical feasibility, data management strategies, and practical implementation of this integrated approach would contribute to promoting sustainable and transparent material reuse practices. Additional, platforms like, *Passports for Construction* (platformcb23.nl), could be further analyzed.

Design changes: Ideally, design changes should be made during the conceptual design phase, as modifications become more challenging as the design phase progresses. Therefore, it is crucial for the matching algorithm to align with the design list rather than with the stock list. According to Batty (2023), designing based on the availability of materials has proven to introduce complications to the design process, based on the experience of HTS. Implementing the option to splice design beams offers a more feasible approach to increase matching results without disrupting the structural grid and predefined design. By adhering to the design list and considering the splicing option, the matching algorithm can optimize the reuse potential of reclaimed materials while maintaining design integrity and minimizing design complexities.

Steel Cost Complexities: In response to the challenges posed by fluctuating steel prices, one potential solution is to link prices to steel price indexes. This would enable the inclusion of pricing information in the reservation system, allowing the project team to estimate the cost of steel elements during the contract drafting and budgeting phase. However, incorporating pricing in advance presents a liability for stock companies due to the unpredictable nature of steel prices. Balancing the need for cost predictability with the stock companies' exposure to price fluctuations requires careful negotiation and clear communication. By implementing strategies that link steel prices to indexes and establishing agreements, it is possible to mitigate financial uncertainties and improve financial planning for construction projects.

Steel Grade Information: Additional research should be conducted to explore methods for ensuring accurate steel grade information within the digital inventory of stock elements, aiming to improve the accuracy of matching algorithms. Batty (2023) highlights the varying significance of steel grade in structural designs, where deflection-driven designs may not require precise steel grade knowledge, while strength-driven designs heavily rely on it. However, the challenge lies in the fact that the steel grade is often unknown until the purchased elements are tested, leading to potential complications if the actual steel grade differs from the initial estimation. This necessitates further investigation into mechanisms that enable the early determination and implementation of steel grade information in the stock digital inventory. Implementing quality control measures and exploring non-destructive testing techniques can help ensure the accuracy of steel grade data before elements enter the inventory.

5.3.1 IMPROVEMENTS ON THE COMPUTATIONAL TOOL

Splicing Matching Algorithm: Due to time constraints, the implementation of the splicing algorithm for 2/3 and 1/3 beams was not included in the script. However, incorporating this algorithm would have yielded promising results and increased the number of successful matches. The decision to incorporate this option lies with the project team, considering that it would require additional coordination for connection design and structural verification of the spliced elements.

Integrate Live Map Data: By integrating QGIS with the Grasshopper tool, it becomes possible to leverage its functionalities to calculate transportation distances accurately. This addition to the computational tool could provide valuable insights for optimizing material transportation and logistics in construction projects.

Implement Parametric Model & Structural Verification Program to Computational Tool: To enhance the capabilities of the computational tool, connecting different software applications can be explored. One improvement could be the integration of the matching script with Karamba 3D, enabling structural analysis with the substituted stock elements incorporated into the design. This would provide valuable insights into the performance and integrity of the structure, considering the specific properties of the reclaimed steel elements. Furthermore, integrating Tekla Structures software within the Grasshopper plug-in would be beneficial in order to make design modifications within Grasshopper. In addition, Tekla Structures offers advanced features for steel detailing and fabrication and integrating it into the computational tool would enable seamless generation of fabrication drawings and accurate material take-offs based on the matched and substituted stock elements. This integration would streamline the design and fabrication process, improving efficiency and ensuring accurate representation of the final structure.

Potentially include new steel providers within the web platform: Integrating new steel providers within the web platform can significantly enhance the user experience and provide more comprehensive options for material seekers. By including both new steel and reclaimed steel within a single platform, users can conveniently compare and evaluate the availability, pricing, and specifications of both types of materials in one place. This integration eliminates the need for users to visit multiple platforms or sources to gather information and simplifies the decision-making process. Furthermore, incorporating new steel providers allows for a wider range of material choices, accommodating projects that require specific steel grades or sizes that may not be available as reclaimed steel.

Add multiple stock lists within the matching algorithm: Due to time constraints and unavailability of stock data, the author was unable to incorporate additional stock lists into the matching algorithm. However, including these stock lists would have been an ideal addition to the thesis, as it would have increased the material availability and further enhanced the reuse potential. One possible consideration for future research is to provide users with the option to choose between finding stock list elements based on length accuracy to the design list element lengths or optimizing the results based on proximity. If the latter option is selected, the script would require additional loops within Python to search the stock lists based on distance proximity. This approach would minimize transportation emissions by sourcing materials from nearby locations. On the other hand, prioritizing length matches over distance matches would minimize repair emissions by reducing the need for cutting and modifying elements. This feature would provide users with greater flexibility and control over their material selection process, considering both environmental and practical factors.

6 APPENDIX

6.1 APPENDIX A: REFLECTION

GRADUATION PROCESS

How is your graduation topic positioned in the studio?

This thesis project is a part of the "Reuse of Load-Bearing Components: Design from Existing Stocks" graduation topic within the theme of "Sustainable Structures." It engages two chairs within the Building Technology track – Structural Design and Design Informatics. The graduation project was conducted under the guidance of Dr. Stijn Brancart and Dr. Serdar Asut of the respective departments. The thesis encompassed the topics of structural design, computational design, and circular design.

How did the research approach work out (and why or why not)? And did it lead to the results you aimed for? (SWOT of the method)

The research approach adopted for this graduation project proved to be effective in achieving the intended goals, although it also had certain strengths, weaknesses, opportunities, and threats (SWOT).

Strengths:

- Comprehensive Literature Review: The project began with a thorough literature review, which provided a strong foundation of knowledge on the topic and informed subsequent research and design decisions.
- Industry Interviews: Conducting interviews with industry professionals allowed for valuable insights into the current practices, challenges, and opportunities related to steel reuse. These firsthand perspectives enriched the research and provided practical input for developing the proposed design workflow and computational tool.
- Holistic Design Approach: The project took a holistic approach by considering the entire lifecycle of steel, including production, reuse, and disposal. This approach enabled a comprehensive understanding of the environmental and economic implications of steel reuse.

Weaknesses:

- Limited Sample Size: The number of industry professionals interviewed may have been limited, which could have restricted the breadth of perspectives and potential challenges identified.
- Time and Resource Constraints: The project's timeline and resource limitations may have impacted the depth of research and the extent of data collection and analysis.

Opportunities:

- Innovation and Advancement: The proposed design workflow and computational tool present opportunities for innovation and advancement in the field of steel reuse. The project provides a solid foundation for further development and refinement of these tools to enhance their effectiveness and usability.

- Collaboration and Partnerships: The research findings and recommendations can serve as a basis for collaboration between stakeholders in the construction industry, including designers, contractors, and stockholders, to foster sustainable practices and promote steel reuse.

Threats:

- Resistance to Change: The implementation of steel reuse practices may face resistance within the industry due to established norms, lack of awareness, or perceived challenges. Overcoming these barriers and driving widespread adoption may be a significant challenge.

In conclusion, while the research approach had some limitations and challenges, it overall yielded positive results. The combination of literature review, industry interviews, and the development of a design workflow and computational tool enabled a comprehensive analysis of steel reuse practices. The findings and recommendations provide valuable insights and guidance for promoting sustainable construction practices and enhancing the integration of reclaimed steel in projects.

If applicable: what is the relationship between the methodical line of approach of the graduation studio (related research program of the department) and your chosen method?

The methodical line of approach for this graduation thesis involved conducting a literature review and case study analysis to gain an understanding of the topic's relevance. This was followed by interviews with industry professionals to explore the current application of steel reuse and to gain insights into the existing workflow process and challenges faced in integrating reclaimed steel. Building upon this knowledge, a design workflow was proposed, which included strategies to address the identified challenges and enhance steel reuse implementation. Additionally, a computational tool comprising of an interface with a digital inventory and matching algorithm was developed to tackle the industry's challenges. The design workflow and computational tool were tested through a design case study, demonstrating their proof of concept. The matching algorithm provided valuable data for calculating environmental impacts, such as transportation emissions and energy consumption during repairs of reclaimed steel elements.

While the methodical line of approach in "structural design" and "computational design" may differ, the chosen method for this thesis project complements and aligns with these fields. The emphasis of structural and computational design is on optimizing performance, exploring design iterations, and evaluating structural behavior through simulation and analysis. However, the main challenge identified through interviews was the "unestablished design process" to find suitable matches between design elements and available stocks. To address this, the graduation project focused on developing a matching algorithm that provides environmental results and can be integrated into a structural analysis program for verification. Thus, while there may be differences in emphasis, the chosen method aligns with the proposed method of the graduation topic.

How are research and design related?

The research and design aspects of this graduation project are closely interrelated and mutually supportive. The research phase, including the literature review, case study analysis, and interviews with industry professionals, provided the foundation and knowledge base necessary for informed design decisions. It allowed for a comprehensive understanding of the current practices, challenges, and opportunities in the field of steel reuse. Based on the insights gained from the research, the proposed design workflow and strategies were formulated to address the identified challenges and improve the process of implementing steel reuse. In addition, the development of a computational tool, including a digital inventory and matching algorithm, efficiently tackled the specific challenges faced in the industry. The design phase implemented and tested the proposed solutions, further validating and expanding upon the research findings. In summary, the research informed design decisions enabled a comprehensive and practical approach to address the challenges of steel reuse in the construction industry.

Did you encounter moral/ethical issues or dilemmas during the process? How did you deal with these?

During the process of this graduation project, several moral and ethical issues and dilemmas were encountered. One prominent issue was the consideration of environmental sustainability in the construction industry. As the project focused on promoting steel reuse, it was essential to address the potential conflict between economic interests and environmental responsibility. To deal with this ethical issue, a strong emphasis was placed on conducting a thorough literature review and research on the environmental impacts of steel production and construction practices. This allowed for an informed understanding of the benefits and drawbacks of steel reuse, enabling the development of strategies and recommendations that aligned with sustainable principles. Additionally, the interviews with industry professionals provided valuable insights into the practical challenges and ethical considerations associated with steel reuse. Their perspectives and experiences helped shape the proposed design workflow and computational tool to address these concerns effectively.

Furthermore, throughout the project, there was a commitment to transparency, integrity, and open communication. This involved acknowledging and discussing the limitations and potential biases of the research and design decisions. By being aware of these ethical considerations and openly addressing them, the project aimed to ensure the reliability and credibility of the findings. Ultimately, the project sought to strike a balance between economic feasibility, environmental sustainability, and social responsibility. Ethical considerations were woven into the fabric of the research and design process, enabling a holistic approach that accounted for the moral implications of promoting steel reuse.

SOCIETAL IMPACT

To what extent are the results applicable in practice?

The results of the thesis project have significant applicability in practice, aiming to facilitate the implementation of steel reuse in construction projects. While steel reuse is not a new concept and is already being implemented to some extent, the objective of this research is to address the existing challenges that hinder the successful integration of reclaimed steel. These challenges often result in increased project costs, time delays, and coordination difficulties. By developing a comprehensive design workflow and a computational tool, the research provides practical strategies to overcome these challenges and enhance the adoption of steel reuse in practice. The proposed methods and tools offer valuable insights and solutions that can be applied by industry professionals to optimize project outcomes, increase efficiency, and promote sustainable construction practices. Through stakeholder engagement and continuous refinement, the research outcomes have the potential to drive positive change and transform the way steel reuse is implemented in the construction industry.

To what extent has the projected innovation been achieved?

The projected innovation has been achieved to a considerable extent. The lack of a well-established design workflow for projects implementing reused steel has been addressed through the development of a comprehensive design workflow in this project. Additionally, the absence of a public match tool to facilitate the exchange of information between material providers and material seekers has been tackled through the development of a matching algorithm. The successful feedback obtained from interviewees during follow-up conversations further confirms the achievement of the projected innovation.

While there may still be opportunities for refinement and enhancement, the projected innovation has made significant strides in addressing the existing gaps and challenges in the reuse of steel in construction projects. It has provided practical solutions and tools that can contribute to the successful implementation of steel reuse, thereby promoting sustainability and circularity in the industry.

Does the project contribute to sustainable development? And what is the impact of your project on sustainability (people, planet, profit/prosperity)?

The project significantly contributes to sustainable development by addressing crucial issues in the construction industry, including the escalating embodied carbon emissions, inadequate waste disposal management, and the depletion of non-renewable resources. The implementation of steel section reuse in new buildings aligns with the principles of circular construction, thereby mitigating the detrimental environmental impacts associated with the steel industry. By promoting resource efficiency and reducing the demand for new steel production, the project positively impacts the sustainability pillars of people, planet, and profit/prosperity. It offers potential benefits such as reduced carbon footprint, minimized waste generation, and the preservation of natural resources. Through the adoption of sustainable practices, the project fosters a more environmentally conscious and responsible construction sector, contributing to a more sustainable future.

What is the socio-cultural and ethical impact?

By implementing steel reuse in building projects, the project contributes to a shift in societal attitudes towards more environmentally friendly and resource-efficient construction methods. It encourages a cultural change by raising awareness about the importance of reducing carbon emissions, minimizing waste, and conserving natural resources. From an ethical standpoint, it addresses the need to mitigate the negative environmental impacts of the steel industry and promotes the concept of circular economy, which emphasizes the responsible use and reuse of materials. Furthermore, the project's socio-cultural impact extends to multiple stakeholders within the value chain by encouraging collaboration and knowledge sharing among material providers, material seekers, and other industry professionals. Overall, the socio-cultural and ethical impact of the project lies in its potential to reshape industry norms, raise awareness about sustainable construction practices, and foster a sense of responsibility towards the environment and circularity in the building industry.

What is the relation between the project and the wider social context?

The project influences and is influenced by various social, economic, and environmental aspects.

- Social: The proposed design workflow and computational tool have the potential to benefit the wider construction industry by sharing knowledge, best practices, and tools. This can foster collaboration and encourage the adoption of sustainable practices beyond the scope of the project itself, promoting positive social change in the industry as a whole.
- Economical: The project can potentially reduce construction costs by utilizing reclaimed materials, enhance resource efficiency, and create new opportunities for businesses involved in the steel reuse value chain.
- Environmental: By promoting the reuse of steel sections in construction, the project contributes to reducing environmental impacts associated with steel production and waste generation.

How does the project affect architecture / the built environment?

The project's impact on architecture and the built environment is significant, as it promotes circular design principles, impacts structural design approaches, develops computational tool advancements, and contributes to the broader integration of sustainability in architectural practices. It promotes circularity by encouraging stakeholders to consider the lifecycle of materials and their reuse potential, rather than relying solely on the linear "take-make-dispose" approach. The project impacts the traditional structural design approaches as integrating reclaimed steel elements in construction projects requires engineers and contractors to consider demountability of structural elements and requires stockholders and fabricator to perform repairs in order to assure the quality of the reclaimed steel. The project's development of computational tools, such as the matching algorithm and digital inventory, facilitates the exchange of information between material providers and seekers, enables informed decision making, and enhances design efficiency. Finally, the project integrates sustainability ideals and encourages industry professionals to think beyond aesthetics and consider the environmental, social, and economic impacts of their design choices.

6.2 APPENDIX B: INTERVIEW REPORTS - YANNICK SMOLDERS

Date: April 21st, 2023

Meeting Place: Online Call

Interviewer: Daniela Martinez (DM)

Interviewee: Yannick Smolders – Engineering Manager at CSM Steel Structures (YS)

This document contains an interview report based on detailed notes taken during the conversation with the interviewee. The interview began with me providing an overview of my thesis topic, research, and objectives, followed by a series of questions that aimed to gather insights and perspectives on the topic of reusing steel in the building industry.

DM: Could you tell me a little bit about you and your role at Cleveland Steel Tubes (CST)?

YS: I'm the engineering manager here at CSM. We are a company with approximately 160 people and situated in Belgium, but we are very active on the Dutch markets as well. CSM does engineering, manufacturing, and erection of steel structures. Our projects vary from architectural projects to more complex structures like bridges.

I shared my screen to explain the focus of my thesis, the work developed, and my objectives.

DM: I am actually searching for a realistic case study project with which I can test out my computational script. I have some sample stock lists but am looking for a design list in order to test out the matching process.

YS: That is something we could help you with. We use a software called Tekla Structures to extract out lists of the individual elements to order the profiles and plates. The target is to get a material list as soon as possible so we can order materials when the project goes into production. Tekla is not used for designing projects, but it is used to create the shop drawings and assembly drawings.

YS: But we can definitely provide you with a design list of a case study project and some shop drawings.

Yannick shared his screen to show an example of a project in the Tekla Structures software. He also demonstrated how a list of elements can be extracted to be sent to a production mill for ordering the profiles and plates. From this list, the profile and length of the elements are used to order any paint or coatings. In addition, he showed how each beam can be linked to an assembly number which is linked to the shop drawings to represent the indicated beam along with the indicated plates as well as any instructed welding or bolt hole locations.

DM: In terms of the workflow process, does CSM always do the assembly, or do you also work with a separate construction contractor?

YS: We do both. Sometimes we are in charge of the fabrication and preassembly and other times, if production is too busy, we have subcontractors that will do the assembly.

DM: Has CSM done any project with reclaimed steel?

YS: No, not yet. We are not very familiar with the reusage of steel, but we have done some projects that are designed to be disassembled since the circularity of steel is important. One case study project is the LAB 42 at the University of Amsterdam.

YS: CSM does detail engineering, not designing. This means that if we were to use reclaimed steel, we would not be able to make any changes to the beams or spans. We follow what is in the drawings to generate the shop drawings and assembly details.

DM: What do you think would be the biggest challenges of implementing reclaimed steel in projects during the following process: the engineering process, the manufacturing process, and the construction process?

YS: It is difficult to tell because the quality or condition of the reclaimed steel elements are unknown. What does it look like? Are there any plates welded to the beam? Are there any bolt holes? Where are these located?

YS: For example, a challenge is the existing location of bolt holes and the fact that this information is unknown, so it would take additional coordination and labor from our end to locate the existing bolt holes and see where we can drill the new bolt holes. Additionally, we order standard lengths from our suppliers , while this would vary if we obtained reclaimed beams.

DM: Well, I do know, based on previous interviews, that stock companies can perform some repairs such as straightening of slightly bent beams, grid blasting to remove the coatings or paint, and cutting of welded plates at the ends of beams. With that said, if those repairs were done at the stock company, would you then be able to use the reclaimed steel?

YS: I think it is economic, you know? If you have to do all of those actions is it still economic?

YS: But yes, if the beams are repaired we could consider them like new beams.

DM: I mean, I think taking into consideration the amount of CO2 emissions and resources that are needed to produce virgin steel, we should take a look at how to implement reclaimed steel and encourage circularity of materials. I have also done some research on the concept of urban mining and looking into the amount of steel that we currently have in buildings now and figuring out what can be done with that material so that it does not go to scrap or waste.

YS: Well, generally that material will be reused as it can be melted down and then a new beam can be produced.

YS: I think the time, resources, and labor that go into repairing reclaimed beams and adapting it to new designs is more costly. In addition, if you have to reuse a building that was not designed to be reused, this is a very difficult.

DM: I understand that. My objective for my research is to have these discussions with different project stakeholders to understand the challenges that they each encounter when reusing structural steel elements and what the priority of those challenges are per the different roles. Not everyone will have the same level of importance for each challenge.

DM: You mentioned if the reclaimed steel elements were repaired by the stock companies, you would consider them like new elements. However, if the stock companies did not do any repairs would CSM take on the additional cost and time to repair the elements in order to reuse steel?

YS: I am wondering if its economical to repair all of the beams by hand or just send them back to the manufacturing plant to be melted down and made into new beams.

DM: In terms of the certificates needed for the handling of steel elements, am I correct that you need the 2.1 and 2.2 certificates from the production mill? Which certificates do you produce? Who does the CE marking? CSM or the production mill?

YS: The CE marking comes from the production mill. We mostly handle the 3.1 and 3.2 certificates. The 3.2 certificate has to be verified by an independent control office. This involves a third party coming into CSM and testing the profiles or plates to verify the information on the certificates.

DM: Who hires the third party to verify the certificates and testing?

YS: That is a good question, I don’t know exactly, but I think it is hired by the client.

DM: A big challenge I have encountered is the fact that regulations are not yet well established for reclaimed steel. So if the history and properties of the reclaimed steel elements is unknown, the stock companies must send all of these elements to be tested to verify their chemical composition and quality. And then from there, from what I understood, they provide an official declaration and the test results and then the steelwork fabricator would then produce the CE marking. Is this correct?

YS: We don’t produce CE marking for the product or individual element. We produce a CE marking for the work that we do, like the welding, but not for the product itself. The CE marking for the product would come from the production mill.

DM: What information is in a CE marking?

YS: Depends on the certificate you need, and the work done. I can show you one as an example.

Yannick kindly provided a sample CE 3.2 certificate.

DM: So if you receive a CE marking from the production mill, when you guys do additional work and welding and everything to those beam elements, then you add on to that original CE marking. Or is this like a separate CE marking from fabrication?

YS: It is a separate certificate. The 3.2 inspection certificate includes information like the steel quality, chemical analysis, tensile test, impact test, and ultrasonic test report. It includes the certificate number which is also indicated on the profile or plate. The ultrasonic test report shows if there are any cracks on the beam.

I thanked Yannick for his time and input and for his willingness to share a case study project and information that will help inform my thesis research.

[End of interview]

This report provides insight on what was discussed during the interview. The interviewee agreed for the information discussed during this interview to be used for my Thesis Report. By signing below, they acknowledge their consent.

Signature:

Date: 21/6/23

6.2 APPENDIX B: INTERVIEW REPORTS - DIMITRI TUINSTRA

Date: April 6th, 2023

Meeting Place: Online call

Interviewer: Daniela Martinez (DM)

Interviewee: Dimitri Tuinstra, Associate Director at ARUP (DT)

This document contains an interview report based on detailed notes taken during the conversation with the interviewee. The interview began with me providing an overview of my thesis topic, research, and objectives, followed by a series of questions that aimed to gather insights and perspectives on the topic of reusing steel in the building industry.

DM: Could you tell me a little bit about you and your role at ARUP?

Tuinstra is part of the infrastructures team at ARUP. He joined the NEN Coding Committee, which resulted in NTA building codes for reusing steel. Within this committee he met Frank van der Loop from Swanenberg Ijzer Groep, who originally shared Tuinstra's contact with me. Tuinstra explained that currently there is no code for implementing reclaimed steel on bridge infrastructure. This is due to the fact that bridges experience fatigue which is complex when testing the reclaimed steel for future reuse.

In addition, Tuinstra recommended me to look at the Thesis research of Fe van Lookeren Campagne, TU Delft alumni from 2022, where she developed a computational tool for reusing steel in a database for bridge design.

DM: Is ARUP currently developing or has developed a computational tool to facilitate the integration of reused building components, do you mind sharing a little about that?

MAGPI is a tool developed by ARUP, but it is not available on the market. The matching tool looks at available profiles to match with the profiles needed, however Tuinstra mentioned that there is a lack of public stock database. He compared the concept of an online database with that of IKEA where one is able to check the stocks from various locations, then order the products and then decide to pick them up or have them shipped. He concluded by stating that this public online database of steel stocks is currently not out there, but it would be ideal.

DM: I am looking to implement a "reservation system" to reserve steel profiles from stock yards to solve the uncertainty of purchase from both parties (design team and stock companies). With this system, designers and contractors can be assured that the reserved elements will be available when needed, providing them with a guarantee of timely delivery. At the same time, the reservation system can provide stock managers with a constant income stream and the assurance that the reserved elements will be purchased. Could you share your thoughts on this?

Tuinstra mentioned the following challenges still need to be tackled when implementing this system: One is that the profiles that are reserved are not able to be utilized by others that might need them. Another challenge is the risk of the fluctuating steel market and the pricing of steel that is constantly changing. Lastly, he mentioned that during the design process there are constant design changes, and it can take several years before the steel profiles are purchased to be used in construction. This is a challenge if designers are utilizing this tool, as opposed of contractors, since they are typically not making the final decision of purchasing the elements.

He suggested that the contractors and manufacturers should be the ones utilizing this tool, as they need the stock immediately and will be making the purchase of the steel stock needed for the project. This could also help manage the long lead times of stock material.

Tuinstra discussed another challenge is the price of reclaimed steel going up as the interest in reusing steel increases. He said stock companies are tradesmen and are interested in a financial profit within this business. If this tool is focused around the design team when no contractor is involved, this becomes an issue due to the time of design being so far from the time that the purchase of the stock is made.

DM: Yes, I also agree with the tool being utilized by contractors when making the purchase of the profiles needed. However, I do not want to restrict the tool just for contractors, as I see a potential for designers to use this during the design process to make informed design decisions and adapt the design to maximize the usage of reclaimed steel. My proposed workflow of this system is to integrate the entire project team during the early planning phases. This means that the contractor would be involved during the design phase and could provide necessary input for the constructability of the project. With that in mind, the idea is to allow different members of the project team to utilize this computational tool and therefore facilitate the coordination and exchange of information.

Tuinstra asked what the objective is of the computational tool (aside from the prototype of the online database web platform).

DM: The computational tool is a grasshopper script that would match the elements needed from a design list with those of the available profiles from a stock list. This can be run multiple times during the design process to make informed design decisions.

Final recommendations:

Tuinstra mentioned that the idea of developing an online database of different stocks would be strong, as there is currently non available. He also mentioned the difficulty of measuring steel availability or prices, as the steel market is constantly changing. He suggested directing my computational tool and online database to be utilized by contractors and manufacturers, who are the ones to make the purchase of steel stock.

Lastly, we discussed the difference between two business models, which would impact how the computational tool would operate: One business model is to design based on availability, possible a donor building, and using the computational tool to optimize the design geometry. The other business model is to start with a conceptual design and use the tool to match and replace the elements needed with those of available stocks. I mentioned, my focus is on the latter business model option.

[End of interview]

This report provides insight on what was discussed during the interview. The interviewee agreed for the information discussed during this interview to be used for my Thesis Report. By signing below, they acknowledge their consent.

Signature: Date:

6.2 APPENDIX B: INTERVIEW REPORTS - FRANK VAN DER LOOP

Date: March 21st, 2023

Meeting Place: Swanenberg Ijzer Groep (Schaijk, Netherlands)

Interviewer: Daniela Martinez (DM)

Interviewee: Frank Van Der Loop, Sales Purchase Manager at Swanenberg Ijzer Groep (FL)

This document contains an interview report based on detailed notes taken during the conversation with the interviewee. The interview began with me providing an overview of my thesis topic, research, and objectives, followed by a series of questions that aimed to gather insights and perspectives on the topic of reusing steel in the building industry.

DM: Could you tell me a little bit about you and your role at Swanenberg Ijzer Groep (SIG)?

Frank has been at Swanenberg for 17 years. He is in charge of the purchasing of materials, which include reclaimed and d-classed.

DM: What is d-classed steel?

"D-classed" or "off-grade" steel refers to steel materials that do not meet the standards required for their original intended use, such as those with defects or those that were over-ordered. These materials may still be usable for certain applications, but they are typically sold at a discounted price compared to prime-grade steel.

In terms of the current process that SIG follows when salvaging reclaimed steel, does SIG purchase the elements after disassembly? Or are these purchased before disassembly?

FL: Swanenberg comes up with the price before disassembly and purchases after. This is because the contractor typically wants to know if the steel is valuable enough, based on the purchase offer, before disassembling the structure.

FL: There have been times that Swanenberg bets on the steel elements before disassembly and after disassembly notices that some elements are bent. Once the elements arrive to the stock yard, Swanenberg inspects the elements and decides which ones to purchase and which ones to not purchase. However, it is also a matter of good working relationship, because I am their costumer and if they are losing money on me, next time they will not call me. It is not always a one-way direction. If there is a good relationship established, there will be future business. For example, there have been times that we offered a price per ton, then the contractor tells us that the disassembly cost will be higher than expected, so Swanenberg will update the original price to be a bit more so the trade is fair for both parties.

DM: When you offer a purchase price before disassembly, do you coordinate anything with the disassembly contractor?

FL: No, anything that needs to be coordinated is discussed once the elements arrive in the stock yard.

DM: *Who holds responsibility during disassembly and transport? Which party takes on the cost of transport?*

FL: The contractor holds responsibility during disassembly. The transportation means and cost depends. Typically, Swanenberg offers to handle the transport by sending out a truck once the elements have been disassembled. But if they have the trucks available for transport, then the contractor will choose to take on the responsibility and we will update our offer price to reflect this. This is part of the negotiation.

DM: During this process is there ever a contract that is developed and signed by both parties?

FL: No, a handshake is more than a contract.

DM: What is typically the process at Swanenberg for organizing and storing of the steel elements? Is there a protocol you follow?

FL: We do have a protocol. The elements are unloaded and then Swanenberg will sort it out and check it. If there is anything that does not meet the quality standards, they will set the element aside. After this, the elements are cleaned and then the elements are recorded within Swanenberg's stock list (excel file).

DM: W*hat is the inspection/repairing process like?*

FL: With experience one learns to know certain information of the steel element buy looking at it. For example, the profile of new beams is different; these are the typical H beams. DIN is the old profile. So when you know it's a newer profile, you can assume the steel grade is at least S225. Sometimes the beams will have a sticker or a stamp from the production mill where it states the steel grade and other information. If that is the case, Swanenberg will not do additional testing to determine the steel grade.

FL: In addition, the rust is a different color, and it makes a different sound when comparing an S235 and an S355. We also do a hardness test on every beam in three places. This is done utilizing an Eco-Tip Hardness Tester.

FL: The repairing of simple things like removing welds, cleaning, minor straightening of bent beams and cutting off edges is done on site.

DM: And what about the removal of paints and coatings?

We can also sand blast to remove coatings on site but this is typically done by the contractor since they know what are the requirements and will typically be the ones responsible for any new coatings.

DM: How is this information stored? Is there a digital inventory? Do you take pictures of the elements or digital scans?

FL: We store the information within the excel stock list. Sometimes we take pictures during the purchasing of the elements and store those along with the digital inventory.

DM: would you be able to provide an example stock list?

Frank shared an excel file of their current stock list.

DM: Who provides the "check-and balances" to ensure the elements meet quality standards and are satisfactory to be reused?

FL: Swanenberg usually ensures the quality but it depends, sometimes there is a third party involved but this is typically directed by a client.

DM: What is the testing process like? Is this done at the stock yard or off site?

FL: We do not do any testing unless a client comes and has further specific requirements. Then Swanenberg will inform the client that further testing needs to be done to verify the elements. This is done off-site at a third party laboratory. We can test a few beams by cutting out a small plate to get an idea of what the steel grade is; these plates are sent to the laboratory. However, this is not typically done on every beam, unless the client requests that, because the testing can be very costly. The cost of testing varies but it can be about $350 per test.

FL: The tests are typically the following: elongation test, impact test, and chemical composition. For pipes, the testing needs to be done in the direction of production.

DM: Who holds the responsibility of the testing and the cost of this?

FL: This is also part of the negotiation with the client. In certain scenarios, if we sell beams assuming they are S355, the client will ask for proof. After testing, if the beams are in fact S355, then the client will bear the cost. Swanenberg will bear the cost of any beams that did not meet the criteria that we had assured.

DM: After the testing occurs, do you produce an official declaration of the chemical composition and steel grade?

FL: No, we don't do this. This information appears on the results obtained from the testing laboratory if the test was requested by the client.

Frank shared an example of testing results.

DM: And who gives out the CE mark of the steel elements?

FL: This is done by the fabricator after the elements are purchased and are being fabricated or remanufactured.

FL: the 2.1 and 2.2 certificate is done during production of the steel elements. 3.1 is used for CE marking.

This discussion is according to the 10204 code of Test Certificates For Stainless Steel Products. Please reference Table A.1 (BSEN 10204) below.

Certificate type	Title	Status	Summary of EN10204 requirements	Notes
2.1	Declaration of compliance with the order	C	Statement of compliance with the order by the manufacturer.	No test results shown.
2.2	Test report	C	Statement of compliance with the order by the manufacturer based on non-specific inspections, (tests), by the manufacturer.	Like the old BS1449 'Cast Test' certificate. Mechanical test sample results from another coil from same cast, manufactured by the same process route, can be used.
2.3	Specific test report	W	With mention of test results from specific inspection and testing	Batch test results needed on the certificate. Difficult to distinguish this from the 3.1B type.
3.1	Inspection certificate	C	Statement of compliance with the order by the manufacturer with results of specific inspection	Replaces 3.1B. Common certificate type issued for 'batch tested' material. Cert. issued and signed by manufacturer's representative, who must be independent of the manufacturing department. E.g. Inspection department or test house manager/supervisor.
3.1A	Inspection certificate 3.1A	W	With mention of test results from specific inspection and testing	Batch test results. Cert. issued by independent inspector required by releasing authority, (e.g. TUV for German pressure vessels). Replaced by 3.2 in 2004
3.1B	Inspection certificate 3.1B	W	With mention of test results from specific inspection and testing	Batch test results. Cert. issued and signed by manufacturer's representative. Replaced by 3.1 in 2004
3.1C	Inspection certificate 3.1C	W	With mention of test results from specific inspection and testing	Batch test results. Cert. issued by independent inspector appointed by customer, (e.g. Lloyds). Replaced by 3.2 in 2004
3.2	Inspection certificate	C	Statement of compliance with order with indication of results of specific inspection	Batch test results. Cert. issued by both manufacturer's representative and an independent inspector appointed either by the customer, (c.f. withdrawn 3.1C), or an inspector designated by official regulations, (c.f. withdrawn 3.1A), i.e. 3.2 now covers scope of both 3.1A and 3.1C of 1991 edition. This covers what is often referred to as 'outside inspection'

DM: Does Swanenberg do any repairs or remanufacturing on site?

FL: Minor repairs we can do on site, but we will not do any remanufacturing. That would typically be done by the steel fabricator after the steel elements have been purchased.

DM: How do designers select these elements during designs? Is there a digital inventory or an excel sheet available of the stock elements?

FL: Yes, we have an excel stock list.

DM: Can you share a bit about the process of communicating with designers trying to match stock elements with their design? What is the coordination process like?

FL: We have not yet had a project where we coordinated with designers. The case study project that you mentioned, Mundo Lab, we provided the project client with the stock list, and he selected which beams he needed for the project.

DM: I was thinking of implementing, within my proposed workflow, a reservation system where the project team can reserve the steel elements that match the design so that they can be assured that the elements will be available once the project finalizes the design phase and entering the construction phase. This will entail a reservation time frame and a monthly fee, which will be a steady income for the stock companies. Can you share your thoughts on this?

FL: Very good. How much would the reservation fee be?

DM: I have not yet determined that, would you have an idea?

FL: I would say 10% of the value per year.

DM: But the value of steel is volatile, and I do not think that I would want the reservation fee to change monthly. What are your thoughts?

FL: It is a gamble to purchase material and not know if you will use it in the end of the design. Swanenberg has thought of offering to clients a buyback policy where they can purchase the elements, leave them at the stock yard, and in the end, if they end up not needing some elements, we will guarantee to buy it back for 70 to 80% of purchased price.

DM: What are your thoughts on having an initial contract with the reservation fee and the price of steel and fixing that price until the elements are purchased?

FL: The problem is that the price of steel is constantly changing, so it would be hard to fix a price. It also happens to us when we agree to purchase a certain amount of tons of steel at an agreed price, and then the price of steel drops, we still have to pay the price that was agreed.

FL: So having a fixed reservation fee would be fine, but fixing the price of the steel elements would not be possible.

FL: Buying steel is a gamble.

FL: You could also implement the idea of having different stock yards give their best price and then the client will select where to purchase the steel elements from.

DM: How does Swanenberg determine the price of steel?

FL: Based on the quality. But this is also negotiated with the client based on the relationship and the needs from both parties.

DM: How do you manage the negative connotation that reclaimed steel is lower quality, in terms of client purchasing steel elements from a stock yard?

FL: The quality of steel does not decrease after its use. Purchasing steel elements from a stock yard is similar to finding products at the local market where the price will most likely be lower than that of the price at the supermarkets.

FL: Swanenberg also offers a “purchase back guarantee” and will buy back the steel elements after the life cycle of the building and its disassembly.

DM: Based on your experience, what are some challenges that you find in the overall process?

FL: Daily beams come and go, and the design process will take months to years before the project starts construction. It would be better to design based on availability.

FL: In addition, it is also hard to tell where the beams come from and the history of them.

Frank kindly gave me a tour of the stock yard at Swanenberg so that I could see where the elements arrive and are unloaded, where they are cleaned and cut, and then where they are stored on site. Please reference the pictures below. He also pointed out how to estimate the quality of the steel elements based on color and appearance. I took a short video of this tour, which is available upon request.

Stock yard:

Where elements are unloaded:

Where elements are cut:

Cranes for lifting and moving the beams:

Storage of beams:

Labeling of beams:

[End of interview]

The following includes a discussion over my **proposed stock list template** for the computational script to read the excel columns clearly.

DM: Would information on the "finish, end cuts, defects, and repairs" be needed on the stock list? or is this better stored within the identity code of the beam (and excluded from the excel)? In addition, do you think that information on certification and testing should go on the excel?

FL: I would keep the information that cannot change in the identity code (like size & steel grades). And the information that can change keep it in the excel list. It is important information when you select the material.

DM: Is it ok to include the steel grade column even though the steel grade is sometimes unknown and requires testing to verify?

FL: I would mark the unknown material as Minimum S235.

This report provides insight on what was discussed during the interview. The interviewee agreed for the information discussed during this interview to be used for my Thesis Report. By signing below, they acknowledge their consent.

Signature:

HANDELSONDERNEMING H. SWANENBERG B.V.

Date:
22-4-2023

Element Materials Technology
Voorerf 18
4824 GN Breda
NL

Swanenberg BV
Postbus 30
5374 ZG SCHAIJK

Date : 21-Oct-16
Element report number :

Customer reference

TEST REPORT

Sample No.:	Item description:	Material:	Identification on sample:
22926-1	Segment from pipe OD = 457 x 22.2 mm	S355	457x22.2
22926-2	Segment from pipe OD = 406 x 12 mm	S355	406x12

TENSILE TEST

Test method: ISO 6892-1 — Test temperature: R.T.

Specimen	Orientation	Size [mm]	Yield strength [MPa] Rp0.2	Tensile strength [MPa] Rm	Elongation [%] After fracture	Reduction of Area [%] After fracture
22926-1	longitudinal	Ø 10.02	521	623	26	80
Requirements acc. EN 10219-1;			≥ 345	470-630	≥ 20	--
22926-2	longitudinal	Ø 7.99	486	574	24	74
Requirements acc. EN 10219-1;			≥ 355	470-630	≥ 20	--

CHEMICAL ANALYSIS

Method: Optical Emission Spectrometry Element W.I. 09.40

	Chemical element in mass %											
Specimen	C	Mn	P	S	Si	Ni	Cr	Mo	N	Cu	V	CEV
22926-1	0.03	1.46	0.007	<0.001	0.32	0.01	0.16	<0.01	0.004	0.01	<0.01	0.31
22926-2	0.14	0.42	0.009	0.002	0.14	<0.01	0.01	<0.01	0.005	0.01	<0.01	0.22
Requirements acc. EN 10219-1	--	--	--	--	--	--	--	--	--	--	--	--
	≤ 0.22	≤ 1.60	≤ 0.030	≤ 0.030	≤ 0.55	--	--	--	--	--	--	≤ 0.45

Note: *All results are an average of minimum 3 measurements. All requirements are maximum unless range given.*

The above mentioned items satisfy the requirements.

Element Materials Technology

element
Belinda Rozenberg

TESTING
RvA L 063

6.2 APPENDIX B: INTERVIEW REPORTS - MICHAEL SANSOM

Date: March 17th, 2023

Meeting Place: Online Call

Interviewer: Daniela Martinez (DM)

Interviewee: Michael Sansom (MS), Sustainability Manager at British Constructional Steelwork Association (BCSA)

This document contains an interview report based on detailed notes taken during the conversation with the interviewee. The interview began with me providing an overview of my thesis topic, research, and objectives, followed by a series of questions that aimed to gather insights and perspectives on the topic of reusing steel in the building industry.

DM: Could you tell me a little bit about you and your role at the British Constructional Steelwork Association (BCSA)?

MS: “I am the Sustainability Manager here. Before BCSA I was working at Steel Construction Institute (SCI) and was co-author of the P427 regulations for using reclaimed steel. I am still interested in working with reused steel but it is hard to find the funding to continue making development. However, I have started a working group here at BCSA that includes all the big players that are interested in reusing steel.”

I shared my screen to explain the focus of my thesis, the work developed, and my objectives.

MS: “Currently in the UK, reusing steel is a bit of a London phenomenon. It is really taking off. When we worked on P427, we based it on the business model that you have chosen, which is based on stockholders holding reclaimed steel alongside new steel. With that said though, most of the reuse projects happening in London are a different business model. The business model is that where a developer is taking down building X and is constructing building Y and will use some steel from building X for this new building Y. However, the reclamation market business model is starting to become popular and there are engineering companies that are at the forefront of this topic and there are two companies, that I know of, that are starting to develop a stock matching tool. Have you been in contact with Heyne Tillet Steel company?”

DM: “Yes, I have done an interview with them.”

MS: “Ah ok, then you are ahead of the game.”

DM: I read your article "Structural Steel Reuse" on NSC and you mentioned the development of a "prototype website and database to facilitate the trading of reclaimed steel and for securely storing structural steel information to enable future deconstruction and reuse." Would you have additional information about this?

MS: Let me share my screen and I can show you some slides from an old presentation."

Michael shared and discussed his presentation, which he kindly shared with me and is available upon request. His work was done with SCI and PROGRESS (provisions for greater reuse of steel structures). PROGRESS is a project that focuses on providing methodologies, tools, and recommendations for the reuse of steel-based components in existing and planned buildings.

MS: "There is the reuse business model of today and the reuse of the future. Reuse of today is current problematic. I am more interested in facilitating reuse for the future. Future reuse is all about capturing digital information, designing for disassembly, and system standardization.

I will skip over these slides which include all the work we have done for P427 as well as some portal frame connections to make them more demountable.

In terms of the portal that we developed 4 or 5 years ago, that you are asking about, we only built a prototype because we never got the money to fully commercialize it. The portal was both a trading portal for today and a establishment of a database for the future. In terms of the "today's" scenario is kind of like an *eBay*. Within the platform, one can post a building and its location and say it will be deconstructed and if anyone is interested. So, this would be a pre-demolition scenario. And then the post-demolition scenario is like an inventory of the elements in a stock yard once they have been tested. These are the two variants of the "reuse today" scenario.

In addition, within this portal, one could search for a specific section. So, one would go to the map and search for a specific section profile within a search radius and it would find you the results. The work that Laura Batty has done at HTS is using their matching tool to look at a design list coming from a Revit or Tekla model and searching for options within a stock list. The work that I was doing at SCI never got as sophisticated as developing a matching tool, but it was more like building an inventory and being able to manually search for the elements that one needs.

The part that I am really interested in is the reuse of the future. Because the current challenge now of not knowing the steel grade of reclaimed elements and having to do testing, this is the scenario of developing a database that captures the information of new structures and buildings. So in 20, 50, or 100 years, this information would be so valuable to have full traceability and would reduce the necessity to test reclaimed steel.

Every engineer and steelwork contractor produces these 3D models of the structure. With these models, they know everything, they know who welded it, they know where it came from, they know how much it costs, they know the test certificate, etc. And all that information is all within the models. For this database, we don't want all that information, but we want a defined subset of information that is uploaded as an IFC file to future proof the data. So, ideally, they would upload those models to this cloud-based database, and we would run some algorithms that strip out all of the steel section information and put it in a separate database.

So, for example, looking at this structural model of Billington Structures, we would be able to read the component information from a particular beam, which would include all of the relevant information like: section size, length, grade, subgrade, weight, etc. We could also include additional information to this data like EPD and mill certificates.”

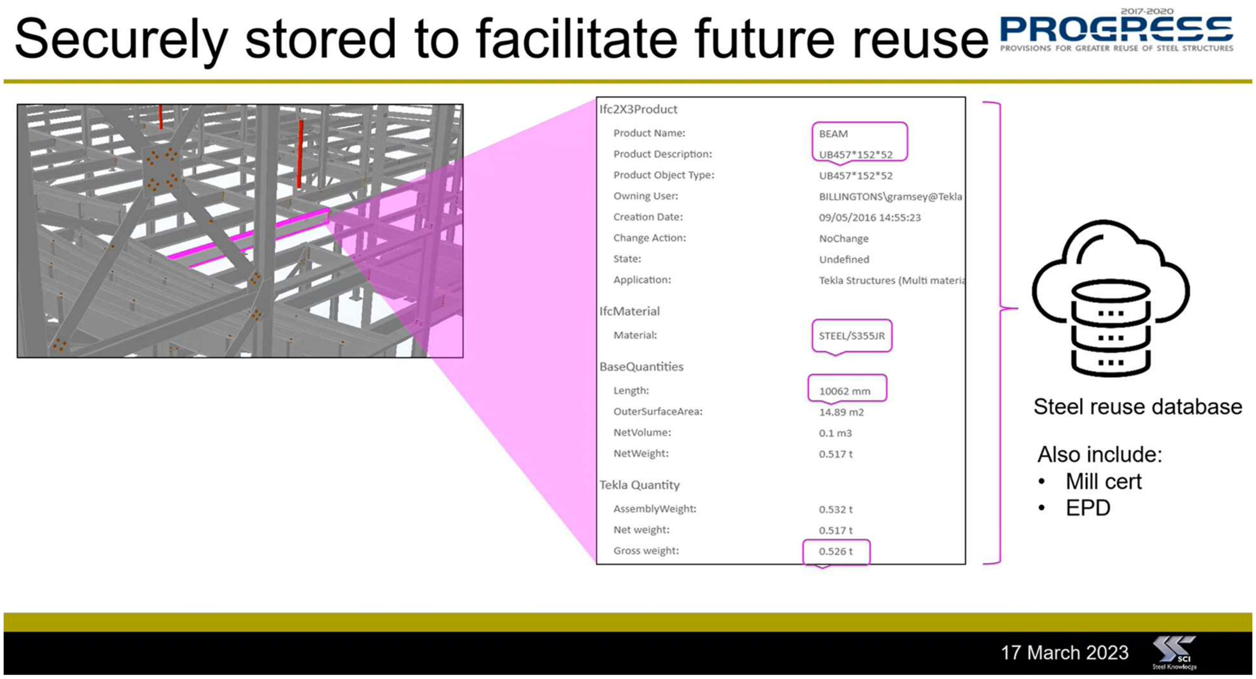


Figure 1: Screenshot of presentation slide (Michael Sansom, 2023)

DM: Is the mill certificate the same as the CE mark?

MS: “No, mill certificate is from the steel producer. It is a document that tells you all the mechanical and chemical properties associated with that member.”

Continuing on the presentation slides:

MS: “So, every new structure has this model. I want to bring it all together in this database and when that building becomes available for deconstruction, we would be able to have all of the information needed. All of the steel sections of that project would be available in the portal and would be able to be searched for by designers or contractors. And this information would be reliable, you know?

This is what I would love for the UK sector to do, and I am still hopeful. This is something that could be done and is very possible with steel. The reuse of steel is easy as compared with concrete, for example. And in the future all of this information for reuse would be super valuable.”

DM: This is all really interesting, thank you for sharing. May I ask something about the logistics? You mentioned the information would be element-based, so when a building is about to be deconstructed, then each element would need to be tagged, no? Like, with a QR code or tag that would hold the BIM information? Or are these already tagged before construction?

MS: "You make a very good point. These are some things that still need more thought. We did not get into the topic of how everything would be tagged. But we are assuming that the BIM model would be the accurate "as built" model. So when deconstructing it, that model should enable you to identify the elements and then they can be labeled then."

DM: Yes, during my initial research of this idea of maintaining a database, I did interviews with material passport companies to see the kind of information that they gather and store. However, from what I understood, it is not data per element but instead, the entire assembled building. Then the results give you the percentage of deconstruction or circularity. But I don't think the information of each individual element is traceable, nor do they save structural information; it is mostly environmental information.

Which then made me think that there should be a component database, like you mentioned from the BIM models, where one can keep record of events. So for example, a building that experienced an earthquake, should have the BIM database updated to state this event and any maintenance or repairs to the structure.

MS: "No, you are right, there are loads of these material exchange websites. And I honestly think the data of material passports is very impressive, but they still don't have the level of detail that a designer would need to make informed decisions based on steel components that have been sitting in a stock yard for 5 years, let's say.

That's why I think this work should be realized, and I am still trying to find the funding so that it can be done."

DM: And are you currently working on something similar at BCSA?

MS: "Kind of, so like I mentioned I am coordinating a group of about 40 people, all interested in the topic of reusing structural steel. I am trying to coordinate it, but there isn't specific project funding currently. The goal of this group is for everyone to communicate their challenges and identify the gaps within the system. So far we have identified three areas of challenges."

Below are some of the main challenges that have been identified within this group of professionals:

- CE marking on reclaimed steel
- Handling the condition assessment of reclaimed steel. More specifically, dealing with defects and repairs. Acceptability of the condition depends on how the steel will be reused.
- Warranties and insurance

"These are sort of the three priority areas that we are working on. But in every meeting everyone shares new information on what they are working on and making advancements on.

You also mentioned P427 which as you know only entails steel that dates to 1970, but here in London, there are a lot of building older than that. We are working with SCI to produce new guidelines that go back to steel from 1932. This will be published soon."

DM: In regards to CE marking, I think that is something multiple people in multiple interviews have mentioned, but I am still not super clear on what is required and how the CE marking works. Could you elaborate a bit on that?

Michael then shared some slides of a presentation in collaboration with Construction Insurance Risk Engineers Group (CIREG). CIREG specialize in Risk Management of Building and Civil Engineering Construction.

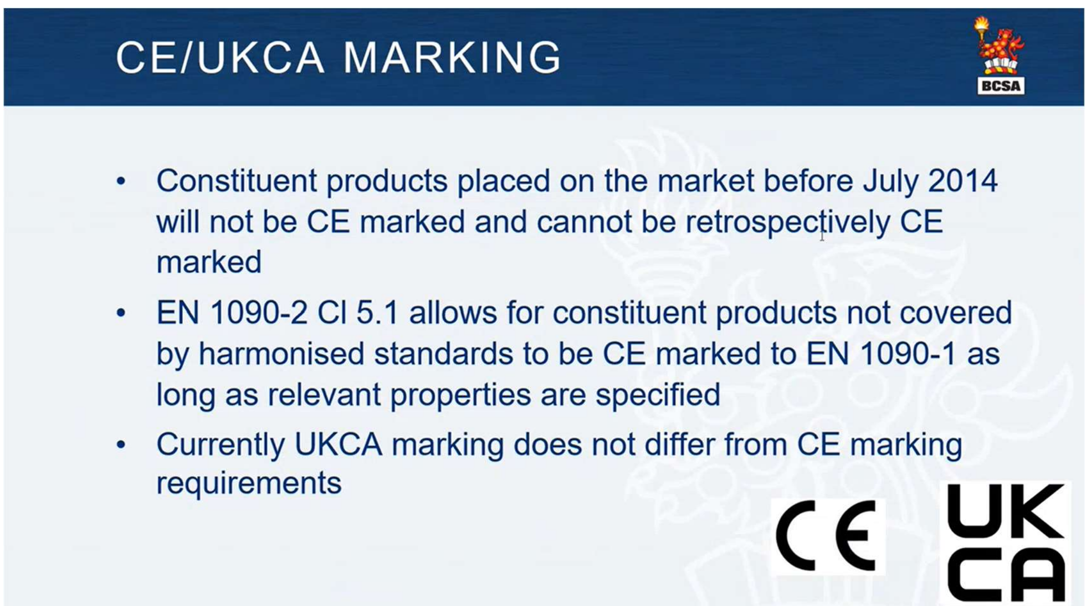


Figure 2: Screenshot of presentation slide (Michael Sansom, 2023)

MS: "If you think of a steel section, there are two harmonized standards: for the production and fabrication. The production is the producer that makes the steel up to production standards. The steelwork fabricators produce fabricated steel in compliance with EN 1090. In a sense they are different. So, this is the table below of the 1090 fabrication standards part 2, section 5.1, which specifies the relevant properties. Some are mandatory and some are if required:"

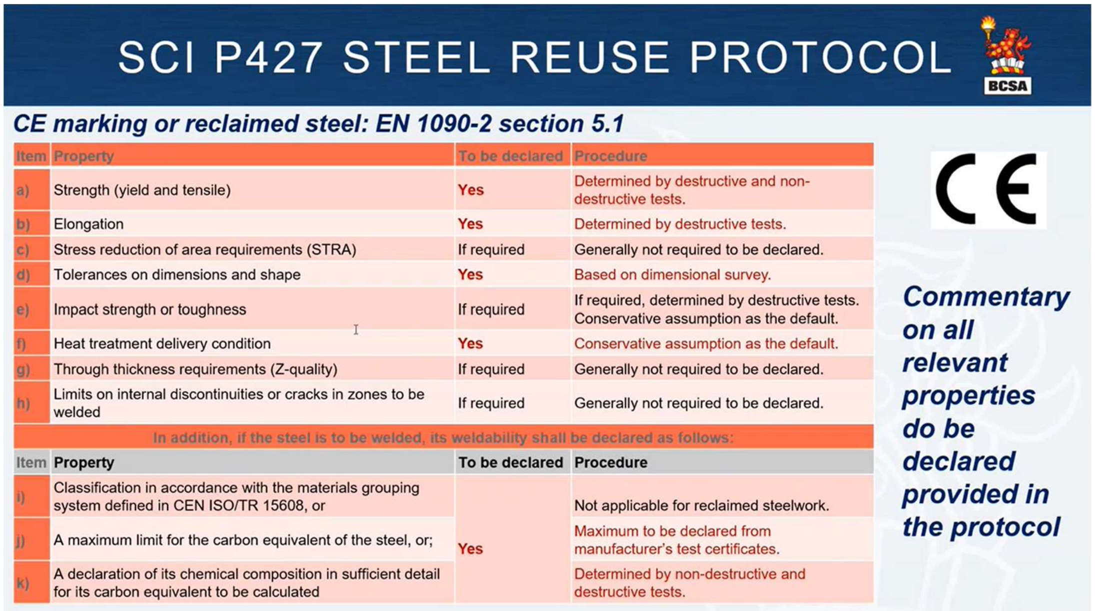


Figure 3: Screenshot of presentation slide (Michael Sansom, 2023)

MS: "So, the European harmonized standards are:

- EN 10025-1 for open sections and plates
- EN 1090-1 for fabricated structural steelworks"

MS: "From our perspective, it is absolutely acceptable to CE mark fabricated structural steel to 1090 using reclaimed steel. And this is the approach we took when formulating P427. Some parts of the supply chain are less comfortable with that and some countries as well. Germany for example doesn't interpret this the same way we do in the UK."

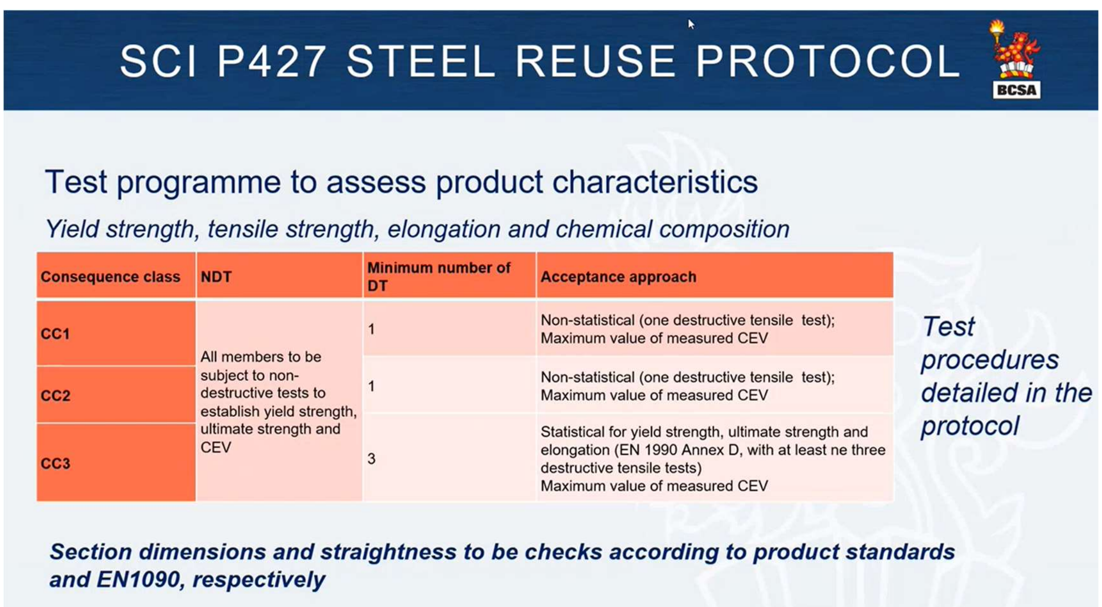


Figure 4: Screenshot of presentation slide (Michael Sansom, 2023)

DM: Ok, I think this is a bit more clear. After talking with CST, they mentioned the produce an official declaration when selling the elements after they have been tested in order for the fabricator will produce the CE marking. Is this correct?

MS: “It is a different model, because CST also does some fabrication. So, CST will act as stockholder and fabricator. CST works more on the business models of donor building than a reclamation market. This is why the scenario is different.”

DM: Another question I wanted to discuss, is the constant change in the price of steel. I want to implement a reservation system with a reservation fee and a time period limit But I am not sure how to manage the constant change of steel price and how to calculate the reservation fee.

MS: “The price of steel is very volatile. And stock yards are very sensitive to these market price changes. The image below shows the price of new steel over the years, in the dark line, and the price of scrap steel, in the gray line. The pink is the potential profit. Of course, there is additional cost when reusing steel for deconstruction, transportation and storage, testing, and refabrication.

But based on your question, I think it would be very hard to fix steel prices on the market. Especially because the design process can take years and it would be hard to estimate the cost of steel by the time the design process is finished. The reservation fee shows potential, and this fee could be fixed. This is because the cost for the stockholder to store and reserve these elements is fixed.”

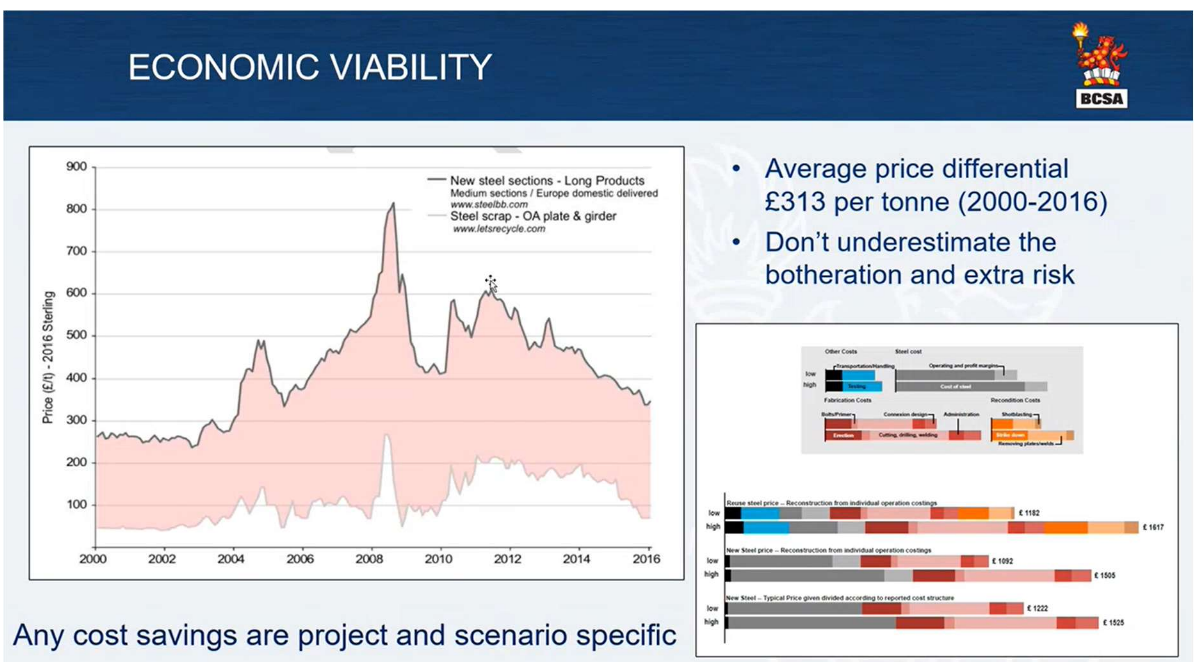


Figure 5: Screenshot of presentation slide (Michael Sansom, 2023)

DM: But in this image, am I buying reclaimed steel at the price of new steel?

MS: “That is a good point. There are two things: the real cost and the actual cost. There are costs to testing it, transporting it, storing it, and refabricating it. So, all of these actions will increase the cost. I am not commercial, so I cannot answer definitely your question. But I think this will vary from stock company to stock company.”

“But I think currently it is costing more money to do all of the work with reclaimed steel. Should we call it the “botheration” of utilizing reclaimed steel? I would guess that this is more costly for clients, but I believe they are doing it for different reasons, whether that is because of carbon savings or as case studies, or to make a stand of reuse.”

DM: I am also curious as to what the price is of the reclaimed steel when the stock yards purchase it. I would be curious to see if they buy it to the scrap steel price.

MS: “Well, I cannot answer that with any kind of confidence.”

“And again, it depends on the business model. For the donor building business models, these sections are not being placed on the market. And you don’t have to CE mark anything that is not being placed on the market. And then you also don’t know if the steel sections are being tested either. And this is why we need to provide some standard regulation with CE marking. But this is quite an important point.”

“It is different than the mainstream model of the reclamation market, in this case I am not sure who sells the building to the stock yard. Is it the demolition contractor or the owner. I am assuming it is the owner. So presumably the price would need to be more than scrap steel but less than the new steel, as there needs to be a profit margin further down the supply chain.”

DM: Another question I have, and this is outside of my research scope, but the topic of contractual agreements I believe is also a big challenge. My previous experience has been mostly in the U.S. where there is the American Institute of Architects who publish standard contract agreements for different types of projects. I am not sure how that works here in Europe, but it is definitely something that I am curious about.

MS: “Well, I think the UK appears to be leading on the topic of reuse steel and we have links with the American Institute of Steel Constructions. We have had couple of calls with them about reuse, but I am not sure how it is developing in the U.S.”

He mentioned the Circular Steel conference in London at the end of June 2023 and that it would definitely be worth my while attending to meet all of the key players within this topic and learn more about the advancements of utilizing reclaimed steel.

I thanked Michael for his time and input and for his willingness to share his work and research that will help inform my thesis project.

[End of interview]

This report provides insight on what was discussed during the interview. The interviewee agreed for the information discussed during this interview to be used for my Thesis Report. By signing below, they acknowledge their consent.

Signature: Date:

6.2 APPENDIX B: INTERVIEW REPORTS - ROY FISHWICK

Date: March 2nd, 2023

Meeting Place: Online Call

Interviewer: Daniela Martinez (DM)

Interviewee: Roy Fishwick, Managing Director at Cleveland Steel Tubes (RF)

This document contains an interview report based on detailed notes taken during the conversation with the interviewee. The interview began with me providing an overview of my thesis topic, research, and objectives, followed by a series of questions that aimed to gather insights and perspectives on the topic of reusing steel in the building industry.

DM: Could you tell me a little bit about you and your role at Cleveland Steel Tubes (CST)?

RF: I am the Research and Innovation Team Leader at CST.

DM: In terms of the current process that CST follows when salvaging reclaimed steel, does CST purchase the elements after disassembly? Or are these purchased before disassembly? Who holds responsibility during disassembly and transport?

RF: Typically, the steel elements are purchased after disassembly, however, CST can also advice the disassembly company. CST will also set the criteria of what is acceptable, but this is through an informal conversation with the disassembly contractor. Once the elements are received after disassembly, they are purchased, however, the price will vary based on the quality. After this, 2 to 3 workers will inspect the material and note down characteristics (in this case, CST has 14 characteristics they note down) and give the steel elements a unique identity.

DM: At CST what is the process for organizing and storing the steel elements? Is there a protocol you guys follow?

RF: The elements are sorted based on size and characteristics.

DM: What is the inspection process like? And the testing process is done at the stock yard or is this at the factory?

RF: Inspection will occur within the stock yard to verify consistency; however, no testing is typically done until the elements are purchased. After purchase, CST will send the elements to an independent laboratory to get tested. The steel fabricator will require any stock company to procure the testing in order for the fabricator to be able to issue a CE mark on the steel elements. The testing allows the steel elements to be reliable when purchased by a contractor and when it is later handled by a steel work fabricator.

DM: Does the stock company provide a CE mark after testing the steel elements?

RF: No, the testing of the steel elements issued by stock companies allows the fabricators to know that the material is fit for purpose, which then allows the fabricators to be able to CE mark the steel structure. There is no CE mark for individual steel components. In addition, CE marking is from EN1090, this requires the constituent product, which are the steel elements, to be CE marked if they were manufactured after 2012. Moreover, steel must have a test certificate if it is coming from the mill, which is not the case for reclaimed steel. This is why fabricators must CE mark the structure. In order to CE mark the structure, the fabricators must know the properties of the material that they are using. So, the independent test lab report issued by the stock company should show this information to satisfy the EN1090 and allow the fabricators to have the necessary data to CE mark the steel structures.

RF: So the fabricator requires the stock company to do proper testing because they want the stock company to warrant the product because they have to warrant the structure (structural frame).

DM: Who provides the "check-and-balances" to ensure the elements meet code and is eligible for reuse per P427?

RF: CST will procure the testing per requirements.

DM: The gathered information is then recorded on an excel document manually, correct? How is this distributed to design and engineering firms? How is the information updated when design firms select the elements desired for the project? Do you provide 3D scans or digital data?

RF: For now, the information is manually recorded on an internal software, which can export the data onto an excel sheet with verbal description. Anything more than that like a 3D scan or BIM model would be ideal but the market is not large enough or profitable enough to make this work viable. This excel sheet is then shared to clients who request it. Then, if the client wants to reserve some beams, they can let CST know and CST will mark it as such on the excel list. An updated excel list is sent out every 2 months or so.

RF: When the steel elements arrive to the stock yard, each element receives a unique identity number so that we can keep track of each element individually. The recorded information within our software is saved, so the data will never be lost. We could also provide this data to project teams and clients so that they save this data with the new project, but we have actually never been asked for this information.

DM: Does CST do coordination with designers in order to sell steel elements?

RF: Designers typically don't buy anything. The specify the elements in the drawings for the contractor to purchase them. The typical supply process goes as follows: architect designs the project, and engineer designs the structure, the appointed main contractor employs a steelwork fabricator, and the fabricator would purchase the steel elements from the stock yard or production mill.

RF: The current challenge in the reuse process is you have designers trying to source material form stock yards without knowing the steelwork fabricator, who comes later down the chain.

DM: would you be able to provide an example stock list?

Roy shared an excel file of their current stock list.

DM: Who is responsible for repairing and maintaining the reclaimed steel elements? Stock companies or the fabrication companies?

RF: What we are seeing in the UK is that the stock companies are expected to do all of the repairs before the steel elements go out to the fabrication companies. None of the fabricators want to do any of that work. CST can do minor repairs, cut off edges, remove coatings, and straighten bent beams to ensure the elements are in good quality when they are sold. The steel fabricator does the fabrication of the structure per the shop drawings.

RF: After this, all elements go to a factory to be fabricated. This occurs with new steel elements and reused steel elements. Once the elements arrive at the factory, the elements should look like new in order to have bolt holes made or have steel plates welded per the shop drawings. Then the structure is transported to the construction site to be assembled.

DM: Has CST worked on case study projects with reused steel?

RF: Holbein Gardens is a project with about 70 tons of steel and about 30 tons were reused. We have done mostly projects with reused pipe because that is what our business has been for the past 50 years. One popular project is the London Olympic Stadium, this follows the same process that we discussed previously to show the quality. But recently there has been an increase interest in steel sections.

DM: Based on your expertise what are the challenges that you have encountered of this process currently?

RF: Some of these are the loss of data, misleading information, and damaged elements. In addition, the uncertainty of selling elements that are reserved for months is a big challenge because of the long-time frame of the design process or in the end, the elements are not purchased.

RF: It can also be tricky to design with stock elements with no foresight on the availability or cost of those elements.

RF: It is also difficult for contractors to handle reclaimed elements because the designers and engineers are telling them where to purchase them.

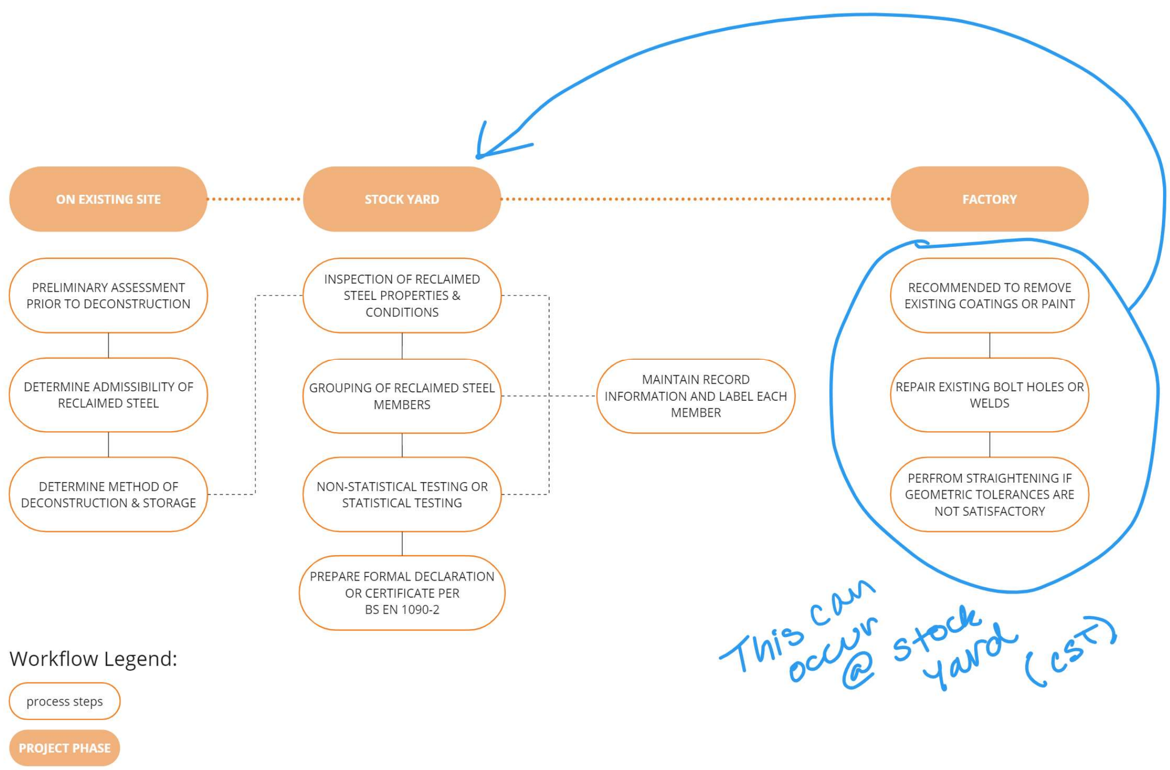
RF: Another challenge is the price of steel is so volatile and it fluctuates constantly.

RF: Moreover, the current standard contracts do not entail this “new” process with reused building components. This process causes more liability to different parties.

RF: Currently in the UK, all new structures being designed are specified to be S355 grade, whereas most buildings that are being disassembled now would have a lower grade such as S275 or S235. When it is a column, it is not subject to deflection which means the grade does not matter. But if it is a beam and it has been to S355, probably a lower grade would not work.

I then presented my workflow diagrams for the design process and computational tool. Roy provided the following feedback:

Based on my developed diagram below, Roy mentioned that the repairs can occur at the stock yard and not at the factory. CST will do those repairs on site.



[End of interview]

The following includes **discussions done by email** based on the development of my thesis and proposed workflow:

DM: I was just thinking that if there was a live inventory of what is available this would facilitate the process for designers and engineers during the planning phase of a project. However, I know you mentioned this is more chaotic on your end as you do not know what elements are reserved and if they would actually be purchased. In your opinion, do you think a "reservation system" could be implemented to reserve elements from the stockyard? What are some pros and cons that you could foresee from this system?

RF: "We are looking at using deposits to secure material for people. There are a few issues. First, the engineers and designers often do not have the cash to purchase material as it would be part of the contract awarded to the main contractor. This means disruption to normal business practice. There are also issues about how people react when the design changes and the fee is lost. Due to volatility of steel prices any contract that secure material well in advance of its use could see big gains or big losses and that would have to be borne by the buyer."

RF: "I think in terms of reservations/fees most of what you say makes sense. There has to be time limits and break points in the agreement. These would need to vary according to the nature of the project."

DM: I think this reservation fee could be added to design contracts with reused structural elements. This way the client knows beforehand about the process and is not caught by surprise. However, the challenge still exists of the volatile steel prices...do you think there is any way to control these better? Or a way to freeze the price during the reservation process?

RF: "As regards to fixing prices I have no problem with it as we would be selling existing stock where we knew what we had paid for it. The problem is that if I agree to sell for £1000/T but by the time the purchaser wants the material the market price has fallen they will tend to try and breach the contract. It could also be possible to link the future price to steel price indexes. Some customers may actually prefer to fix the prices early though as it gives price certainty for their contract."

DM: On another note, we also discussed that ideally the steel elements could potentially be 3D scanned with an available BIM model to allow possible buyers to visualize the elements better. What do you think are the pros and cons of implementing this? Do you think that there is a possibility for stockholders to become part of the project team as consultants and provide the BIM model of the inventory as a service as well as the testing and repairing? What would be the additional liability of doing this?

RF: I think this is very valuable and yes, the stockholders could supply this info. The issue would still be design changes down the line but the more info the better. I can foresee no additional liability.

DM: What are your thoughts on a buyback or prepurchase policy? For example, if a contractor purchases beams from CST to use in a project, when that project is ready for disassembly (and after on-site inspection to make sure the beams are in good condition for purchase), CST would purchase them at an agreed price. I think this might help to prevent loss of history information of steel beams, since you would have that info in your database. Would you think this is adding complexity to the process? Or do you think this could work and help solve some challenges?

RF: “Buyback and prepurchase are both services we do offer. Buyback is fine but the timescales between the sale and the buyback can be very long and so agreeing a price in advance is not viable. This is not true for temporary works. In regards to beams being bought before the design is finalized there are 2 issues: the first is that cash is rarely available for materials at this stage of a project and definitely not available to the designers. Second is that we have to buy back at a heavily discounted price, or we don’t make any money. Most designers are not very accepting of this and seem to think we should be able to operate on very small margins whereas we need to achieve a similar margin when we sell it whether they keep it or not.”

DM: Based on future potentials, do you think stockists could work as consultants on projects? Or what if the information you provide on the excel could be linked to the BIM model in the design phases? Or what if the excel was a live inventory so that it did not have to be updated manually?

RF: In terms of a live inventory, CST right now does it based on inquiry because designers or engineers could be planning on using certain elements and CST would not be aware of it.

RF: Regarding the information linked to the BIM models, CST currently provides the information of the elements when they are purchased. So, technically the engineer or designer could link the CST data to the BIM models.

The following includes a discussion over my **proposed stock list template** to be utilized within the computational script as part of this thesis.

DM: What are your thoughts on having a stock list template that becomes standards for stock companies to follow?

RF: “It is key to have stock lists that match project need but also that are detailed enough to demonstrate item characteristics that may affect fitness for purpose. I think our stock system already caters for this.”

DM: Should the information of "usage history, finish, end cuts, defects, and repairs" be information stored within the identity code of the beam and not on the excel?

RF: “They should be stored in both.”

DM: I also noticed the updated stock list that you sent contains columns on certification or testing (whether it has been done or not). Would you think this should also go on the excel stock list? or would this also be information within the identity code, so when you look up the code all of this information will come up.

RF: "It must be visible prepurchase and at a glance. If you have to look at each beam record individually to see details, it is very laborious. Our stock system has summary screens and detail screens to overcome this."

DM: I am not trying to imply that the excel list that you provided should be different, but also trying to synthesize the number of columns in order for the computational program to read the data faster. Basically, the information I need for the computational script (as far as I can think of) is the cross-section size, steel grade, and length.

RF: "Not sure but of the 3 computer models I know being developed currently they all use more data than that."

DM: And lastly, I had included the cost... but I think that it would be hard to add on the excel list since the prices vary. I believe I will remove this.

RF: "Cost is variable, and we do not offer fixed prices for a variety of reasons."

The following are Roy's comments on the different excel columns of my proposed stock list template. C# represents the column and the number in sequence.

RES	CDE	PON	STG	CSP	LEN	WKG	FIN	END	DEF	REP
RESERVATION: • 1 = YES • 2 = NO	IDENTITY CODE AA-000-1111.22 • AA = STOCK COMPANY • 000 = PROJECT CODE • 1111 = BEAM CODE • .22 = MODIFICATION CODE	PURCHASE ORDER NUMBER	Steel grade • year of production	CROSS SECTION PROPERTY • EX: HE200A	LENGTH IN MM	WEIGHT IN KG	EXTERIOR FINISH & QUALITY • 1 = NONE • 2 = COATING • 3 = PAINT • .1 = GOOD • .2 = POOR • 0 = OTHER - COMMENTS	END CONDITION • 1 = FLAME CUT • 2 = SQUARE CUT	DEFECTS • TEMPLATE OF NUMBERS • EX: 0 = NONE • 1 = BENT • 2 = HOLES • 3 = WELDED	REPAIRS NEEDED
• IMPLEMENT TIME LIMIT ON RESERVATION? • EX: 1 YR LIMIT (COUNTDOWN ON EXCEL OF REMAINING TIME RESERVED)	• DOES THIS NEED TO BE CATEGORIZED BY CROSS SECTION TYPE AND LENGTH? • EX: ALL BEAMS HE200A OF 4000 FROM THAT PROJECT WILL BE IN ORDER 0001, 0002 AND THEN THE NEXT ONE WITH LARGER CS TYPE WILL BE 0003	• HOW IS THIS FORMATED? • WHERE DOES IT COME FROM?		• BASED ON STEEL BLUE BOOK			• IS THIS NECESSARY IF ALL COATINGS AND PAINT NEEDS TO BE REMOVED?	• WHAT ARE ALL TYPES OF END CUTS?	• WHAT ARE THE VARIOUS DEFECTS TYPES?	• THIS WOULD BE HELPFUL TO TAG EACH ELEMENT TO KNOW THE COMPLEXITY OF THE REPAIRS • NOT SURE IF THIS WOULD BE A CODE • WOULD THIS BE TIED TO THE DEFECTS? • MAYBE THIS IS A 1-5 NUMBER OF REPAIR COMPLEXITY (THE LOWER THE NUMBER THE LESS REPAIR REQUIRED)

RF:

- **C1 - Reservation**: we do have a limit but do not currently display it as it keeps varying on different jobs, ie if you agree a 3 month reservation but they ask for another month at the end as the order is certain we would likely extend. On our tubes we do not let anyone prebook ever. They have to come when they have an order to place. The reservation without sale is to encourage the market at the moment but is very messy.
- **C-2 - Identity Code**: our numbers are purely sequential, and our stock system displays by size and groups like material together so we don't need a reference in the code

- **C-3 - Purchase Order Number**: comes from our accounts system.
- **C-4 - Usage history**: this has to be recorded somewhere. We assign a batch number and then hold the information against the batch.
- **C-5 – Coatings**: we look to leave on if possible, so we display the detail.
- **C-6 – Ends**: flame cut, saw cut, plated, mixed.
- **C-7 – Defects**: bent, dented, holes, midwelds, split, lamination, out of dimension.
- **C-8 – Repair**: this depends just as much on the new application as the current condition. We do use a grade system but 1 to 10.
- **C-9 – Cost**: this is entirely variable, so I see no way of including.

This report provides insight on what was discussed during the interview. The interviewee agreed for the information discussed during this interview to be used for my Thesis Report. By signing below, they acknowledge their consent.

Signature:

Date: 10/5/23

6.2 APPENDIX B: INTERVIEW REPORTS - LAURA BATTY

Date: February 17th, 2023

Meeting Place: Online call

Interviewer: Daniela Martinez (DM)

Interviewee: Laura Batty, Associate of Technical Research & Sustainability at Heyne Tillett Steel (LB)

This document contains an interview report based on detailed notes taken during the conversation with the interviewee. The interview began with me providing an overview of my thesis topic, research, and objectives, followed by a series of questions that aimed to gather insights and perspectives on the topic of reusing steel in the building industry.

DM: Could you tell me a little bit about you and HTS?

LB: Laura is the research & innovation team leader at HTS

DM: I read an article on LinkedIn about the Steel Stock Matcher Tool that HTS is currently developing. Could you share more about what the tool does?

LB: The Matcher Tool is a Python script that analyzes a design list and finds suitable matches within the stock list.

DM: Could you share more about what the workflow (computational path) of this tool is?

LB: The Python script works within excel (runs in the background) and compares the stock list with the design list. It will begin by comparing the first value and finding a short list with sufficient length and strength. Then it finds the one where the least amount of steel will be wasted or cut off. If an element needs to be cut and the remaining part has sufficient length, the script will place the element back in the stock list.

DM: For the matching process, what are the selection criteria?

LB: The matching is based on geometrical properties and material for an efficient design. With that said, we compare carbon savings when reusing steel elements and sending the cut offs to scrap. We limit the extra weight at 30%. If the reclaimed steel exceeds the 30% limit, then it is not efficient and new steel would be more efficient.

DM: How is the input from the stock lists updated?

LB: Varies per stock company, but typically the data is updated in the excel file on a month-by-month basis. The stock companies will input information about the properties, quality and length of the reclaimed steel elements.

DM: Are you currently utilizing the Steel Stock Matcher Tool in projects with reuse steel?

LB: It is currently being tested with different projects. So far, the code runs well and it is efficient.

DM: Could you share some project case studies that have successfully reused steel elements?

LB: *Holbein Gardens* is the first commercial redevelopment steel reuse project in London. It was difficult to get the elements needed when they were needed as well as getting them tested. The frame was finished last year but the architectural completion has not been finished. This project was a learning experience for HTS and it has driven the firm to develop more of these projects. However, the process is still challenging and while we are pushing for it, some contractors have never been involved in projects with reclaimed steel elements. But we are seeing clients asking for reused steel projects.

LB: Other HTS projects include:

- *1 Exchange Square*, the refurbishment of an existing office building where we are looking to include reused steel in the vertical extension.
- *Broadgate Tower*, a ground floor timber and steel extension.
- *Woolgate Exchange*, a major office refurbishment where we are planning to incorporate reused steel on 221 out of 512 members (43%).

LB: Another example you can look at is the *Olympic Stadium* in London 2012 by Buro Happold. This project reused gas industry steel pipes.

DM: What are the challenges that you have so far encountered when reusing steel components in projects? And with this computational tool?

LB: The challenges are not necessarily technical but mostly logistical. How do you procure steel in this environment? It is difficult for people who are used to working a certain way and used to knowing what they are buying and in what quality standards. Because in this scenario, you don't know exactly what you are buying, and you have to take that risk.

LB: The following bullet point list depicts the discussed challenges Laura mentioned.

In terms of stock data:

- The basic information from the stock yard is not very detailed.
- There is information about quality and defects, but it is somewhat qualitative/descriptive and not visual as there is no available scan or 3D information of the elements in stock.

- The testing of steel elements occurs after the steel has been selected and purchased. Because of this, the properties and quality of the steel is usually unconfirmed prior to purchasing. There is usually no test information on the stock lists.
- When contractors are buying the steel and incorporating reclaimed steel and asking the architects if the list is accurate, the architects confirm the aesthetic considerations of the reused steel if necessary, as reused steel does not look "like new"
- This business model entails multiple changes of ownership of the steel elements
- Stock lists are not live – we might select beams for a project and then when we want to purchase the stock company will tell us those beams have already been purchased.
- The availability of steel components is difficult to predict.

In terms of regulations:

- There are currently no regulations on geometrical and tolerance requirements specific for reused steel. We are currently using new steel regulations, but this can be challenging to comply with when using reclaimed steel. Reference the CEN in Europe and the British Building Standards.
- Insurance companies require the steel properties of reclaimed steel to be tested and declared.

In terms of remanufacturing:

- One cannot rely on original coatings. This implies additional repairs.
- Coatings are the most intensive step in re-fabrication - no warranty if there is paint on top of existing coating.
- Bolt holes can be sliced off - in the middle of beams not a big problem - can be welded in but not necessary.
- Remaining stiffeners can remain on, they don't do anything to the performance.
- Lose concrete remains on the steel elements needs to be removed because it explodes in the furnace (this is only relevant when recycling steel as reused steel does not go in a furnace).
- There is the possibility to flip a beam (top wobbly flip it to the bottom) if there is some signs of top flange damage.
- In addition, a damaged column could be used for a beam. But a damaged beam cannot be used for a column. However, it is difficult to make general rules for this when steel is in a stockpile.

DM: Based on your experience, what are some strategies to facilitate the implementation of reclaimed steel in new projects?

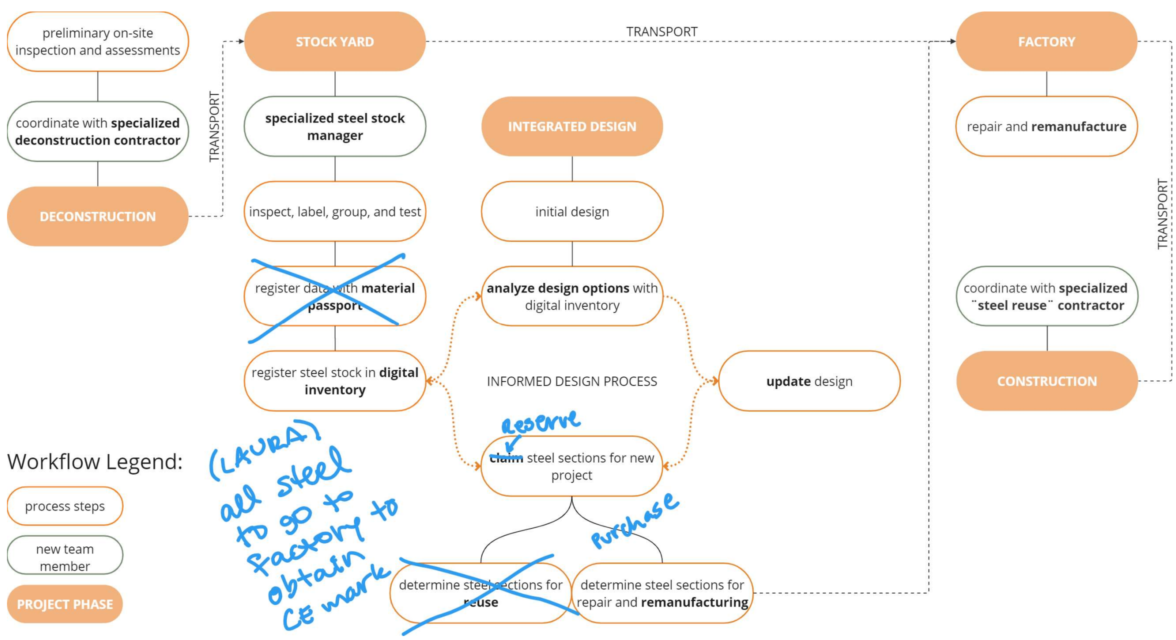
LB: Laura commented the following:

- "If you make the geometry fit the reused steel rather than the other way around, the steel wont be utilized efficiently. In my mind, the optimum process is to design the structure to its maximum efficiency, which means column grids that are not enormous, columns that are regular, and making the structural frame repetitive so that the connections can be made efficiently. Once the structure is designed efficiently, then one can look at the reclaimed stock and find elements that can fit the optimum geometry, rather than the other way around."

- Reclaimed steel should be used efficiently within industry rather than per building basis. If the reclaimed steel is not used in one project, it will get used in another project.

I then presented my workflow diagrams for the design process and computational tool. Laura provided the following feedback:

Based on my developed diagram below, Laura mentioned all steel sections are required to go to fabrication company to be CE marked and fabricated. There is never a case where the reclaimed steel purchased from the stock yard goes directly to the construction site.



[End of interview]

This report provides insight on what was discussed during the interview. The interviewee agreed for the information discussed during this interview to be used for my Thesis Report. By signing below, they acknowledge their consent.

Signature:

Date:

26/05/2023

6.2 APPENDIX B: INTERVIEW REPORTS - LAURA BATTY

Date: May 5th, 2023

Meeting Place: Online call

Interviewer: Daniela Martinez (DM)

Interviewee: Laura Batty, Associate of Technical Research & Sustainability at Heyne Tillett Steel (LB)

This document contains an interview report based on detailed notes taken during the conversation with the interviewee. The interview began with me providing an update of the work developed since the first interview on February 17th, 2023.

In regards to my developed stock list template:

DM: I am struggling to figure out how to integrate the steel grade as an input parameter in the stock list, since most of the time this information is unknown until the elements are tested. However, I think the steel grade is critical to know when designing a structure with these elements

LB: "Yeah, I think that's just the way the model works right now, because they're not going to preemptively test a bunch of stuff because it's expensive, right? So they only test it if you know it's been reserved and then you do have to go through a cycle of checking whether what you assumed in the design is actually met with the reuse piece of steel. So the way we've addressed that is basically flagging any element that is steel grade dependent. Not all the designs are steel grade dependent, but some are. This is something that I think in conversations with Roy Fishwick (CST), they think they're going to have to develop ways to quickly and cheaply estimate the grade by nondestructive hardness testing or something. And then obviously still wait until purchase or purchase order to do proper destructive testing. But CST is aware that the consumer will need to know a little bit more than they currently do, so I expect that to change on the stockholders."

DM: in what case is the structure not dependent on steel grade?

LB: If the design is controlled by deflection criteria and not strength. Most steel, for example, in generic floor arrangements are controlled by deflection and not strength.

DM: But yes, regarding the non-destructive hardness test, Swanenberg IJzer Groep, a stock company here in the Netherlands, mentioned they perform this test to get an estimate of the steel grade. So I am thinking this could be a requirement as part of my design workflow for stock companies to provide an estimate of the steel grade to later be confirmed with the testing.

LB: "Is it really a reliable way to, as steel is coming through the door and the stock yard to poke it and then get a reliable reading of the grade, it is a way. But like I said, it needs to be calibrated. But again, I think all this stuff is things that the stockholders have to figure out because yeah, like I said it, it does affect the purchase ability. I suppose if they're stuck, they need to figure out a way to get some sort of insurance. I don't know how that's going to happen, so we have to basically assume that it won't happen for a little while, you know?”

DM: Furthermore, I also removed the “quality” column from the stock list template because when speaking with CSM, a steel engineer and fabrication company, they expect the steel to come in a good condition “like new” and that they would not bear the labor and cost of doing the repairs on reclaimed beams. So based on that conversation, and assuming that no one would want to buy steel elements in poor quality, I was thinking of making the repairs part of the stock companies responsibility in my design workflow. What are your thoughts on this.

LB: “Yeah that is something else that we are struggling with. We've heard from some of the big steel work fabricators that, like you said they don't accept anything unless it's “like new” because there are mills that are so precise that they can't handle a piece that has a slight defect. And so that means that they, the steel work fabricators, would need to bear additional responsibility.

Other smaller fabricators who can do things by hand are going to be much more important in this; we are seeing larger fabricators struggle with this. So, we're seeing kind of smaller fabricators who accept that they're going to do things a little bit more labor intensive, and a little bit more by hand, so that they can deliver this product. Because in 99% of the case you're never going to get a reclaimed steel piece to be “like new.”

In regards to my developed design workflow and the responsibilities of the different project stakeholders:

DM: In terms of the repair cost and labor to make the steel elements “like new”, who do you think should be responsible for it?

LB: “I think we have to be careful not to promise “like new” steel products. The steel elements will be “like new” technically speaking but physically they wont be “like new” and there is no reason for them to be “like new” in certain scenarios. If there is any repair work that can be avoided, then it should be avoided. For example, leaving existing bolt holes or some welded plates or stiffeners, if they are not in the way. The only restriction is you cannot make a new hole within 100mm of an existing bolt hole. So, in most cases they can just be left open. There's no point of infilling existing bolt holes because it's just a waste of energy and material and it doesn't affect anything except for if it's only to fit into a hyper efficient steel mill manufacturing plant. And this will probably vary based on country and on what the steel industry looks like.”

“The only defect that that definitely needs to be rectified overall is lack of straightness. So, if the whole beam itself is bowed beyond a certain threshold and that threshold is laid out in the standards. And so that can be done, like you said, by the stockholder. The other thing that does have to be done by the stockholder is the removal of coatings.”

In regards to my developed matching tool and web platform interface:

DM: Looking at the Python script, I am doing various loop iterations to first find exact matches, and then increasing the length by 2%, then 5% and up to 10% to find close matches while controlling the cut off waste.

LB: “The waste limit is pretty well defined for reclaimed steel at 30%. Any more than 30% then you're better off reusing the element elsewhere, but 30% will give you a lot more matches because 2% is very, very stringent. Someone at another company here in the UK did a study on it and they found that 30% is the threshold.”

Laura shared the study from Elliot Wood in regards to the 30% waste threshold to utilize reclaimed steel efficiently.

DM: In addition, I am struggling to figure out what to do with the list of unmatched results in terms of optimizing the matched results. I thought of implementing a length decrease range to see if there are elements that could be of shorter lengths and this increases the match results. So for example, if I am searching for 3m span beams and tell the program to search within a 10% length decrease, it could come back and tell me that there are 40 beams with lengths at 2.8m. Then this can be updated within the design and the matching tool could be run again to check if there is a higher percentage of matched elements. Could you share your thoughts on this?

LB: “As you know, we are working on the Stock Matcher Tool with a very similar concept and are in the final stages of getting it launched. Be very careful about searching for shorter lengths and arbitrarily removing 100 or 200 millimeters off a design element, because that can have repercussions on the connection design and make the connections a lot trickier.”

“What you can do is search for an element that is 2/3 of the length that I want, and then another one that's 1/3 the length that I want because that's a good place to put a splice where you join the two beams together and make the length that you want. So that could give you a bit more flexibility when you're searching for options.”

DM: Structurally, is there any problem with creating splices?

LB: “You don’t want the splice in the middle of the element, but if its not in the middle, then it is ok. Splices can be designed. They can be a bit intense regarding connections sometimes. And if you have a very, very stringent structural zone, it can be hard to make that connection. But this is an option.”

LB: “A lot of this structural design as well as the consideration of the steel grade depends on what the structural element is doing (whether it is a column or a beam). Technically the procedure should be split between those two types of elements. Looking at an S275 and an S460, for example, they have the same deflection properties but very different compressive strength properties. So, for instance, using them in column is very different while using them in a beam would be the same. Basically, the end use is important. What you're designing the element to do is important because it will affect what I'm alternative pieces of steel are suitable.”

DM: So, you are saying that there should be a separate design list for beams and columns?

LB: “Yeah, like I said, the suitability of the match depends on the end use and that's something that again this this whole industry is not sure what to do with. And that's why us as engineers we have a big role to play in this because we know exactly what the design is and what the underlying design calculations are and we can say what is and what is not important for a certain element.”

In regards to my concept for a reservation system:

DM: After our previous conversation and after talking with stock companies, I thought of proposing a reservation system so that the project team has assurance that the steel elements they need for the designed project will be available after the design phase. In addition, the stock companies would receive a steady income for the elements being reserved. So far the feedback received about implementing this system has been positive.

LB: Who would pay the fee, the client or the deign team?

DM: I mean, technically this should be included within the contract and the client should bear the costs of the reservation fees, in my opinion. However, I am not tackling the financial challenges within my thesis research because of the constant fluctuation of steel prices. But I am proposing the reservation system as part of my strategies and proposing a time limit of 2 years.

Lastly, Laura provided a design list of a case study project, some structural calculations for beams and columns, and the study by Elliot Wood regarding the 30% waste limit for reclaimed steel.

[End of interview]

This report provides insight on what was discussed during the interview. The interviewee agreed for the information discussed during this interview to be used for my Thesis Report. By signing below, they acknowledge their consent.

Signature:

Date:

26/05/2023

6.2 APPENDIX B: INTERVIEW REPORTS - DR. MARK GORGOLEWSKI

Date: January 16th, 2023

Email Communication

Interviewer: Daniela Martinez (DM)

Interviewee: Dr. Mark Gorgolewski, Professor & Chair of the Department of Architectural Science at Toronto Metropolitan University (MG)

This document contains an email communication with the objective of gathering insights and perspectives on the topic of reusing steel in the building industry.

Introduction to Mark Gorgolewski:

Dr. Mark Gorgolewski is a renowned researcher and professor at Toronto Metropolitan University (TMU) with a specialization in building material circularity and closed-loop concepts in building design. He emphasizes the importance of designing for disassembly to enable the circularity of building components. Gorgolewski's book, "Resource Salvation: The Architecture of Reuse," delves further into these topics, providing insights and perspectives on sustainable architectural practices. In his papers, Gorgolewski explores the implications of reusing building materials, particularly steel, which often have longer lifespans than the buildings they were initially used to construct. Some of his research focuses on the environmental benefits of reusing structural steel elements and finding solutions to facilitate the use of reclaimed steel in construction. He has done several research projects in the topic of reusing structural steel with TMU and the Canadian Institute of Steel Construction (CISC). In 2012 he was the recipient of the H.A. Krentz Research Award from the CISC.

During the email communication with Gorgolewski, he shared several research papers and the following contacts that could provide some insights on this research topic:

- In the UK, the Steel Construction Institute and the Alliance for Sustainable Building Products (ASBP) have worked on steel reuse.
- Michael Sansom, Sustainability Manager at British Constructional Steelwork Association (BCSA), previously worked as an Associate Director of Sustainability at the Steel Construction Institute (SCI).
- Danielle Densley Tingley, researcher at Sheffield University
- “Sustainable Materials with Both Eyes Open” by Julian Allwood & Jonathan Cullen (2011) from Cambridge University.

DM: In your report, "Facilitating Greater Reuse and Recycling of Structural Steel in the Construction and Demolition Process", you mention the establishment of a reuse-steel.org website. I was unable to find it and was wondering if it was still active or if you still had that data.

MG: Unfortunately, the reuse-steel.org website is no longer active since the Canadian Institute of Steel Construction did not keep it updated.

[End of communication]

This report provides insight on what was discussed in the email communications. The interviewee agreed for the information discussed to be used for my Thesis Report. By signing below, they acknowledge their consent.

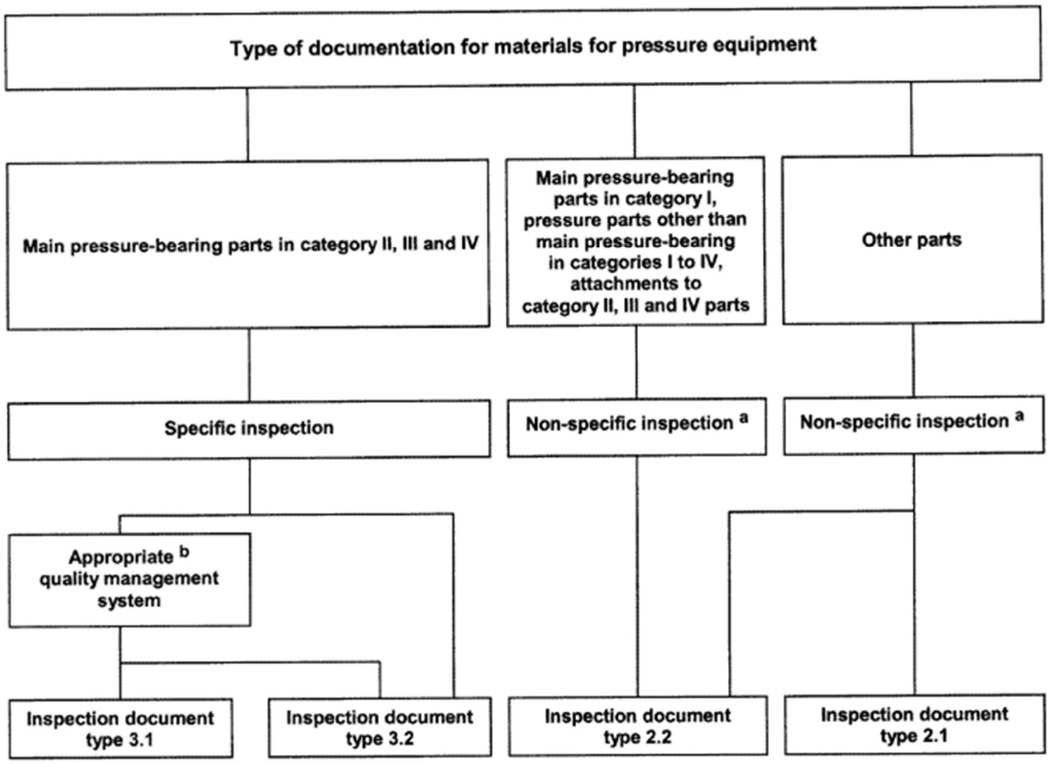
Signature: M T Gorgolewski   Date: May 17th 2023

6.3 APPENDIX C: DOCUMENTATION TO REFERENCE

Table A.1 — Summary of inspection documents

EN 10204 Reference	Designation of the document type			Document content	Document validated by
	English version	German version	French version		
Type 2.1	Declaration of compliance with the order	Werksbeschei-nigung	Attestation de conformité à la commande	Statement of compliance with the order	The manufacturer
Type 2.2	Test report	Werkszeugnis	Relevé de contrôle	Statement of compliance with the order, with indication of results of non-specific inspection	The manufacturer
Type 3.1	Inspection certificate 3.1	Abnahmeprüf-zeugnis 3.1	Certificat de réception 3.1	Statement of compliance with the order, with indication of results of specific inspection	The manufacturer's authorized inspection representative independent of the manufacturing department
Type 3.2	Inspection certificate 3.2	Abnahmeprüf-zeugnis 3.2	Certificat de réception 3.2	Statement of compliance with the order, with indication of results of specific inspection	The manufacturer's authorized inspection representative independent of the manufacturing department and either the purchaser's authorized inspection representative or the inspector designated by the official regulations

Figure 54: Table A.1 - Summary of inspection documents per EN 10204



a Non-specific inspection may be replaced by specific inspection if specified in the material standard or the order.

b Quality management system of the material manufacturer certified by a competent body established within the Community and having undergone a specific assessment for materials.

Figure ZA.1 — Conformity with Annex I section 4.3 of Directive 97/23/EC

Figure 55: Guideline to necessary inspection documents per EN 10204

8 Documentation requirements

The following data records shall be provided to or collected by the supplier:

Table 5 Documentation required by the supplier

Item	Documentation type	Additional description
Building information	Documentation prepared for the specific reclaimed steel products	Including pre-deconstruction audit, age, location, form of construction, e.g. braced or continuous, drawings, if available, etc. *Note: See item Nos.* 1 *and* 2 *in Section* 4.

The supplier shall provide the following data records to the purchaser:

Table 6 Documentation provided by the supplier

Item	Documentation type	Additional description
Survey of individual members: dimensions and visual inspection	Quality record	— Surface condition, including corrosion. *Note: See item No.* 3, 11 *and* 12 *in Section* 4. — Type and condition of the coating and any surface preparation. *Note: See item No.* 4 *in Section* 4. — Member individual identification.
	Geometry record	— Section dimensions and nominal section designation. *Note: See items No.* 7, 8 *and* 9 *in Section* 4. *See also Section* 5.2. — Length and straightness, and any straightness operations. *Note: See item No.* 10 *in Section* 4.
Inspection	Test units records	— Follow requirements given in Section 6.1 of SCI-P427. — Assign a unique identifier to each member in each test unit, e.g. using consecutive integer identifiers.
	Sampling	— Including sampling strategies for members, and the location of drilling or cutting of samples. *Note: Samples are usually selected randomly: each member of the test unit has the same probability of being sampled.*
Testing of materials	Laboratory test reports and any supplementary test(s)	— See Sections 5.3 and 6. — Nominal steel grade, see Section C.1 of SCI-P427.

Figure 56: Documentation requirements per BCSA's model specifications (BCSA, 2022)

REUSABLE STEEL ENVIRONMENTAL PRODUCT DECLARATION

IN ACCORDANCE WITH ISO 14025 AND EN 15804:2012+A2:2019

Programme
The International EPD® System
www.environdec.com

Programme Operator
EPD International AB

S-P Code
S-P-06356

Revision Date
2022.07.22

Publication Date
2022.06.27

Validity Date
2027.06.26

An EPD should provide current information and may be updated if conditions change.
The stated validity is therefore subject to the continued registration and publication at www.environdec.com

THE INTERNATIONAL EPD® SYSTEM

PRODUCT INFORMATION

This declaration is for reusable steel sections supplied for the fabrication of structural steelwork in accordance with:

Brown DG, Pimentel RJ, Sansom MR (2019). Structural steel reuse - assessment, testing and design principles (SCI-P427). The Steel Construction Institute, Ascot. SCI-P427 is founded on the principle that given appropriate determination of material characteristics and tolerances, re-fabricated reusable steelwork can be fabricated and CE marked in accordance with BS EN 1090.

Reusable steel sections are defined as individual elements recovered from and existing steel structure during its demolition/deconstruction and/or those which have been designed and fabricated for use within a defined structure which was not erected.

The types of sections declared and supplied will be detailed between EMR and the customer and will include but not be limited to Universal Beams and Universal Columns.

As the raw materials for Reusable Steels are sourced and extracted from existing structures within the urban mine, this positively increases resource efficiency whilst decreasing carbon intensity.

EMR's typical reusable steel workflow is shown below:

1 → 2 → 3 → 4 → 5

1. **Pre-demolition**
Reusable steel identification

2. **Demolition/ Deconstruction**
Careful removal of potentially reusable steel sections

3. **EMR Reusable Steel Facility**
Initial assessment, testing and characterisation

4. **Reusable Steel Manufacturing**
Removal of extraneous materials, size reduction and shot-blasting

5. **Product**
Sales and distribution of reusable steel sections

LCA INFORMATION

Declared Unit	Time Representativeness	Database(s) and LCA Software Used
1 tonne of Reusable Steel	2021	Ecoinvent 3.5, SimaPro 9.0

This EPD's system boundary is cradle to gate with options. The results of the LCA with the indicators as per EPD requirement are given in the following tables for product manufacture (A1, A2, A3), end of life stage (C1, C2, C3, C4) and benefits and load stage (D).

There is no biogenic carbon content in the reusable steel product.

The system boundaries in tabular form for all modules are shown in the table below.

	Product Stage			Construction Process Stage		Use Stage							End of Life Stage				Benefits and Loads
	Raw Material Supply	Transport	Manufacturing	Transport	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction/demolition	Transport	Waste Processing	Disposal	Future reuse, recycling or energy recovery potentials
Module	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Modules Declared	X	X	X	NR	NR	NR	NR	NR	NR	NR	NR	NR	X	X	X	X	X
Geography	GB	GB	GB	GLO	GLO	GLO	GLO	GLO	GLO	GLO	GLO	GLO	GLO	GLO	GLO	GLO	GLO
Specific Data Used	90%					–	–	–	–	–	–	–	–	–	–	–	–
Variation – Products	NR					–	–	–	–	–	–	–	–	–	–	–	–
Variation – Sites	NR					–	–	–	–	–	–	–	–	–	–	–	–

Description of the system boundary (X = Included in LCA, NR: Not Relevant)
Note: The LCA was modelled for specific product at plant so there is no variation.
Note: All primary data is taken from EMR and Ecoinvent was used for secondary data.

SYSTEM BOUNDARY

System Boundary

Out of System Boundary

A1 — Raw Material

Raw materials for resuable steels consist of steel sections extracted from demolition/deconstruction projects and fabricated sections which were never installed.

A2 — Upstream Transportation

Transport is relevant for delivery of the extracted steel to EMR Reusable Steel facility.

A3 — Manufacturing

The manufacturing phase includes de-fabrication to remove extraneous materials and cutting to enable reuse.

C1 — Deconstruction / Demolition

Electricity consumptions during the extraction of steel sections from demolition/deconstruction are considered.

C2 — Transport to Disposal Site

An average of 50 km is taken as a distance from construction site to waste processing and disposal sites

C3 — Waste Processing

Waste processing refers to the processing steps for the deconstructed steel for its final end-of-life phase. Sorting and size reduction processes are included in C3.

C4 — Disposal

Disposal is the final stage of product life and it is assumed that 96% of the steel is recycled or reused while the remainder is subjected to disposal.

D — Benefits & Loads

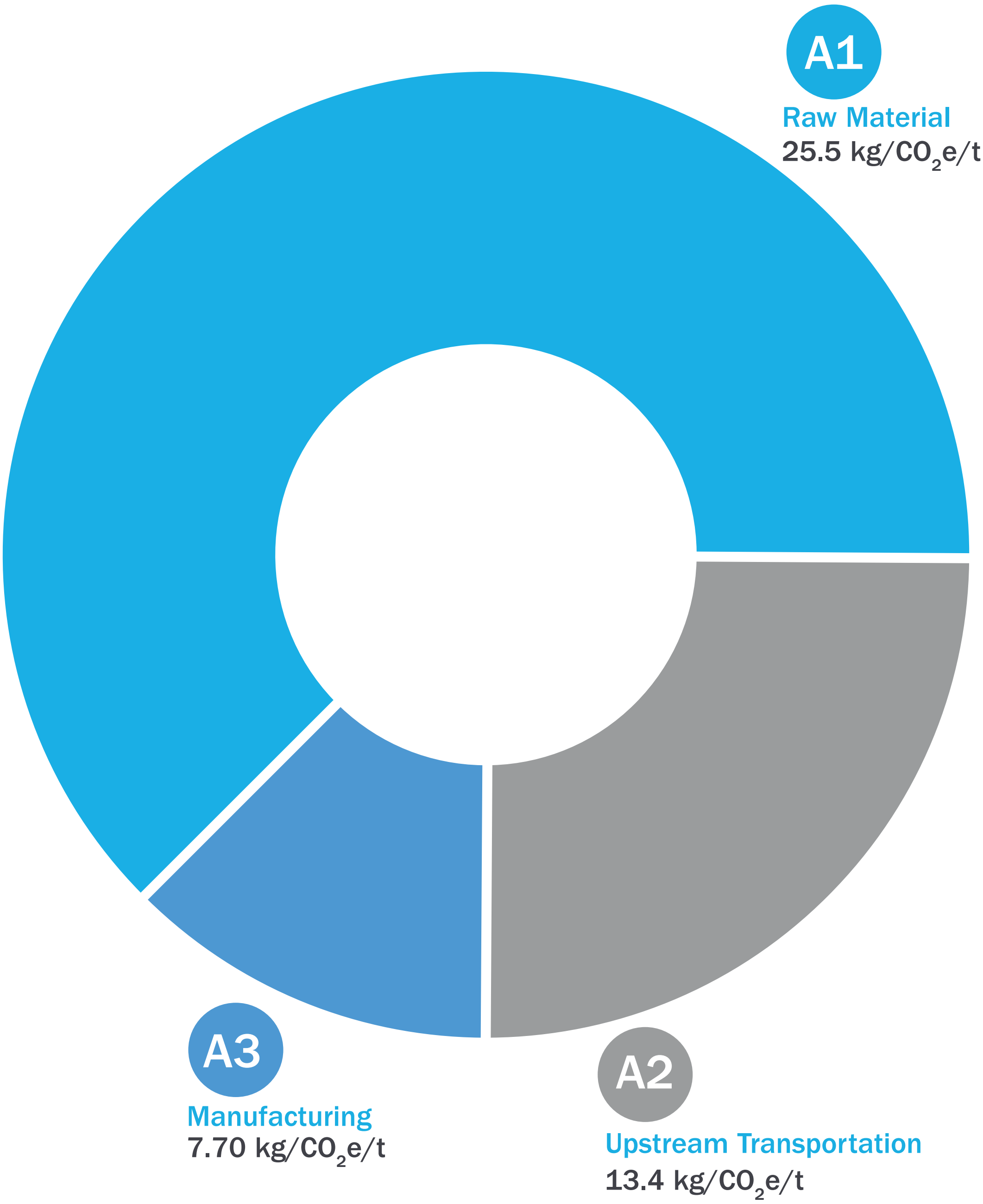
At this stage, benefits and loads from the reusable steel are calculated.

Modules A4-B7 (transport to site and the use phase) fall outside of the system boundary as these activities are undertaken by other parties in the supply chain.

THE GWP CONTRIBUTIONS

for the modules A1-A3 for our Reusable Steel product are shown below

+ + = 46.6 kg/CO_2e/t



Modules A4-B7 fall outside of the system boundary as these activities are undertaken by other parties in the supply chain.

LCA
RESULTS

LCA Results										
Impact Category	Unit	A1	A2	A3	A1-A3	C1	C2	C3	C4	D
GWP- Fossil	kg CO_2 eq	25.6	13.4	7.69	46.6	23.1	4.34	4.84	0.172	0
GWP- Biogenic	kg CO_2 eq	-0.046	0.006	0.004	-0.036	-0.041	0.002	-0.009	699E-6	0
GWP- Luluc	kg CO_2 eq	0.023	0.004	0.009	0.036	0.020	0.001	0.004	27.9E-6	0
GWP- Total	kg CO_2 eq	25.5	13.4	7.70	46.6	23.1	4.34	4.84	0.173	0
ODP	kg CFC11 eq	1.58E-6	3.25E-6	1.71E-6	6.54E-6	1.4E-6	1.08E-6	300E-9	85.6E-9	0
AP	mol H^+ eq	0.154	0.042	0.080	0.276	0.139	0.014	0.029	1.70E-3	0
*EP - Freshwater	kg P eq	0.010	0.001	433E-6	0.012	0.009	0.000	0.002	13.0E-6	0
EP - Freshwater	kg PO_4 eq	0.031	0.004	0.001	0.036	0.028	0.001	0.006	39.8E-6	0
EP - Marine	kg N eq	0.024	0.009	0.034	0.067	0.022	0.003	0.005	619E-6	0
EP - Terrestrial	mol N eq	0.259	0.096	0.378	0.733	0.233	0.033	0.049	6.88E-3	0
POCP	kg NMVOC eq	0.066	0.038	0.104	0.207	0.060	0.013	0.013	1.95E-3	0
ADPE	kg Sb eq	9.21E-6	34.9E-6	3.27E-6	4.73E-5	8.3E-6	8.41E-6	1.74E-6	184E-9	0
ADPF	MJ	489	217	112	818	442	71.9	92.7	5.70	0
WDP	m^3 depriv.	4.10	1.60	0.626	6.33	3.70	0.533	0.776	24.1E-3	0
PM	disease inc.	334E-9	1.07E-6	0.000	3.47E-6	301E-9	381E-9	63.2E-9	36.0E-9	0
IR	kBq U-235 eq	13.0	1.07	0.591	14.6	11.7	0.356	2.46	29.6E-3	0
ETP-FW	CTUe	432	154	68.7	655	390	50.1	81.7	2.93	0
HTTP-C	CTUh	6.02E-9	4.33E-9	2.33E-9	1.27E-8	5.44E-9	1.29E-9	1.14E-9	60.7E-12	0
HTTP-NC	CTUh	283E-9	180E-9	58.7E-9	5.21E-7	255E-9	59.8E-9	53.5E-9	1.65E-9	0
SQP	Pt	207	217	30.2	455	187	80.1	39.2	12	0
Acronyms	GWP-total: Climate change. GWP-fossil: Climate change- fossil. GWP-biogenic: Climate change - biogenic. GWP-luluc: Climate change - land use and transformation. ODP: Ozone layer depletion. AP: Acidification terrestrial and freshwater. EP-freshwater: Eutrophication freshwater. EP-marine: Eutrophication marine. EP-terrestrial: Eutrophication terrestrial. POCP: Photochemical oxidation. ADPE: Abiotic depletion - elements. ADPF: Abiotic depletion - fossil resources. WDP: Water scarcity. PM: Respiratory inorganics - particulate matter. IR: Ionising radiation. ETP-FW: Ecotoxicity freshwater. HTP-c: Cancer human health effects. HTP-nc: Non-cancer human health effects. SQP: Land use related impacts. soil quality.									
Legend	1: Raw Material Supply. A2: Transport. A3: Manufacturing. A1-A3: Sum of A1. A2. and A3. A4: Transport. C1: Deconstruction / Demolition. C2: Transport. C3: Waste Processing. C4: Disposal. D: Benefits and Loads Beyond the System Boundary.									
Disclaimer 1	This impact category deals mainly with the eventual impact of low dose ionizing radiation on human health of the nuclear fuel cycle. It does not consider effects due to possible nuclear accidents. occupational exposure nor due to radioactive waste disposal in underground facilities. Potential ionizing radiation from the soil. from radon and from some construction materials is also not measured by this indicator.									
Disclaimer 2	The results of this environmental impact indicator shall be used with care as the uncertainties on these results are high or as there is limited experienced with the indicator.									
*Disclaimer 3	EP-freshwater: This indicator is calculated both in kg PO_4 eq and kg P eq as required in the charactarization model. (EUTREND model. Struijs et al. 2009b. as implemented in ReCiPe; http://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml)									

LCA RESULTS

Climate Impact										
Impact Category	Unit	A1	A2	A3	A1-A3	C1	C2	C3	C4	D
GWP-GHG	kg CO_2 eq	25.2	13.3	7.62	46.1	22.8	4.30	4.78	0.172	0
Acronyms	GWP-GHG = Global Warming Potential total excl. biogenic carbon following IPCC AR5 methodology* The indicator includes all greenhouse gases included in GWP-total but excludes biogenic carbon dioxide uptake and emissions and biogenic carbon stored in the product. This indicator is thus equal to the GWP indicator originally defined * The indicator includes all greenhouse gases included in GWP-total but excludes biogenic carbon dioxide uptake and emissions and biogenic carbon stored in the product. This indicator is thus equal to the GWP indicator originally defined in EN 15804:2012+A1:2013in EN 15804:2012+A1:2013									

Resource Use										
Impact Category	Unit	A1	A2	A3	A1-A3	C1	C2	C3	C4	D
PERE	MJ	61.4	2.41	13.3	77.2	55.5	0.761	11.6	0.075	0
PERM	MJ	0	0	0	0	0	0	0	0	0
PERT	MJ	61.4	2.41	13.3	77.2	55.5	0.761	11.6	0.075	0
PENRE	MJ	489	217	112	818	442	71.9	92.7	5.70	0
PENRM	MJ	0	0	0	0	0	0	0	0	0
PENRT	MJ	489	217	112	818	442	71.9	92.7	5.70	0
SM	kg	1000	0	0	0	0	0	0	0	0
RSF	MJ	0	0	0	0	0	0	0	0	0
NRSF	MJ	0	0	0	0	0	0	0	0	0
FW	m^3	0.114	0.045	0.011	0.169	0.103	0.015	0.022	0.006	0
Acronyms	PERE: Use of renewable primary energy excluding resources used as raw materials. PERM: Use of renewable primary energy resources used as raw materials. PERT: Total use of renewable primary energy. PENRE: Use of non-renewable primary energy excluding resources used as raw materials. PENRM: Use of non-renewable primary energy resources used as raw materials. PENRT: Total use of non-renewable primary energy. SM: Secondary material. RSF: Renewable secondary fuels. NRSF: Non-renewable secondary fuels. FW: Net use of fresh water.									

Waste & Output Flows										
Impact Category	Unit	A1	A2	A3	A1-A3	C1	C2	C3	C4	D
HWD	kg	30	0	0	30	0	0	0	0	0
NHWD	kg	0	0	10	10	0	0	0	0	0
RWD	kg	0	0	0	0	0	0	0	0	0
CRU	kg	0	0	0	0	0	0	0	0	0
MFR	kg	0	0	0	0	0	0	0	0	0
MER	kg	0	0	0	0	0	0	0	0	0
EE (Electrical)	MJ	0	0	0	0	0	0	0	0	0
EE (Thermal)	MJ	0	0	0	0	0	0	0	0	0
Acronyms	HWD: Hazardous waste disposed, NHWD: Non-hazardous waste disposed, RWD: Radioactive waste disposed, CRU: Components for reuse, MFR: Material for recycling, MER: Materials for energy recovery, EE (Electrical): Exported energy electrical, EE (Thermal): Exported energy, Thermal.									
Legend	1: Raw Material Supply, A2: Transport, A3: Manufacturing, A1-A3: Sum of A1, A2, and A3, A4: Transport, C1: Deconstruction / Demolition, C2: Transport, C3: Waste Processing, C4: Disposal, D: Benefits and Loads Beyond the System Boundary.									

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