buildings

Review

Utilisation of Reused Steel and Slag: Analysing the Circular Economy Benefits through Three Case Studies

Genesis Camila Cervantes Puma [1,*], Adriana Salles [1], Janez Turk [2], Viorel Ungureanu [3,*] and Luís Bragança [1,*]

[1] Institute for Sustainability and Innovation in Structural Engineering—ISISE, Advanced Production & Intelligent Systems—ARISE, Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal; adfsalles@gmail.com
[2] Slovenian National Building and Civil Engineering Institute, Dimičeva ulica 12, 1000 Ljubljana, Slovenia; janez.turk@zag.si
[3] Civil Engineering Faculty, Department of Steel Structures and Structural Mechanics, The Politehnica University of Timișoara/Technical Sciences Academy of Romanian (ASTR), 300224 Timișoara, Romania
* Correspondence: cami_cervantes@hotmail.com (G.C.C.P.); viorel.ungureanu@upt.ro (V.U.); braganca@civil.uminho.pt (L.B.); Tel.: +351-915-845-377 (G.C.C.P.); +40-740-137-640 (V.U.); +351-966-042-447 (L.B.)

Abstract: This research explores sustainable construction practices focusing on material reuse, specifically reclaimed structural steel and slag. In general, the building stock is not designed for deconstruction, and material recovery for reuse at the end of life of buildings is complex and challenging. The study evaluates the benefits of content reuse through a thorough analysis of three case studies—BedZED eco-friendly housing, Angus Technopôle building, and the use of steel slag aggregate in road construction. It highlights the value of reclaimed structural steel and by-products like steel slag in waste reduction, energy conservation, and resource preservation. The BedZED case study showcases recycled steel's cost-effectiveness and economic viability in construction, while the Angus Technopôle building exemplifies the adaptive reuse of an old steel frame building. Additionally, the third case study showcases the benefits of using Electric Arc Furnace C slag in asphalt-wearing courses, highlighting the reduction in greenhouse gas emissions and environmental impact. The versatility of reclaimed structural steel and slag is evident in integrating material reuse in building construction and road infrastructure. These case studies illustrate the potential for reusing steel and its by-products in various construction contexts, from eco-friendly housing to road development. Therefore, the study aims to demonstrate the feasibility and benefits of sustainable practices within the construction industry by showcasing the successful incorporation of reclaimed steel and slag in these projects. Considering the significant contributions of building construction to global greenhouse gas emissions, raw material extraction, and waste production, the study advocates for adopting circular economy (CE) principles within the construction industry. Finally, the analysis of case studies underscores the advantages of reclaimed structural steel and the valorisation of steel slag through the lens of CE and their contribution to sustainable development.

Keywords: circular economy; reused steel; steel slag aggregate; reclaimed steel; steel members

Citation: Cervantes Puma, G.C.; Salles, A.; Turk, J.; Ungureanu, V.; Bragança, L. Utilisation of Reused Steel and Slag: Analysing the Circular Economy Benefits through Three Case Studies. *Buildings* **2024**, *14*, 979. https://doi.org/10.3390/buildings14040979

Academic Editor: Harry Far

Received: 20 February 2024
Revised: 27 March 2024
Accepted: 30 March 2024
Published: 2 April 2024

1. Introduction

Steel is an increasingly popular choice for sustainable construction due to its high recyclability rate. Steel is 100% recyclable and can be recycled indefinitely without losing its physical or chemical properties, making it a circular material for generations. Structural steel is 93% recycled on average [1,2], reducing the need for raw products and resource consumption. Therefore, by promoting steel reuse and recycling in construction projects, the industry can reduce its environmental footprint and contribute to a more sustainable future [3].

Steel can play a significant role in sustainable construction. It can contribute to sustainable development through various stages of a building's life cycle, including design, construction, in-use, and end-of-life phases. Steel can minimise the impact on the local community during construction and reduce waste through prefabrication. Moreover, offsite prefabrication of steel components can minimise site activity, noise, dust, pollution, and traffic congestion. This approach also reduces waste throughout design and manufacturing processes, with typical wastage rates between 1% and 4% for steel construction [3].

In the in-use phase, operational energy consumption (energy required to operate the building) is a significant concern. Steel construction can help reduce energy consumption by providing efficient building envelopes, such as insulated panels, and enabling renewable energy systems. The embodied energy of steel (the energy required to manufacture products) is relatively low compared to its operational energy, making it a sustainable choice [3].

Steel products can be easily dismantled, reused, or recycled in the end-of-life phase. Steel components can be standardised and designed for future flexibility, allowing for the extension and adaptation of buildings. This approach minimises waste and ensures the recovery and reuse of materials, contributing to sustainable development. Steel construction can offer improved energy efficiency, reduced waste generation, and the ability to adapt and extend buildings, making it a valuable material for sustainable construction [3].

Road construction is an essential aspect of infrastructure development, but it can significantly impact the environment. Sustainable road construction practices are becoming increasingly important to reduce the environmental impact associated with road construction. Reusing steel members and structures can substantially reduce the carbon footprint of road construction by reducing energy consumption, waste, embodied carbon, and transportation emissions [4]. Another approach to reduce the environmental impacts associated with road construction is to use secondary materials as a substitute for virgin materials [4]. Recycled aggregates deriving from the steel industry, e.g., electric arc furnace (EAF) slag, may represent an essential step toward achieving environmental sustainability in the road construction industry [5].

Several best practices for sustainable road construction have been developed in recent years using secondary materials such as industrial waste and by-products [6]. Carbon steel slag (EAF C) is a secondary material suitable for road construction [7]. EAF C slag is a by-product of low-carbon steel production in an electric arc furnace. Around 20 million tons of steel slag are generated annually [8], most of which are still landfilled [7]. Thus, the beneficial use of EAF C slag results in avoided burdens related to landfilling and in saving non-renewable (mineral) resources, considering applications where EAF C slag aggregate replaces high-quality silicate aggregate. The EAF slag must meet the legal conditions required for use in the construction sector. The beneficial use of these secondary materials in road construction projects reduces waste. Moreover, circular design principles are promoted with such best practices [1].

2. Literature Review

To begin, an extensive review of the literature was conducted to gain a comprehensive understanding of the current state of knowledge on circular economy and the utilisation of reused steel and slag. The review was based on seminal works in the field of CE and the reuse of steel and slag. It was expanded through three case studies using an iterative approach. This method allowed for a nuanced exploration of the relevant literature, uncovering both foundational and contemporary insights on the subject matter. As a result, users can now easily access a wide range of scientific publications and research data, facilitating the comparison and discovery of relevant information. Through this analysis, it is evident that there is a strong correlation between CE, steel, waste management, and steel slag, indicating a growing interest in CE within the construction industry. This study focuses on the reuse of steel, waste management, and their impacts on CE, which is consistent with this trend.

3. Circular Economy in Built Environment: Reuse of Steel in Buildings and Sustainable Road Construction

This paper explores the synergistic integration of reused steel in new buildings and the utilisation of steel slag in road construction as a comprehensive approach to advancing circular economy concepts in the built environment. This integrated approach encourages a holistic view of how the steel industry can contribute to circular economy principles, addressing both primary material reuse and by-product utilisation. This synergistic combination addresses resource efficiency, waste reduction, and life cycle considerations, as well as economic and environmental co-benefits.

3.1. Circular Economy

The CE is a basis for economic production and consumption that promotes the use of resources for as long as possible, minimising waste and pollution while creating new growth opportunities. In an urban context, the CE involves a shift away from traditional "take-make-dispose" models of production and consumption toward more sustainable practices, such as urban farming, renewable energy systems, and closed-loop material cycles [9].

At the policy level, the European Commission has been at the forefront of driving the CE agenda. In 2015, the European Union (EU) adopted the Circular Economy Action Plan [10], which outlines a comprehensive strategy to transition to a more sustainable economic model. The plan sets ambitious goals for waste reduction, recycling rates, and eco-design requirements. It also promotes sustainable consumption and production patterns, resource efficiency, and the development of circular business models.

The European Commission has strongly advocated for CE and has introduced policies and initiatives to support its implementation. In 2015, the European Commission launched its Circular Economy Package [10], resulting from the Circular Economy Action Plan, which includes measures to promote waste reduction, recycling, and sustainable production and consumption. The package sets targets to increase the recycling rate of municipal waste to 65% by 2030 and reduce landfilling to a maximum of 10% of all waste by the same year [10].

One key focus of the EU's CE efforts is waste management and recycling. The European Commission has implemented waste management systems and recycling targets to minimise landfilling and increase material recovery [11]. Extended Producer Responsibility schemes hold manufacturers responsible for the end-of-life management of their products, encouraging them to design for durability, reparability, and recyclability.

In addition to waste management, the European Commission emphasises the importance of resource efficiency. The European Commission encourages businesses to adopt sustainable practices through programs such as the Eco-Management and Audit Scheme (EMAS) [12] and the Energy Efficiency Directive. Resource-efficient models, such as industrial symbiosis and sharing platforms, are gaining popularity, fostering collaboration and optimising resource utilisation [12].

3.2. Reused Steel Members and Structures

Reused steel members and structures refer to repurposing and reusing steel components from existing buildings or structures in new construction projects. This involves salvaging steel members, such as beams and columns, from demolished or decommissioned buildings and incorporating them into new designs, partially or entirely [13].

Reusing steel members and structures offers several benefits, including reduced environmental impact, cost savings, and preservation of valuable resources [14]. Steel is a highly recyclable material, and the reuse of steel members helps minimise waste and reduce the energy and emissions associated with manufacturing new steel components. Moreover, reusing steel members can also provide economic advantages by lowering fabrication costs and expanding business opportunities for fabricators [1].

The process of reusing steel members involves assessing the structural integrity of the salvaged components, designing new construction projects that incorporate the reused elements, and coordinating with stakeholders such as designers, constructors, and building owners [14]. Successful steel reuse can occur through various scenarios, including reusing elements left on-site, reinforcing used structural components, or reusing a complete structure [1].

In addition to constructing new designs, steel reuse can also be applied to extend the lifespan of existing structures. This involves assessing the strength of the old frame, designing new extensions or refurbishments, and utilising the existing inventory of steel components. Reusing steel members and structures presents a sustainable and efficient approach to construction, promoting resource conservation and reducing environmental impact.

In [15], 26 case studies are presented of reusing steel at different levels, i.e., from the entire building to structural components (frames, trusses, columns, and beams) and to constituent materials (profiles and plates), reused in situ or in another site, with the same configuration or a different configuration.

In 2019, Hradil proposed a method of assessing the reusability of steel components and structures in steel-framed buildings [16]. This method evaluates the potential for reuse by analysing factors such as deconstruction and disassembly [16]. The method was tested on an industrial hall structure, which revealed that about 60% of the steel structural elements were suitable for reuse [16].

The proposed Construction Product Regulation of 2022 aims to address the issue of declaring the performance of reused building products, including constructional steel, before placing them on the market in the European Union [17]. This regulation seeks to provide guidance on the reuse of constructional steel and promote its use in the construction industry [17].

Extending the lifespan of steel structures in buildings can help minimise their environmental impact. Often, when steel structural members are demolished, they are recycled for new use [18]. However, reusing them instead can lead to even greater environmental benefits compared to producing new steel. Therefore, longevity and environmental considerations are crucial when it comes to building with steel structures [18].

In order to support greater reuse of steel structures, ref. [19] demonstrates the calculation of the economic potential and environmental impact of reused steel building elements [20]. They show the environmental benefits together with the structural feasibility of a strategy based on the reuse approach in construction for a single-storey steel industrial building. The results present that the greatest gain is achieved in the production stage when the reuse approach is adopted rather than recycling, also including significant financial benefits.

The Steel Construction Institute is currently working on a protocol to make it easier to reuse structural steel sections that have been salvaged from existing buildings. The protocol proposes a process of investigation and testing to determine the material properties of these sections, and it also provides designers with guidance on how to verify their strength. The main objective of this protocol is to maintain the quality and value of steel components for reuse [21].

When designing buildings, adaptability and disassembly should be considered. This makes it easier to reuse steel members and structures in the future. Carefully selecting materials and components and implementing design strategies for easy disassembly can increase the potential for reuse [22].

3.3. The Importance of Reused Steel in the Circular Economy

Integrating reused steel into the CE has far-reaching implications in various dimensions. First, the reuse of steel serves as a powerful mechanism for the reduction in waste by diverting materials away from landfills [23]. This proactive approach, which involves the repurposing of steel from dismantled structures or recycling processes, aligns seamlessly with the fundamental principle of CE, emphasising waste reduction and promoting sustainable resource use.

Moreover, reused steel in road construction significantly reduces its carbon footprint. Traditional steel production involves energy-intensive processes while reusing steel requires substantially less energy [24]. Beyond addressing the environmental impact of steel production, this practice aligns with the broader objectives of CE, focusing on sustainable resource use and emission reduction [25]. As such, incorporating reused steel emerges as a key strategy for the construction industry to align with environmental sustainability and circularity principles.

Furthermore, the use of reused steel underscores the importance of adopting a circular lifecycle approach in infrastructure development [2]. Structures constructed with reused steel exhibit durability and resilience, contributing to the creation of long-lasting infrastructure. After its lifecycle, reused steel can be easily repurposed or recycled, establishing a closed-loop system actively participating in resource regeneration [23]. This circular approach extends the lifespan of materials. It aligns with the CE vision of a regenerative system, where materials continually contribute to the production cycle, minimising waste and maximising resource efficiency [26]. Reused steel in road construction addresses environmental concerns and embodies a holistic approach, intertwining economic, social, and ecological sustainability within the CE framework [24].

In parallel, CE's focus on waste minimisation and resource maximisation finds a perfect application in the use of reused steel for road construction [27]. Obtained from dismantled structures or recycled steel, reused steel not only diverts materials from landfills but also decreases the reliance on virgin materials, leading to a substantial decrease in carbon emissions. The proven reliability and durability of recycled steel make it ideal for road construction and is capable of withstanding heavy traffic and adverse weather conditions [23]. Additionally, the inherent recyclability of reused steel offers a sustainable end-of-life solution, contributing to the CE by minimising waste and promoting resource regeneration [24]. Incorporating reused steel into road construction thus represents a harmonious convergence of environmental responsibility, economic prudence, and resource efficiency within the overarching framework of the CE.

3.4. Sustainable Road Construction

Sustainable road construction is essential in transportation to minimise adverse environmental and human health effects. The construction and operation of roads contribute significantly to global greenhouse gas emissions, with approximately 72% of emissions attributed to road construction, rehabilitation, maintenance, and usage [27]. To achieve sustainability in road construction, assessing and mitigating the environmental impacts of various activities and processes involved, such as earthmoving, materials production and transportation, tunnel and bridge building, and machinery and plant operation, is necessary. It is essential to evaluate and mitigate the impacts of road construction on air quality, as the transport sector accounts for nearly 14% of global greenhouse gas emissions [28].

Firstly, sustainable road construction requires a comprehensive understanding of the factors that affect adaptability, detailed strategies, and interventions to minimise environmental impacts. It involves evaluating construction processes, selecting materials and components, and implementing mitigation measures to reduce emissions and improve air quality.

Furthermore, sustainable road construction involves integrating environmentally friendly practices throughout construction. This approach aims to minimise the negative impact on the environment, reduce carbon emissions, and improve the overall sustainability of the road infrastructure [28]. One of the critical benefits of sustainable road construction is the preservation of natural resources. Reusing steel instead of virgin materials can conserve valuable resources such as iron ore and reduce the need for energy-intensive mining and extraction processes [29]. This not only helps in conserving natural resources but also reduces the associated environmental impact.

In addition to resource conservation, sustainable road construction contributes to a healthier environment [23]. Minimising pollution and reducing the carbon footprint associated with the construction industry can improve air quality and mitigate the effects of climate change [30]. This is particularly important considering the significant contribution of the transportation sector to global greenhouse gas emissions.

CE practices in road construction typically refer to in situ recycling and the use of secondary materials as a substitute for virgin materials, mainly in the sub-base layer of the road [28]. Different industrial by-products have been successfully used in road construction projects. Good practice examples refer to the use of industrial by-products/waste materials deriving from steel works such as electric arc furnace slag (EAF C) and blast furnace slag (BFS), as well as crushed concrete waste, foundry sand, and coal ash, all deriving from other industries [4,6]. These secondary materials can be used as possible replacements for natural aggregate [31]. The technical adequacy of secondary materials is required, which means that the expected pavement performance should remain the same.

Both BFS and EAF slag exhibit potential for applications in the circular economy. However, the specific applications (e.g., the extent of their reuse) can vary based on their composition and the processes involved in their production. For instance, BFS slag has a higher potential for use in concrete due to its vitrified granulates, which can partially replace natural aggregate or cement binder [4,6]. On the other hand, EAF slag, particularly EAF-C, is more commonly used as an aggregate in road construction and concrete, making it a versatile material for infrastructure development [8,32,33].

EAF steel slag discussed in this paper can vary in how it looks and behaves physically, based on the type and quality of steel scrap that enters the furnace, the kind of furnace, the grade of steel, and the methods of refinement. However, EAF slag usually has a hardness of 6–7 on the Mohs scale, even though its chemical and physical composition may differ. Chemical, physical, and mechanical properties have a direct influence on the quality of EAF C steel slag and consequently on its application [8,34]. The environmental acceptability of EAF C slag, when integrated into construction products, requires evaluation through leaching tests. Steel slags may contain potentially toxic elements, which have the potential to be released to some extent when the slag comes into contact with water [8]. The environmental acceptability of these construction products is determined by the threshold value of leached potentially toxic elements, measured in mg/kg.

EAF steel slag can be considered an artificial rock aggregate. Characteristics of this slag are high strength, good weathering resistance, and high resistance to abrasion [35]. Compared to natural aggregates, EAF slag yields better mechanical characteristics in road applications [36]. For this reason, asphalt layers containing EAF slag aggregates produce higher durability and dynamic creep modulus than asphalt layers based on natural aggregates [8]. Moreover, using EAF C slag aggregates in the asphalt wearing course results in improved skid resistance compared to the wearing course with virgin aggregates [37]. The mechanical–physical properties of EAF steel slag are very similar to those of aggregates of the highest quality natural silicate rocks. Laboratory tests show minor differences, such as a slightly increased value of water absorption in the slag, which is due to the slightly higher porosity of the slag, and in the bulk density, which is on average approximately 15 to 25% higher than that of the eruptive rocks. The bulk-specific gravity of EAF steel slag is 3.95 Mg/m^3, the resistance to fragmentation is 16%, and the water absorption (24 h) is 2.5% [37].

3.5. The Role of Reused Steel in Sustainable Road Construction

Reused steel plays a crucial role in achieving sustainable road construction. Using recycled or repurposed steel can significantly reduce the environmental impact of road development [38]. The versatility and durability of reused steel make it an excellent choice for various road components, including bridges, culverts, guardrails, and retaining walls.

One of the critical advantages of reused steel is its high strength-to-weight ratio. This allows for the construction of lighter and more efficient road structures, reducing material requirements and transportation costs [39]. Additionally, using reused steel can extend the lifespan of road infrastructure, reducing the frequency of maintenance and repair activities.

Moreover, reused steel can be easily integrated into existing road networks, making it a cost-effective solution for infrastructure upgrades and expansions. Repurposing existing steel structures can eliminate the need for extensive demolition and reduce the associated waste generation.

The EAF C steel slag considered in this study is a by-product of the SIJ Acroni steel mill, the largest Slovenian steel producer [40]. Steel is produced via two methods: the Basic Oxygen Process (BOP), which is the traditional method of steel production, and EAF steelmaking. The BOP is a traditional method that involves converting molten pig iron into steel by blowing oxygen through a lance over the molten pig iron inside a converter. This process generates exothermic heat through the oxidation reactions. During the steelmaking process, oxygen is blown through a lance into the converter containing molten pig iron. This process creates heat and removes impurities like carbon and silicon, resulting in the formation of steel. In the steelmaking process, pig iron is heated in a ladle, removing impurities such as carbon and silicon and creating steel. This pretreatment involves lowering a lance into the molten iron in the ladle and adding powdered magnesium to reduce sulphur impurities to magnesium sulphide in an exothermic reaction. The sulphide is then raked off, and similar pretreatments are possible for desalinisation and dephosphorisation. The BOP process is autogenous, meaning the required thermal energy is produced during the oxidation process. The furnace is charged with steel or iron scrap (25–30%), and molten iron from the ladle is added as required for the charge balance. The typical chemistry of hot metal charged into the BOP vessel includes carbon, silicon, phosphorus, and sulphur, all of which can be oxidised by the supplied oxygen except for sulphur, which requires reducing conditions [41,42].

EAF steelmaking, on the other hand, is a more modern method that uses electric power to melt steel scrap and pig iron. This process is significantly different from BOP in that it utilises scrap steel as its primary raw material, representing around 75% of EAF steel costs, compared to the 70–80% liquid hot metal from the blast furnace used in BOP. The EAF process is known for its lower capital investment costs compared to BOP, making it a more attractive option for new steel mills [43]. However, the choice between BOP and EAF steelmaking often depends on the specific needs and resources of the steel producer. Both methods of steel production generate by-products, including steel slag, which is a significant consideration in the environmental and economic aspects of steel production [40].

3.6. Challenges and Solutions in Implementing Reused Steel in Road Construction

While reusing steel offers numerous benefits, challenges exist in implementing this approach in road construction. A critical obstacle is the availability and quality of reused steel, as sourcing a sufficient quantity of high-quality material for large-scale projects proves challenging. The variability in steel properties and specifications further complicates the assurance of consistent quality and performance [28]. Collaboration between the construction industry, steel manufacturers, and recycling facilities is crucial to address these challenges [44]. Developing robust supply chains and quality control measures can help ensure a reliable and sustainable source of reused steel. Furthermore, advancements in technology and material testing can improve the quality and performance of reused steel, making it a more viable option for road construction [44].

Implementing reused steel in road construction brings numerous benefits but is not without challenges. A critical obstacle lies in the availability and quality of reused steel, as selecting a sufficient amount of high-quality material for large-scale projects proves challenging. The variation in steel properties and specifications further complicates the assurance of consistent quality and performance [44]. Collaborative efforts among the construction industry, steel manufacturers, and recycling facilities are crucial in addressing these challenges [44]. Establishing robust supply chains, improving quality control measures, and fostering collaboration can ensure a reliable and sustainable source of reused steel. Additionally, technological advancements and innovations in material testing play a crucial role in improving the quality and performance of reused steel, thereby making it a more viable and accepted option for road construction [28]. Overcoming these challenges is essential to fully realise the potential of reused steel, which contributes to a more sustainable CE within the construction industry.

3.7. Circular Economy Policies and Regulations for Reused Steel and Sustainable Road Construction

Policymakers and regulators play a vital role in promoting the adoption of reusable steel in sustainable road construction. Implementing supportive policies and regulations can encourage the use of reused steel and create a favourable environment for CE practices in the construction industry [25].

One practical policy approach is including sustainability criteria in public procurement processes. Governments can drive market demand and encourage industry-wide adoption by requiring reused steel and other sustainable materials in road construction projects [14]. Financial incentives, such as tax credits or grants, can motivate construction companies to embrace sustainable practices [23].

Furthermore, regulatory frameworks can be established to ensure the reused steel quality and safety standards. This can include the development of certification programs, guidelines for material testing, and standards for the design and construction of road infrastructure using reused steel. These measures ensure the reliability and performance of reused steel and provide confidence to project developers and investors [23].

Circular economy policies and regulations are crucial in promoting the adoption of reusable steel and sustainable road construction [25]. However, there are some issues and challenges that need to be addressed [25].

- Lack of Standardisation: Without standardised guidelines and regulations for the reuse of steel in road construction, implementation can be uncertain and inconsistent. Establishing standardised guidelines and certification programs can help address this issue [45].
- Limited Market Demand: Simply including sustainability criteria in public procurement processes may not effectively drive the market demand for reused steel in road construction. Stronger incentives and requirements, such as financial incentives like tax credits or grants, can motivate construction companies to embrace sustainable practices more readily [46].
- Complexity of Material Testing: Ensuring the quality and safety of reused steel components requires comprehensive material testing. Developing guidelines and standards for material testing can help ensure the reliability and performance of reused steel, providing confidence to project developers and investors.
- Limited Scope of Policies: The current policies may focus primarily on the use of reused steel in road construction, but a more comprehensive approach that considers the entire lifecycle of steel, including its production, use, and end-of-life management, can further enhance the circularity of steel in the construction industry [47].
- Lack of Collaboration and Coordination: Effective implementation of circular economy policies requires collaboration and coordination among various stakeholders. The existing policies may not adequately facilitate such collaboration, hindering the holistic adoption of circular practices in the construction industry [47].

3.8. Barriers to Implementing the Circular Economy in Construction

The literature has identified several obstacles to implementing circular economy principles in the construction industry. It is worth noting that these barriers may differ depending on the specific context and region.

- The lack of infrastructure for a circular economy is a major challenge. Many existing buildings and infrastructure do not follow circularity principles, making it difficult to retrofit them. The issues include monolithic form, absence of standards, and inadequate closed-loop supply chains [48].

- The construction sector lacks clarity and understanding of circular economy principles, hindering their promotion [49].
- The construction sector's unique industrial characteristics and the complexity of the construction value chain make implementing circular principles challenging. To overcome these challenges, integrated waste and information management systems need to be developed [49].
- Economic and market barriers are major factors that affect the adoption of circular practices in the construction industry. The cost of implementing circular strategies and the lack of economic incentives can prevent the wider adoption of circular practices [48].
- The construction industry's fragmentation hinders circular practices. Exploring new collaboration models can improve logistics for end-of-life scenarios [50].
- The implementation of a circular economy in the construction sector is hindered by the absence of a supportive policy and regulatory framework. A governance policy that comprises regulatory and tax measures can provide the necessary support for circular practices to thrive [49].
- The construction industry can benefit from implementing circular practices with the help of effective use of information and communication technologies (ICTs) and decision support tools. However, there is a need for further research and development of comprehensive information systems that take into account the complex landscape of the circular economy [51].

The building stock is not designed for deconstruction, and material recovery for reuse at the end of life of buildings is complex and challenging.

Some of the barriers that hinder the implementation of circular practices in construction include the absence of a circular economy infrastructure, limited awareness and understanding, technical difficulties, economic and market obstacles, fragmentation and collaboration issues, policy and regulatory frameworks, as well as the need for effective use of information and communication technologies. It is essential to overcome these barriers for the successful adoption of circular practices in the construction sector.

3.9. Barriers and Enablers of Circular Reused Steel Materials

Barriers and enablers of circular reuse materials play a crucial role in successfully implementing sustainable practices in the construction industry. These barriers can hold back the adoption of circular practices and require targeted strategies to overcome them. On the other hand, social and cultural enablers, organisational enablers, and financial enablers can facilitate the transition towards circular reuse materials [1].

It emphasises addressing technology, knowledge, and collaboration barriers to promote circular practices. Additionally, the lock-in of distribution channels and the unpredictable return flow of materials are significant barriers in circular practices involving remanufacturing and reusing products [15].

Transitioning to a CE in the building sector faces challenges such as limited knowledge and experience and the need for robust regulatory frameworks [52]. Overcoming these barriers requires education and awareness programs, collaboration among stakeholders, and the integration of advanced technologies.

It is important to note that these provide valuable insights into the barriers and enablers of circular reuse materials. Further research is needed to comprehensively evaluate the pros and cons of implementing circular practices in the construction industry [53]. By addressing these barriers and leveraging enablers, the industry can unlock the full potential of circular reuse materials, leading to more sustainable and resilient construction practices.

3.10. Economic and Regulatory Barriers to Reusing Steel and Slag Materials

Reusing steel and slag materials in the construction industry faces several economic barriers. A study highlights the reduction in the incidence of steel reuse despite its potential to reduce construction projects' carbon and energy impact [15]. Economic factors may play a role in limiting the reuse of steel materials. The need to standardise components can also be a technical barrier that impacts the economic reuse of construction materials, including steel [52]. This lack of standardisation can lead to increased costs and inefficiencies in the reuse process, making it less economically viable [54]. Furthermore, the availability and accessibility of reclaimed construction products, including structural steel, can be challenging. Procuring recycled materials may require additional effort and resources, which can increase costs compared to using new materials [52].

However, some enablers can help overcome these challenges. For example, financial incentives, such as cost savings from reclaimed materials, can incentivise the adoption of circular reuse practices. Additionally, technological advancements and innovative solutions can help reduce costs and improve the economic feasibility of material reuse [13].

The primary economic obstacle to implementing circular economy (CE) practices in the construction sector is the maturation needs of more developed markets. This is because there is a low demand for reused and recycled materials. The construction industry often faces criticism for being inflexible in adopting innovative practices due to the perceived risk of losing profits [52].

The adoption of CE practices in the construction industry faces a significant challenge due to the higher cost of resources associated with deconstruction compared to demolition. Virgin materials are less expensive than recycled ones, while recycling costs more than CDW disposal [55]. Circular economy practices in construction face cost challenges due to the higher expenses of deconstruction compared to demolition. Virgin materials are cheaper than recycled ones while recycling costs more than disposing of CDW [52].

On the other hand, the construction industry can benefit significantly from the integration of CE practices. Adopting new business models, evaluating assets, and prioritising material value is essential to achieve this [24]. This way, the construction industry can reap the rewards of CE practices by embracing innovative strategies, appraising their resources, and placing material value at the forefront [25]. This approach involves providing a product or service to customers as a subscription or on a pay-per-use basis rather than selling it outright [54]. The construction industry stands to gain significant advantages by embracing CE practices through the implementation of novel business models, asset assessment, and material prioritisation. A viable strategy is to make enduring investments that promote the CE business case by leveraging whole-life costing. This may include offering customers products or services on a subscription or pay-per-use basis to mitigate waste and enhance resource efficiency. Moreover, integrating CE practices can open up new revenue streams by reclaiming and reselling valuable materials from waste streams.

3.11. The Economic and Environmental Impact of Reused Steel in Road Construction

The economic and environmental impact of reusing steel in road construction is significant. Reusing steel helps conserve natural resources and reduces associated extraction and manufacturing costs by reducing the reliance on virgin materials. This, in turn, contributes to the overall economic efficiency of road construction projects [56].

From an environmental perspective, using reused steel in road construction reduces carbon emissions. Energy-intensive processes that produce virgin steel, such as mining, smelting, and refining, contribute to greenhouse gas emissions [57]. Reusing reused steel can minimise these emissions and help mitigate climate change.

In addition, the use of reused steel in road construction reduces waste generation and landfill usage. This aligns with the principles of CE, where materials are kept in use for as long as possible, minimising the need for disposal or further extraction of resources.

3.12. Maximise the Value of Steel and Slag Waste Materials

Steel and slag waste materials can be transformed into valuable resources by implementing several strategies. These materials often contain valuable metals that can be recovered through various processing techniques [40]. Steel metallics can be retrieved from slag-by-slag processors, and non-metallic steel slag can be used as a construction aggregate. Steel slag can also be used in various construction applications, such as road construction, dams, asphalt pavement, and concrete masonry [53]. In addition, steel slag can be recycled and reprocessed to produce valuable construction materials, including cement, brick, concrete aggregates, wall materials, and glass ceramic tiles [58]. These uses help reduce the need for virgin materials and provide a sustainable alternative.

Research and development efforts are focused on finding new ways to maximise the value of steel and slag waste materials [54]. Studies explore the characteristics of different types of slag and their potential for extensive use. Innovations in processing techniques and applications can further enhance the value extraction of these waste materials.

Collaboration among stakeholders, including steel producers, researchers, policymakers, and regulatory bodies, is crucial for maximising the value of steel and slag waste materials. Sharing knowledge, best practices and research findings can drive innovation and promote the adoption of sustainable waste management practices [24].

By implementing these strategies, the steel industry can transform waste materials into valuable resources, reducing waste generation, conserving resources, and contributing to a more sustainable CE [24].

3.13. The Future of Reused Steel in Sustainable Road Construction

The future of reused steel in sustainable road construction looks promising. As the demand for sustainable infrastructure grows, reusing steel usage is expected to increase [59]. The advancements in technology and material science will further enhance the quality, durability, and cost-effectiveness of reusing steel, making it an even more attractive option for road development.

Moreover, the CE approach is gaining traction worldwide, with governments and organisations recognising the importance of resource conservation and environmental sustainability [60]. This growing awareness and commitment to sustainability will drive the adoption of steel reuse and other CE practices in road construction.

Not only does reusing steel in road construction have environmental benefits, but it also provides economic advantages. The cost of producing new steel far exceeds the cost of recycling and reusing existing steel [44]. This makes reusing steel an ideal option for reducing construction expenses, which is especially attractive for public and private road construction projects in developing countries with limited budgets.

Moreover, reusing steel in road construction can also reduce carbon emissions. Steel production is highly energy-intensive and emits considerable greenhouse gases [28]. By reusing steel, we can decrease the demand for new steel production, ultimately reducing the carbon footprint of road construction projects.

The CE approach minimises waste and conserves resources, creating a closed-loop system. In road construction, this means using recycled and reused materials wherever possible, including steel. By embracing CE practices, we can reduce the waste generated by road construction projects and improve the industry's overall sustainability [30].

4. Case Studies and Best Practices

4.1. BedZED (Beddington Zero Energy Development)

BedZED is an eco-friendly housing development in Beddington, South London, that stands out for its sustainable design and commitment to reducing its environmental impact (see Figure 1). The Bioregional Development Group developed it; the project was designed to showcase innovative sustainable practices, energy efficiency, and principles of ecological urban living [61].

One of BedZED's primary goals was to create a zero-energy development by incorporating several sustainable features. These include passive solar design, energy-efficient building systems, and renewable energy sources like photovoltaic panels. BedZED also aims to reduce water consumption, promote public transportation, and foster community among its residents [62].

BedZED is a zero-energy community developed by implementing sustainable design practices, including the use of reclaimed and recycled structural steel components during construction. According to Bioregional, approximately 510 tonnes, or 15% of the total construction material used in BedZED, was reclaimed or recycled, saving energy, reducing waste, and preserving valuable resources. Consequently, this approach made BedZED a sustainable and cost-effective choice [61].

Figure 1. BedZED (source: Bioregional [62]).

BedZED's construction project stands out for its noteworthy use of reclaimed structural steel, particularly in the workspaces where load-bearing masonry incorporated these elements. During the demolition process, the BedZED team preserved these components, refurbishing and repurposing them for new buildings at the site [61].

BedZED's innovative approach to sustainable building materials and techniques highlights the practicality and cost-effectiveness of this strategy for sustainable development. Its success and exemplary sustainable design practices serve as an invaluable example for similar projects, emphasising the potential to promote ecological urban living through initiatives such as reusing reclaimed structural steel. These initiatives reduce waste, conserve energy, and preserve resources, creating a more sustainable future [62].

Steel Reused in BedZED

BedZED's project has successfully incorporated 98 tonnes of reclaimed structural steel, which represents 95% of the total structural steel used in the scheme. Throughout the construction process, the steel frames in the workspaces were the primary recipients of the reclaimed material sourced from demolition sites within a 35-mile radius [15].

In order to maintain a level of flexibility in the procurement of reclaimed sections, the engineers established a set of specifications that outlined a range of allowable section sizes for each individual component. As an added measure of adaptability, the connection details were intentionally designed to accommodate this range of section sizes [62].

Before ordering any reclaimed steel, the structural engineers carried out a thorough visual inspection of the elements and a material quality check, which involved checking its condition, date of manufacture, number and type of existing connections, and suitability for fabrication [63].

The steelwork contractor's workshop carried out the sandblasting, fabrication, and painting of all new and reclaimed structural steel sections. An extra pass through the sandblaster and treatment with a zinc-rich coating was required for the reclaimed steel [61].

While reclaimed steel was used for most sections, it was impossible to use the curved sections on BedZED. The decision was made to use new steel for these pieces. However, there is no technical reason why reclaimed steel cannot be carved in the future [64].

Reclaimed steel was 4% cheaper overall than the use of new steel on BedZED. Primarily, the variance in cost was a result of the reclaimed steel's average price standing at GBP

300/tonne, in contrast to the new steel's comparative tender price of GBP 313/tonne. Nevertheless, it is worth noting that the expense of sourcing reclaimed steel and conducting visual inspections by additional staff was evaluated at GBP 1000, rendering the use of reclaimed steel financially balanced [64].

Acquiring top-notch reclaimed structural steel necessitates a diligent search and a stroke of luck to come across the necessary materials. To safeguard the client's interests, the Construction Manager procured the reclaimed steel on their behalf. In the meantime, the structural engineer was responsible for ensuring the structural integrity of the steel and bore any associated risks [63]. Table 1 summarises the benefits associated with the use of reclaimed steel.

Table 1. BedZED's benefits.

Benefit Areas	Quantities
Reclaimed structural steel	11.5 tonnes
Embodied energy	303 GJ
CO_2 saved	21 tonnes
Reduction in eco-footprint	12.6 hectares

4.2. Angus Technopôle Building

The Angus Technopôle building is a compelling example of sustainable construction and development, achieved through the adaptive reuse of an old steel frame building (see Figure 2). This project, located in Montreal on previously developed land, utilised environmentally conscious methods to transform the area into a lively mixed-use community. Anchoring the development is the Angus Technopôle facility, originally a Canadian Pacific Railway locomotive assembly plant, which has been repurposed into the Innovation Centre of Montréal and recognised by the Québec government. Preserving the historic structure from demolition, the building boasts outstanding steel and brick architecture. Eco-friendly techniques were implemented to convert the building, including reusing the existing steel framework, showcasing open-web riveted structural members, and employing the existing exterior brick walls as screen walls. Additionally, over 85% of the materials on-site, including most of the steel, were repurposed from the previous structure, and the interior furnishings and fittings were also reused, reflecting a strong commitment to sustainability [65].

Figure 2. The Angus Technopôle building (source: Société de développement [66]).

The Angus Technopôle building was thoughtfully crafted with both environmental sustainability and the preservation of its original aesthetic in mind. Notably, the building's historic steel structure is showcased as a cherished feature. This remarkable example of sustainable building design and development has garnered numerous accolades, including LEED v4 Platinum certification for sustainable neighbourhood design and multiple National Urban Design Awards. The development plan for Technopôle Angus prioritises sustainable building construction, maintenance, and operation to cater to a range of clients, from students to families [65].

The sprawling industrial complex located at 2600 William-Tremblay Street in Montreal spanned 6.5 hectares of railway yards and featured expansive steel and brick sheds without columns. These impressive structures, over 400 m in length, were built in stages throughout the early 1900s and originally housed the locomotives produced on-site. Over the years, they played a vital role in providing employment opportunities for the local community and served as a central hub for the area. Today, the site is being repurposed into a bustling business park, breathing new life into this historic location [66].

The architects and engineers involved in the project took great care to preserve the original steel and brick structure, opting to make minimal changes in order to maintain its authenticity. In the initial phase of the project, certain portions of the 200 m long and over 50 m wide building had to be removed to make way for parking and loading areas, but the walls were left intact in many cases, serving as external screens even after the rooftops were removed. The architectural team made a conscious effort to honour the building's industrial heritage by highlighting unique features like overhead rails and lifting cranes, which were exposed in the central circulation zone. The building's large, riveted steel structures provided the flexibility necessary to accommodate the new building's purpose and lightweight steel frame additions were seamlessly integrated with the existing structure to create office and workshop spaces [5].

In order to minimise the impact of additional supports on the existing structure, the architects devised a system that relied on a limited number of new support columns placed at a distance from the building. It was also imperative to avoid any damage to the current foundations, which led to the decision to maintain the ground slab and introduce a new concrete slab. This approach proved to be a cost-effective solution, eliminating the need for excavation and disposal. The lateral bracing was reinforced by incorporating multiple vertical circulation cores along the central circulation zone, situated farther away from the original structure [15].

To maximise the use of materials and minimise waste, the architects recommended incorporating various steel and other components removed from the building as part of the design. These materials were integrated into multiple uses, such as landscaping and parking limits, although this approach posed problems during snow removal. Even the steel rails from the locomotive shop were integrated into bollards and other architectural features after straightening them [67].

Other Features

The initial intention behind the construction of the edifice was to offer expansive areas for industrial operations. However, the current architectural plan facilitates the optimal utilisation of versatile, small-scale workshops and offices that can be modified to suit the fluctuating demands of occupants. The malleable steel framework permits the inclusion of mezzanine levels and even the possibility of augmenting the number of stories if necessary [68]. The expansive roof structure provides the opportunity to add floor levels within the structural bays that easily link through the old steel roof trusses, creating exceptional spaces and views and enabling the building to evolve per the shifting demands of time [65].

The efficient use of energy was a top priority during the construction process. The building was designed to optimise cooling and ventilation, with natural lighting incorporated throughout the space. The building's layout allows for plenty of windows, and airflow is aided by a central street that acts as both a ventilation flue and a source of illumination. The building envelope was greatly improved by adding insulation to the roof and superior insulation to the outside walls and windows, which feature low-emissivity glass. The building's open design allows for free cooling during summer nights, thanks to operable, louvred windows and air extractors with skylights. In 2000, the building was selected to represent Canada in the International Green Building Challenge, where it achieved high marks for its use of eco-friendly materials and on-site amenities. A green assessment was conducted using the GBTool green rating system, and the project exceeded expectations in all areas [65]. Tables 2–4 summarise the environmental, social, and economic impacts of the Angus Technopôle building.

Table 2. Angus Technopôle building environment impact.

Environment Impact	Quantities
LEED-certified buildings	5
In energy savings thanks to energy looping	40%
Sq. Ft. Of decontaminated sites	1.6 m s.q
Ecological corridors	5

Table 3. Angus Technopôle building social impact.

Social Impact	Quantities
Social and student housing units	200
Cultural organisations becoming property owners	7
Sq. Ft. Dedicated to community health care	68.000
Daycares (cpes)	2
Units designed specifically for families	200
Vulnerable individuals reintegrated into the workplace	3000

Table 4. Angus Technopôle building economic impact.

Economic Impact	Quantities
In real estate assets	$77 m
Sq. Ft. Dedicated to social economy	40.000
Independent restaurants downtown	25
New jobs on the Saint-Laurent boulevard	1.000
Organisations and businesses	100
In payroll	$1.2 b

4.3. The Use of EAF C Slag in Road Construction

The beneficial use of steel slag aggregate (EAF C) in road construction represents good practice for preserving natural resources (e.g., high-quality natural aggregate) and removing landfills of industrial waste and by-products. However, environmental and social sustainability in the road construction sector can be improved due to the beneficial use of secondary materials such as wastes or by-products [69]. A Slovenian case study is presented as an example of best practice, considering the environmental performance of the road constructed using an artificial aggregate in the form of steel slag (EAF C) compared to the road built solely with traditional materials [5].

A Life Cycle Assessment was carried out to compare the environmental impacts of the construction of asphalt-wearing courses with the use of siliceous aggregates (the "conventional scenario") and the use of alternative steel slag aggregates (the "alternative scenario").

The main advantage of the alternative scenario is that a reduction can be achieved in the consumption of natural aggregate and the quantity of slag deposited on landfill sites. On the other hand, more bitumen is needed as a binder [5].

The slag aggregate yields a higher relative density than the silicate aggregate. For this reason, the mass of the aggregates in the asphalt ready-mix is 25% higher. Moreover, more resources are required to produce an alternative asphalt ready-mix with comparable technical specifications; carbonate aggregate mass increases by 5%, filler mass by 7%, and bitumen mass by 5% (Table 5). The higher the resource requirements, the higher the environmental burdens. Due to higher resource requirements, the mass of the ready-to-use asphalt mixture increases by 15% (Table 5) [5]. The environmental impacts associated with the delivery of resources to the asphalt plant are expected to be higher when producing alternative ready-mix asphalt. However, impacts related to the delivery of artificial steel slag aggregate may be lower than impacts associated with the delivery of silicate aggregate despite the higher mass of the former (e.g., more trucks are needed). Steel slag aggregate is produced at steel plants, usually in urban areas. At the same time, quarries of suitable quality silicate aggregate may be relatively remote from the construction works, where these aggregates are needed. The greater mass of the resources means that more energy is required to produce the alternative asphalt mix at the asphalt plant. Moreover, more trucks are required for transportation to the construction site [5].

Table 5. Raw materials and their amounts for the production of asphalt ready-mix considering baseline and alternative scenarios.

Material	Baseline Scenario (tons)	Alternative Scenario (tons)
Bitumen	15.660	16.500
Carbonate sand (0/2)	107.793	114.000
Carbonate filler	11.223	12.000
Coarse-grained aggregate (2/8)—silicate or steel slag	126.324	157.500
Final product: ready-mixed asphalt	261.000	300.000

Several disadvantages appear from the point of environmental sustainability due to all the mentioned considerations. On the other hand, the processes involved in producing steel slag aggregate are relatively less energy-intensive than the extraction of silica aggregate from a quarry. Moreover, in the case of the beneficial use of the steel slag, its disposal (e.g., landfilling) is avoided, meaning that impacts associated with landfilling are prevented. Finally, the use of secondary materials such as steel slag aggregate to substitute natural aggregate results in the preservation of non-renewable (mineral) resources [70,71].

Considering the Slovenian case study, where high-quality silicate aggregates need to be delivered from foreign countries over a relatively long distance, the use of locally available alternative raw material (e.g., artificial steel slag aggregate) in road construction projects generally reduces environmental impacts. Using local raw materials is aligned with CE and is one of the principles for reducing the global warming potential of building materials [72]. The Life Cycle Assessment results show that the limited delivery distance of the steel slag aggregate as a replacement for the siliceous aggregate is 160 km, considering the impact on the global warming potential (GWP) [5]. The alternative scenario yields lower impacts on GWP at delivery distances of the aggregate shorter than 160 km. In comparison, the baseline scenario produces lower impacts on GWP at longer delivery distances of the aggregate. Considering some other impact categories (acidification, eutrophication, human toxicity, photochemical ozone creation, and abiotic depletion potentials), the delivery distance of the aggregate should be even longer to reject favour of the alternative scenario versus the baseline scenario [5]. Such transport sensitivity analysis provides results that could be useful for road managers working on case studies using similar construction materials.

Excluding the delivery of raw materials required to produce asphalt ready-mix from system boundaries of LCA and considering only the production of raw materials and the production of the final asphalt ready-mix, the results show that GWP can be reduced by around 5% in the case of using steel slag aggregate for the production of the asphalt mix. The difference is more significant with respect to acidification, eutrophication, and photochemical ozone formation potentials in favour of the alternative scenario, as indicated in Table 6. Regarding the abiotic depletion of resources, the favour is in the baseline scenario, yielding a 4% lower impact than in the alternative scenario [5]. This is because the latter scenario requires less bitumen as a binder (see Table 6). Despite reducing the consumption of natural aggregate in the alternative scenario, bitumen consumption increases, resulting in a relatively higher impact on the abiotic depletion of resources than in the baseline scenario. The consumption of bitumen yields a significantly higher impact on the abiotic depletion of resources than the consumption of the same mass of natural aggregate [5].

Table 6. Environmental benefits of the alternative scenario (asphalt ready-mix with use of steel slag EAF C aggregate) versus baseline scenario (asphalt ready-mix with use of silicate aggregate).

Benefits Areas	Quantities
GWP reduction	5%
Reduction in acidification potential	25%
Reduction in eutrophication potential	19%
Reduction in photochemical ozone formation potential	21%

Considering the improvement in social sustainability in the road construction sector associated with the use of a locally available steel slag aggregate on asphalt-wearing courses, the stakeholder category that can benefit the most is the local community. Steel slag accumulating on waste deposit sites threatens safe and healthy living conditions. Moreover, land that could be used for more beneficial applications is occupied with waste materials. Both problems are solved with the practical use of steel slag. Society can benefit from the support of national suppliers if the primary resource (silicate aggregate) that needs to be imported from a foreign country is replaced by the locally available secondary resource (steel slag aggregate), as is the case of the presented study. Contribution to society is also related to technological progress, e.g., research to provide new technical solutions. From these points of view, the social benefits associated with the alternative scenario (e.g., the use of steel slag aggregate in asphalt-wearing courses) favour the social benefits of the baseline scenario; the latter does not provide any clear benefits to the local community, society, and workers. However, the pros and cons of the two scenarios affecting consumers and value chain actors require more in-depth research to be appropriately evaluated.

5. Discussion

The construction industry is poised to reap substantial benefits by embracing reused steel and slag management practices and promoting environmental responsibility. Strategic reuse of structural steel reduces the reliance on new production and conserves vital resources while mitigating waste generation. Additionally, incorporating steel slag aggregate in road construction emerges as a powerful strategy, offering dual benefits by saving natural resources and addressing the challenges posed by landfill burdens, thus contributing to waste disposal solutions for local communities.

This study explored the critical importance of adopting sustainable practices in the construction industry, specifically focusing on material reuse, mainly reclaimed structural steel and secondary materials, such as steel slag. Through a comprehensive analysis of three key case studies, BedZED, the Angus Technopôle building, and the integration of steel slag in road construction, a variety of environmental, economic, and social benefits have been identified, highlighting the effectiveness of these practices within the framework of a CE.

Firstly, BedZED underscores the economic viability and positive impacts on environmental sustainability of using reclaimed structural steel in construction. This practice contributes to waste reduction and plays a key role in conserving energy and preserving essential resources. The successful implementation of this strategy emphasises how material reuse can be both economically viable and environmentally responsible.

The Angus Technopôle building has provided a compelling example of the adaptive reuse of an old steel-framed structure. This transformation demonstrates the versatility and durability of reclaimed steel and emphasises the importance of maximising the life cycle of construction materials. In this case, reuse is not only a sustainable option but also one that can breathe new life into existing structures, reducing the need for new constructions.

The integration of steel slag in road construction has emerged as an effective strategy to address steel waste management and the challenges associated with landfills. This practice contributes to environmental sustainability by saving natural resources and offers practical solutions for waste disposal in local communities. Reducing the dependency on landfills by incorporating by-products, such as steel slag, into construction projects is a tangible contribution to addressing local waste management issues.

The significance of these cases goes beyond environmental benefits; they also highlight the economic and social relevance of embracing the principles of CE in the construction industry. The CE minimises ecological impact and generates cost savings through material reuse, enhances resource efficiency, promotes job creation, and stimulates economic growth through sustainable practices.

6. Conclusions

Addressing the challenges and barriers associated with their widespread adoption is imperative to fully unlock the potential of circular materials in construction. Collaboration between the public and private sectors is essential, and technological advancements are crucial to the general acceptance of sustainable practices. Additionally, establishing robust regulatory frameworks and educational initiatives focused on circular practices is fundamental to standardising approaches and ensuring consistent implementation.

Nevertheless, addressing the challenges and barriers associated with their widespread adoption is imperative to unlock the full potential of circular construction materials. Collaborative efforts, including dynamic public–private partnerships and technological advancements, play a pivotal role in driving industry-wide acceptance of sustainable and CE practices. Such collaborations foster innovation and facilitate knowledge sharing, ultimately promoting sustainability in the construction sector. In tandem, establishing robust regulatory frameworks and educational initiatives focused on circular practices is essential to standardise approaches and ensure consistent implementation.

The construction industry can implement design principles that emphasise the usage of circular materials to reduce environmental impact and fortify communities. These include designing with circularity, judiciously selecting and managing materials, and minimising construction waste. The comprehensive adoption of these principles promotes environmental stewardship and delivers tangible benefits such as cost savings, increased resource efficiency, job creation, and the stimulation of economic growth.

In order to improve circularity, careful consideration should be considered during the design process, from the types of connections employed for prefabricated and modular elements, in such a way as to ensure ease of deconstruction and facilitate reuse at the end of the building's life cycle. Design for deconstruction should concentrate on several aspects, such as (1) durability—the service life of each structural element; (2) accessibility; (3) exposed connection; (4) reversible connections; (5) interdependence; (6) avoidance of unnecessary finishes; (7) simplicity; and (8) standardisation. At the level of the building, for the future, a set of indicators has to be considered to address circularity, i.e., (1) ease of disassembly, (2) ease of reuse, and (3) ease of recycling.

The path toward a sustainable and resilient future within the construction industry is based on the optimal embrace of steel and slag management practices. Prioritising resource efficiency, fostering collaboration, nurturing innovation, and engaging stakeholders is crucial in minimising environmental impact and maximising sustainable practices. Implementing CE principles seamlessly aligns with the global sustainability agenda, steering the construction sector towards sustainability and resilience.

Within the realm of road construction, the application of CE concepts, mainly through steel reuse, promises many benefits for sustainability and resource conservation. This innovative approach has the potential to reshape the landscape of infrastructure systems, creating an eco-friendly paradigm that minimises waste, reduces carbon emissions, and fosters a healthier environment.

However, challenges persist in seamlessly integrating reused steel in road construction. These barriers can be overcome through concerted collaboration, continuous technological advancements, and supportive policies. Promising case studies and an increasing commitment to sustainability present a bright outlook for the future of reused steel in the context of sustainable road development.

In addition to the ongoing commitment to drive the adoption of reused steel and other circular economy practices, future efforts should also focus on establishing KPIs to measure and track the progress of sustainability initiatives in the construction industry. By setting clear KPIs, stakeholders can effectively monitor and evaluate their efforts, ensuring that the construction industry continues to move towards a more sustainable and resilient future.

As the process progresses, stakeholders in the construction industry, policymakers, and regulators must continue to work to drive the adoption of reused steel and other CE practices. This ongoing commitment catalyses the transformation of the trajectory of road construction, contributing significantly to creating a more sustainable world for present and future generations. Committing to sustainability and integrating CE principles should be at the forefront of decision-making processes, guiding the construction industry towards a more sustainable and resilient future.

Author Contributions: Conceptualisation, G.C.C.P. and J.T.; methodology, G.C.C.P. and A.S.; software, G.C.C.P.; formal analysis, G.C.C.P., J.T., A.S., V.U. and L.B.; investigation, G.C.C.P., J.T., A.S., V.U. and L.B.; resources, L.B.; writing—original draft preparation, G.C.C.P., J.T., A.S., V.U. and L.B.; writing—review and editing, G.C.C.P., V.U., A.S. and L.B.; visualisation, G.C.C.P.; supervision, G.C.C.P. and A.S.; project administration, V.U. and L.B.; funding acquisition, L.B. All authors have read and agreed to the published version of the manuscript.

Funding: Part of the research was financially supported by the Slovenian Research and Innovation Agency (research core funding No. P2-0273).

Data Availability Statement: Not applicable.

Acknowledgments: The authors of this article would like to thank the European Union and COST (European Cooperation in Science and Technology) for supporting the COST Action CircularB CA21103 www.circularb.eu (accessed on 31 January 2024). The authors acknowledge the support of CYTED Network ECoEICo—Circular Economy as a Strategy for a More Sustainable Construction Industry and the COST Action CircularB—Implementation of Circular Economy in the Built Environment.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Dunant, C.F.; Drewniok, M.P.; Sansom, M.; Corbey, S.; Cullen, J.M.; Allwood, J.M. Options to make steel reuse profitable: An analysis of cost and risk distribution across the UK construction value chain. *J. Clean. Prod.* **2018**, *183*, 102–111. [CrossRef]
2. Structural Steel Sustainability | American Institute of Steel Construction. Available online: https://www.aisc.org/why-steel/sustainability/ (accessed on 23 January 2024).
3. Burgan, B.A.; Sansom, M.R. Sustainable steel construction. *J. Constr. Steel Res.* **2006**, *62*, 1178–1183. [CrossRef]
4. Balaguera, A.; Carvajal, G.I.; Albertí, J.; Fullana-i-Palmer, P. Life cycle assessment of road construction alternative materials: A literature review. *Resour. Conserv. Recycl.* **2018**, *132*, 37–48. [CrossRef]
5. Mladenovič, A.; Turk, J.; Kovač, J.; Mauko, A.; Cotič, Z. Environmental evaluation of two scenarios for the selection of materials for asphalt wearing courses. *J. Clean. Prod.* **2015**, *87*, 683–691. [CrossRef]
6. Hu, W.; Shu, X.; Huang, B. Sustainability innovations in transportation infrastructure: An overview of the special volume on sustainable road paving. *J. Clean. Prod.* **2019**, *235*, 369–377. [CrossRef]
7. Faleschini, F.; Brunelli, K.; Zanini, M.A.; Dabalà, M.; Pellegrino, C. Electric Arc Furnace Slag as Coarse Recycled Aggregate for Concrete Production. *J. Sustain. Metall.* **2016**, *2*, 44–50. [CrossRef]

8. Teo, P.T.; Zakaria, S.K.; Salleh, S.Z.; Taib, M.A.A.; Mohd Sharif, N.; Abu Seman, A.; Mohamed, J.J.; Yusoff, M.; Yusoff, A.H.; Mohamad, M.; et al. Assessment of Electric Arc Furnace (EAF) Steel Slag Waste's Recycling Options into Value Added Green Products: A Review. *Metals* **2020**, *10*, 1347. [CrossRef]
9. Banjerdpaiboon, A.; Limleamthong, P. Assessment of national circular economy performance using super-efficiency dual data envelopment analysis and Malmquist productivity index: Case study of 27 European countries. *Heliyon* **2023**, *9*, e16584. [CrossRef]
10. First Circular Economy Action Plan—European Commission. Available online: https://environment.ec.europa.eu/topics/circular-economy/first-circular-economy-action-plan_en (accessed on 23 January 2024).
11. Arranz, C.F.A.; Arroyabe, M.F. Institutional theory and circular economy business models: The case of the European Union and the role of consumption policies. *J. Environ. Manag.* **2023**, *340*, 117906. [CrossRef]
12. Eco-Management and Audit Scheme (EMAS). Available online: https://green-business.ec.europa.eu/eco-management-and-audit-scheme-emas_en (accessed on 23 January 2024).
13. Fujita, M.; Iwata, M. Reuse system of building steel structures. *Struct. Infrastruct. Eng.* **2008**, *4*, 207–220. [CrossRef]
14. Bartsch, H.; Eyben, F.; Voelkel, J.; Feldmann, M. On the development of regulations for the increased reuse of steel structures. In *Life-Cycle of Structures and Infrastructure Systems*, 1st ed.; CRC Press: London, UK, 2023; pp. 1287–1294. [CrossRef]
15. Coelho, A.M.G.; Pimentel, R.; Ungureanu, V.; Hradil, P.; Kesti, J. *European Recommendations for Reuse of Steel Products in Single-Storey Buildings*; ECCS: Brussels, Belgium, 2020.
16. Hradil, P.; Fülöp, L.; Ungureanu, V. Reusability of components from single-storey steel-framed buildings. *Steel Constr.-Des. Res.* **2019**, *12*, 91–97. [CrossRef]
17. Iceberg. The New Construction Products Regulation: Opportunity for or Barrier to Reused Constructional Steel? Available online: https://iceberg-project.eu/the-new-construction-products-regulation-opportunity-for-or-barrier-to-reused-constructional-steel/ (accessed on 14 March 2024).
18. Kanyilmaz, A.; Birhane, M.; Fishwick, R.; Del Castillo, C. Reuse of Steel in the Construction Industry: Challenges and Opportunities. *Int. J. Steel Struct.* **2023**, *23*, 1399–1416. [CrossRef]
19. Vares, S.; Hradil, P.; Sansom, M.; Ungureanu, V. Economic potential and environmental impacts of reused steel structures. *Struct. Infrastruct. Eng.* **2020**, *16*, 750–761. [CrossRef]
20. Buzatu, R.; Ungureanu, V.; Hradil, P. Environmental and economic impact of steel industrial buildings made of reclaimed elements. In *Life-Cycle of Structures and Infrastructure Systems*, 1st ed.; CRC Press: London, UK, 2023; pp. 1303–1311. [CrossRef]
21. Sketchley, E. A New Protocol for Reusing Structural Steel. Planning, Building & Construction Today. Available online: https://www.pbctoday.co.uk/news/building-control-news/reusing-structural-steel/62082/ (accessed on 14 March 2024).
22. U.S. Environmental Protection Agency. Best Practices for Reducing, Reusing, and Recycling Construction and Demolition Materials. Available online: https://www.epa.gov/smm/best-practices-reducing-reusing-and-recycling-construction-and-demolition-materials (accessed on 14 March 2024).
23. Broadbent, C. Steel's recyclability: Demonstrating the benefits of recycling steel to achieve a circular economy. *Int. J. Life Cycle Assess.* **2016**, *21*, 1658–1665. [CrossRef]
24. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [CrossRef]
25. Holappa, L.; Kekkonen, M.; Jokilaakso, A.; Koskinen, J. A Review of Circular Economy Prospects for Stainless Steelmaking Slags. *J. Sustain. Metall.* **2021**, *7*, 806–817. [CrossRef]
26. Selvaraj, S.; Chan, T.-M. Recommendations for Implementing Circular Economy in Construction: Direct Reuse of Steel Structures. *J. Constr. Steel Res.* **2024**, *214*, 108439. [CrossRef]
27. Giunta, M. Sustainable Practices in Road Constructions: Estimation and Mitigation of Impact on Air Quality. *Transp. Res. Procedia* **2023**, *69*, 139–146. [CrossRef]
28. Tarimo, M.; Wondimu, P.; Odeck, J.; Lohne, J.; Lædre, O. Sustainable roads in Serengeti National Park:—Gravel roads construction and maintenance. *Procedia Comput. Sci.* **2017**, *121*, 329–336. [CrossRef]
29. Georgiou, P.; Loizos, A. Characterization of Sustainable Asphalt Mixtures Containing High Reclaimed Asphalt and Steel Slag. *Materials* **2021**, *14*, 4938. [CrossRef]
30. Branca, T.A.; Colla, V.; Algermissen, D.; Granbom, H.; Martini, U.; Morillon, A.; Pietruck, R.; Rosendahl, S. Reuse and Recycling of By-Products in the Steel Sector: Recent Achievements Paving the Way to Circular Economy and Industrial Symbiosis in Europe. *Metals* **2020**, *10*, 345. [CrossRef]
31. Schneider, P.; Ahmed, N.; Mihai, F.-C.; Belousova, A.; Kucera, R.; Oswald, K.-D.; Lange, T.; Le Hung, A. Life Cycle Assessment for Substitutive Building Materials Using the Example of the Vietnamese Road Sector. *Appl. Sci.* **2023**, *13*, 6264. [CrossRef]
32. Shatnawi, A.S.; Abdel-Jaber, M.S.; Abdel-Jaber, M.S.; Ramadan, K.Z. Effect of Jordanian Steel Blast Furnace Slag on Asphalt Concrete Hot Mixes. *Jordan J. Civ. Eng.* **2008**, *2*, 197–207.
33. Piemonti, A.; Conforti, A.; Cominoli, L.; Luciano, A.; Plizzari, G.; Sorlini, S. Exploring the Potential for Steel Slags Valorisation in an Industrial Symbiosis Perspective at Meso-scale Level. *Waste Biomass Valorization* **2023**, *14*, 3355–3375. [CrossRef] [PubMed]
34. Vlcek, J.; Tomkova, V.; Ovcacikova, H.; Ovcacik, F.; Topinkova, M.; Matejka, V. Slags from steel production: Properties and their utilization. *Metalurgija* **2013**, *52*, 329–333.
35. Commission of the European Union. *Best Available Techniques (BAT) Reference Document for Iron and Steel Production*; EU: Maastricht, The Netherlands, 2013. Available online: https://data.europa.eu/doi/10.2791/98516 (accessed on 22 January 2024).

36. Pasetto, M.; Baldo, N. Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags. *J. Hazard. Mater.* **2010**, *181*, 938–948. [CrossRef]
37. Liapis, I.; Likoydis, S. Use of Electric Arc Furnace Slag in Thin Skid–Resistant Surfacing. *Procedia-Soc. Behav. Sci.* **2012**, *48*, 907–918. [CrossRef]
38. Goli, H.; Latifi, M.; Sadeghian, M. Moisture characteristics of warm mix asphalt containing reclaimed asphalt pavement (RAP) or steel slag. *Mater. Struct.* **2022**, *55*, 53. [CrossRef]
39. Lee, H.; Peng, Y.-L.; Whang, L.-M.; Liao, J.-D. Recycled Steel Slag as a Porous Adsorbent to Filter Phosphorus-Rich Water with 8 Filtration Circles. *Materials* **2021**, *14*, 3187. [CrossRef]
40. Kvočka, D.; Šušteršič, J.; Mauko Pranjić, A.; Mladenović, A. Mass Concrete with EAF Steel Slag Aggregate: Workability, Strength, Temperature Rise, and Environmental Performance. *Sustainability* **2022**, *14*, 15502. [CrossRef]
41. Li, X.; Sun, W.; Zhao, L.; Cai, J. Material Metabolism and Environmental Emissions of BF-BOF and EAF Steel Production Routes. *Miner. Process. Extr. Metall. Rev.* **2018**, *39*, 50–58. [CrossRef]
42. Fan, Z.; Friedmann, S.J. Low-carbon production of iron and steel: Technology options, economic assessment, and policy. *Joule* **2021**, *5*, 829–862. [CrossRef]
43. Toulouevski, Y.N.; Zinurov, I.Y. EAF in Global Steel Production; Energy and Productivity Problems. In *Fuel Arc Furnace (FAF) for Effective Scrap Melting*; SpringerBriefs in Applied Sciences and Technology; Springer: Singapore, 2017; pp. 1–6. [CrossRef]
44. Hainin, M.R.; Aziz, M.M.A.; Ali, Z.; Jaya, R.P.; El-Sergany, M.M.; Yaacob, H. Steel Slag as A Road Construction Material. *J. Teknol.* **2015**, *73*, 33–38. [CrossRef]
45. Standards for the Circular Economy | ASTM Standardization News. Available online: https://sn.astm.org/features/standards-circular-economy.html (accessed on 13 March 2024).
46. The Role of Standards in the Circular Economy | NSAI. Available online: https://www.nsai.ie/standards/sectors/circular-economy-standards/ (accessed on 13 March 2024).
47. Key Players in European Standardisation—European Commission. Available online: https://single-market-economy.ec.europa.eu/single-market/european-standards/key-players-european-standardisation_en (accessed on 13 March 2024).
48. AlJaber, A.; Martinez-Vazquez, P.; Baniotopoulos, C. Barriers and Enablers to the Adoption of Circular Economy Concept in the Building Sector: A Systematic Literature Review. *Buildings* **2023**, *13*, 2778. [CrossRef]
49. Munaro, M.R.; Tavares, S.F. A review on barriers, drivers, and stakeholders towards the circular economy: The construction sector perspective. *Clean. Responsible Consum.* **2023**, *8*, 100107. [CrossRef]
50. Gasparri, E.; Arasteh, S.; Kuru, A.; Stracchi, P.; Brambilla, A. Circular economy in construction: A systematic review of knowledge gaps towards a novel research framework. *Front. Built Environ.* **2023**, *9*, 1239757. [CrossRef]
51. Yu, Y.; Yazan, D.M.; Junjan, V.; Iacob, M.-E. Circular economy in the construction industry: A review of decision support tools based on Information & Communication Technologies. *J. Clean. Prod.* **2022**, *349*, 131335. [CrossRef]
52. Dunant, C.F.; Drewniok, M.P.; Sansom, M.; Corbey, S.; Allwood, J.M.; Cullen, J.M. Real and perceived barriers to steel reuse across the UK construction value chain. *Resour. Conserv. Recycl.* **2017**, *126*, 118–131. [CrossRef]
53. Gao, W.; Zhou, W.; Lyu, X.; Liu, X.; Su, H.; Li, C.; Wang, H. Comprehensive utilization of steel slag: A review. *Powder Technol.* **2023**, *422*, 118449. [CrossRef]
54. Ayati, S.M.; Shekarian, E.; Majava, J.; Wæhrens, B.V. Toward a circular supply chain: Understanding barriers from the perspective of recovery approaches. *J. Clean. Prod.* **2022**, *359*, 131775. [CrossRef]
55. Kayikci, Y.; Kazancoglu, Y.; Lafci, C.; Gozacan, N. Exploring barriers to smart and sustainable circular economy: The case of an automotive eco-cluster. *J. Clean. Prod.* **2021**, *314*, 127920. [CrossRef]
56. Loureiro, C.D.A.; Moura, C.F.N.; Rodrigues, M.; Martinho, F.C.G.; Silva, H.M.R.D.; Oliveira, J.R.M. Steel Slag and Recycled Concrete Aggregates: Replacing Quarries to Supply Sustainable Materials for the Asphalt Paving Industry. *Sustainability* **2022**, *14*, 5022. [CrossRef]
57. Chou, C.-W.; Lin, H.-M.; Chen, G.-B.; Wu, F.-H.; Chen, C.-Y. A Study on the Fire-Retardant and Sound-Proofing Properties of Stainless Steel EAF Oxidizing Slag Applied to the Cement Panel. *Materials* **2023**, *16*, 3103. [CrossRef]
58. Bamigboye, G.O.; Bassey, D.E.; Olukanni, D.O.; Ngene, B.U.; Adegoke, D.; Odetoyan, A.O.; Kareem, M.A.; Enabulele, D.O.; Nworgu, A.T. Waste materials in highway applications: An overview on generation and utilization implications on sustainability. *J. Clean. Prod.* **2021**, *283*, 124581. [CrossRef]
59. Lewandowski, M. Designing the Business Models for Circular Economy—Towards the Conceptual Framework. *Sustainability* **2016**, *8*, 43. [CrossRef]
60. Parron-Rubio, M.E.; Kissi, B.; Perez-García, F.; Rubio-Cintas, M.D. Development in Sustainable Concrete with the Replacement of Fume Dust and Slag from the Steel Industry. *Materials* **2022**, *15*, 5980. [CrossRef] [PubMed]
61. 'BedZED', Zedfactory. Available online: https://www.zedfactory.com/bedzed (accessed on 23 January 2024).
62. BedZED—The UK's First Major Zero-Carbon Community—Bioregional. Available online: https://www.bioregional.com/projects-and-services/case-studies/bedzed-the-uks-first-large-scale-eco-village (accessed on 23 January 2024).
63. BedZED Seven Years on. Available online: www.peabody.org.uk (accessed on 29 March 2024).
64. Gorgolewski, M.; Straka, V.; Edmonds, J.; Sergio-Dzoutzidis, C. Designing Buildings Using Reclaimed Steel Components. *J. Green Build.* **2008**, *3*, 97–107. Available online: https://www.researchgate.net/publication/269493543_Designing_Buildings_Using_Reclaimed_Steel_Components (accessed on 29 March 2024). [CrossRef]

65. Société de développement Angus. Technopôle Angus Named "Best Overall" Project in Canada by Canadian Urban Institute. Available online: https://sda-angus.com/en/booklet/technopole-angus-named-best-overall-project-in-canada-by-canadian-urban-institute (accessed on 23 January 2024).
66. Société de développement Angus. Locoshop Angus. Available online: https://sda-angus.com/en/revitalize/technopole-angus/locoshop-angus (accessed on 6 February 2024).
67. Technopole Angus—Montreal. Available online: https://use.metropolis.org/case-studies/technopole-angus--montreal (accessed on 6 February 2024).
68. Technopôle Angus. Technopole Angus District—Rosemont—Montreal. Available online: https://technopoleangus.com/en/ (accessed on 6 February 2024).
69. Alhjouj, A.; Bonoli, A.; Zamorano, M. A Critical Perspective and Inclusive Analysis of Sustainable Road Infrastructure Literature. *Appl. Sci.* **2022**, *12*, 12996. [CrossRef]
70. Atta, I.; Bakhoum, E.S. Environmental feasibility of recycling construction and demolition waste. *Int. J. Environ. Sci. Technol.* **2024**, *21*, 2675–2694. [CrossRef]
71. Perkins, L.; Royal, A.C.D.; Jefferson, I.; Hills, C.D. The Use of Recycled and Secondary Aggregates to Achieve a Circular Economy within Geotechnical Engineering. *Geotechnics* **2021**, *1*, 416–438. [CrossRef]
72. Orsini, F.; Marrone, P. Approaches for a low-carbon production of building materials: A review. *J. Clean. Prod.* **2019**, *241*, 118380. [CrossRef]