POLICY IMPLICATIONS FOR FACTORS OF STEEL REUSE IN CIRCULAR CONSTRUCTION SUPPLY CHAINS: A SYSTEM THINKING PERSPECTIVE

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The construction industry consumed over half of the steel manufactured. Steel has strong credentials for circular economy for being recyclable and reusable. However, steel reuse at its end of life has been a rare practice in construction due to various barriers, compared with its recycling. This study aims to investigate causal relationships between factors influencing stakeholders' considerations for steel reuse initiatives through the lens of system thinking. It draws upon secondary data provided by the 'Delivering Innovative Steel ReUse ProjecT' database. Twenty-one factors were identified and classified into four groups with four types of intervention policies proposed. Findings showed the significance of early supply chain engagement, cost, time, and technical capability in stakeholders' decision-making. The interplay among the factors and stakeholders exhibited reinforcing feedback loops revealing that the leverage point for promoting steel reuse resides at the integration of the supply chain. Future studies may consider collecting primary data to validate the factors and the associated causal relationships and undertaking quantitative analysis using system dynamics simulation to inform policy decision-making.

Keywords: circular economy; steel; construction supply chains; reuse; system thinking

INTRODUCTION

The steel industry emitted 2.6 billion tonnes of CO2 accounting for 7% to 9% of the global carbon footprint in 2020 (World Steel Association, 2021). This impact is largely driven by the construction sector that consumes more than half (52%) of steel manufactured (World Steel Association, 2024). The International Energy Agency (2021) predicts steel demand for construction will continue to rise in the upcoming years. These facts signal a growing imperative for eco-conscious solutions to achieve Net Zero Emissions by 2050 with the concept of circular economy (CE) gaining traction in research and practices (Khalifa *et al.,* 2022). CE contributes to industrial decarbonisation by reimagining construction supply chains to create material loops thereby mitigating resource consumption through recycling, reuse, and reducing the demand for new materials (Abadi *et al.,* 2023).

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Huang, J, Abadi, M and Yeow, J (2024) Policy Implications for Factors of Steel Reuse in Circular Construction Supply Chains: A System Thinking Perspective *In:* Thomson, C and Neilson, C J (Eds) *Proceedings of the 40th Annual ARCOM Conference,* 2-4 September 2024, London, UK, Association of Researchers in Construction Management, 799-808.

Steel has strong CE credentials for its recyclability and reusability. It can be produced solely from recycled scrap or from a combination of recycled scrap and iron (Kanyilmaz *et al.,* 2023). While steel recycling saves about 50% of energy and carbon over new steel production, it still manifests considerable environmental impact in energy-intensive recycling processes (Dunant *et al.,* 2018). In contrast, reusing steel, which requires minimal physical transformation, has much lower environmental burden. For instance, new steel products embedded with 60% recycled content still have twenty-five times the environmental impact of reused equivalents (WRAP, 2008). Despite its advantages, steel reuse remains underutilised with most steel scrap being directed towards recycling. Sansom and Avery (2014) even revealed a reduction in steel reuse in the UK considering cost, market supply and demand, health and safety requirements, and project time pressure. Several studies (e.g., Densley Tingley *et al.,* 2017; Dunant *et al.,* 2017; Hartwell *et al.,* 2021; Kanyilmaz *et al.,* 2023) explored the factors influencing steel reuse, whereas possible interactions among these factors are understudied. It is of low efficacy to address each factor in isolation from the impacts of other factors, where system thinking comes into view. System dynamics presents significant potential to develop such understanding, as it enables to explore non-linear and dynamic interactions among system components (Sterman, 2002). Causal loop diagrams, the qualitative aspect of system dynamics, provide the visual representation of the relationships between steel reuse factors. These diagrams aid in the identification of cause-and-effect relationships and feedback loops as well as the development of intervention strategies. Therefore, this paper leans on secondary data derived from previous cases of steel reuse as an approach to looking back to move forward. It presents the initial phase of system dynamic modelling by developing causal-loop diagrams that unveils factors of steel reuse and their potential interrelationship to inform future practices.

LITERATURE REVIEW

Reuse of Steel Components in Construction

ISO 20887 defines reuse as "the use of products or components for more than once for the same purposes without reprocessing" (ISO, 2020), where preparation for reuse is not considered reprocessing, e.g., removal of connectors, cleaning, trimming, stripping of coatings, packaging, etc. Repurposing sometimes is also referred to as reuse in which products or components are given a new use with alternative functions (Knoth *et al.,* 2022). According to Gorgolewski (2008), building component reuse manifests in three main approaches: Adaptive reuse that repurposes an existing building; relocation that moves an existing building mostly or entirely to a new location; and reuse individual components extracted from building demolition.

Material recovery from demolition has been a long-standing research inquiry due to the massive amount of waste generated and the imperative of CE. Most of the construction and demolition waste arose from concrete, brick, masonry, and steel that are the most common building materials embedded in structural components (Hopkinson *et al.,* 2019). Reuse from steel structures gained more attention in research due to their relative ease of deconstruction (Cai and Waldmann, 2019). For instance, Ness *et al.,* (2015) used smart technologies to track structural steel and support reuse practices. Yeung *et al.,* (2015) demonstrated the role of geometric characterisation in facilitating decision-making and maximise the rate of structural steel reuse. Kitayama and Iuorio (2023) examined structural connection systems in steel-framed buildings to develop easily demountable and reusable steel members.

Despite technical advancements achieved through research, the successful implementation of steel reuse practices hinges on effective collaboration across the entire supply chain.

Challenges in Steel Reuse Supply Chain

The reuse of steel in construction, while technically feasible, faces numerous challenges that span the supply chain due to the differing roles and interest of the actors involved. Figure 1 regenerated based on ASBP (2024), Densley Tingley *et al.,* (2017), and Dunant *et al.,* (2017), presents a common supply chain model of steel recovery from demolition that depicts steel flow, and the main actors involved. Actual supply chain models could vary from different contexts with specific procurement arrangements. Sourcing reused steel could be driven by the client who reclaims from their demolished buildings with ownership over the reused steel, and by the stocklist who purchases reclaimed steel from demolition contractors for sale in the market (ASBP, 2024). The stockist undertakes the initial processing of reclaimed steel, coordinates with testing bodies for certification, and sells to the steel fabricator for reconditioning and erection.

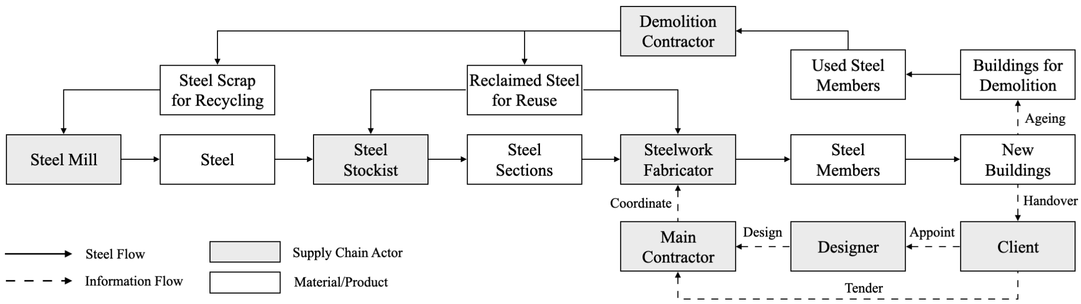


Figure 1: Steel Supply Chain Model

The observed low rate of steel reuse is indicative of the reluctance among the actors, with each having different concerns. The interviews by Dunant *et al.,* (2018) unveiled that the decision to proceed with a reused steel project typically resides with the steel fabricator. However, they are often disincentivised by the cost of labour and time involved with reconditioning and subsequent fabrication from reused steel which take about one and half times more than that of working with new steel (Dunant *et al.,* 2018), coupled with the time-consuming process of sourcing reused steel and the insecure availability of required dimensions or quantities (Densley Tingley *et al.,* 2017). Meanwhile, the consideration for demolition contractors is the absence of a well-established market for reused steel as opposed to the clear demand for steel scrap, inclining them to sell steel scrap for recycling (Dunant *et al.,* 2017). For the client, their unreceptive attitude could stem from concerns over the performance and aesthetic quality of reused components (Hartwell *et al.,* 2021). Moreover, there is a lack of industry codes of practice or standards to guide designers to work with reused steel (Hopkinson *et al.,* 2019). It is thus apparent that the widespread adoption of steel reuse necessitates a systemic approach with interventions across the supply chain.

System Thinking to Address Supply Chain Challenges

The construction supply chain exemplifies a complex system due to the large number of actors involved and their interdependencies among processes and resources, including information exchange, financial and contractual relationships (Hatmoko and Scott, 2010). System thinking is an approach that seeks to understand this complexity by focusing on wholes and interplay rather than individual parts (Anderson and

Johnson, 1997). It perceives a system as a set of interconnected elements, where any change in any element affects the set as a whole and the complexity emerges from the interactions of the elements over time (Sterman, 2002). The systemic view prompted numerous studies on improving construction supply chains, such as enablers of resilience and sustainability (Ghufran *et al.,* 2022), barriers to circularity (Abadi *et al.,* 2023), and issues in material procurement and logistics (Bajomo *et al.,* 2022).

Embracing CE at the supply chain level features greater complexity as a result of additional actors involved and the need for wider acceptance of new methods of working (Abadi *et al.,* 2023). As reflected in Figure 1, the initiative for steel reuse is unable to proceed if one single actor in the supply chain shows unwillingness (Dunant *et al.,* 2017). Nonetheless, the construction industry is intrinsically characterised by fragmentation giving rise to the deficiency in communication and coordination across the supply chain which is commonly highlighted as a pivotal obstacle to steel reuse (Densley Tingley *et al.,* 2017; Dunant *et al.,* 2017). This could cause other ripple effects, such as low market maturity of reused steel, lack of trust among the actors, and discontinuity of design changes, which further escalate the industrial fragmentation forming a feedback loop. These causal relations entail a system-wide perspective that not only addresses concerns from each actor but also identifies potential interrelationships among these concerns to devise more effective intervention strategies.

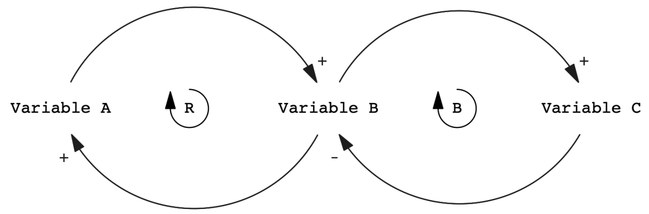
METHOD

This study adopted a system thinking of the factors associated with steel reuse supply chains and draws upon secondary data to develop the qualitative aspect of system dynamics (i.e. causal loop diagrams). System dynamics originates from the theory of nonlinear dynamics and feedback control in mathematics, physics, and engineering (Sterman, 2002). It has gained increasing traction in management research that contributes to the analysis of system complexity arising from the dynamic interplay among the constituent elements, and the design of intervention strategies to improve systems' performance (Li *et al.,* 2014). The two main tools in system dynamics are causal loop diagrams and stock-flow diagrams. The former establishes a qualitative structure revealing causal relationships and feedback loops within a system, built on which the latter defines different types of variables for quantitative simulation.

Feedback is one of the main features of system thinking that assists the interpretation of causal loop diagrams (Sterman, 2002). It recognises that one cause leads to an effect that will, in turn, affect the cause in various ways resulting in the emergency of circular paths (also known as feedback loops). Reinforcing (or positive) feedback loops amplify system changes and accelerate growth or decline, whereas balancing (or negative) feedback loops counteract the changes and seek equilibration. Figure 2 illustrates a system comprising the two types of feedback loops ("R" for reinforcing loops and "B" for balancing loops). The arrows denote the causal relationships between variables, with the symbol "+" and "-" signifying whether the variables change in the same or the inverse direction, respectively.

The secondary data was retrieved from the database of the Delivering Innovative Steel ReUse ProjecTs (DISRUPT) project led by the Alliance for Sustainable Building Products (ASBP, 2024). The project has yielded a rich data source that provides stakeholders across the steel supply chain with guidance, a knowledge base, and case studies to boost steel reuse in the construction industry. With the supplement of the literature, the database offered invaluable insights into supply chain models for steel reuse, critical factors of steel reuse considered by different actors, and causal relationships among these factors. These informed the development of causal loop diagrams that illustrate the complexity, feedback loops, and dynamics associated with the uptake of steel reuse at the supply chain level.

Figure 2: Causal Loop Diagram



FINDINGS

Summary of Steel Reuse Cases

The DISRUPT project database, accessed in March 2024, documents eleven steel reuse case studies (nine successes and two failures). Cases that managed to incorporate reused steel in new construction and yielded embodied carbon savings were deemed successful in the database, whereas cases that explored the possibility but failed to embed reused steel in design due to time/cost constraints or insufficient information on reused steel were deemed unsuccessful. Table 1 presents the nine successes that cover different project types, sizes, and procurement routes. Irrespective of the initiators, all reuse initiatives were strongly supported by the client to fulfil CE goals and low-carbon commitments. Most reused steel is procured from the stockist with some supplied by demolition, especially when the client has ongoing demolition projects or established partnerships with demolishers.

Table 1: Successful Steel Reuse Cases

No	Project Information	Initiator	Source	Amount of Steel Reused
1	Warehouse retrofit	Client	Demolition, stockist	20.35 tonnes
2	Public artwork	Designer	Stockist	33.46 tonnes
3	Town centre redevelopment	Contractor	Stockist	At least 96 tonnes
4	Office building refurbishment	Client	Demolition, stockist	24 tonnes
5	1950s office block extension	Client	Stockist	21 tonnes
6	Agricultural building	Designer	Stockist	17 tonnes
7	Domestic refurbishment	Client	Stockist	1.45 tonnes
8	Subsea cable ducts	Client	Stockist, mill	136 tonnes
9	Building canopy	Client	Stockist	3.79 tonnes

Factors of Stakeholder Considerations

The analysis of the cases revealed twenty-one factors affecting stakeholders' decision-making on steel reuse initiatives. These factors were identified from the 'lessons learnt' reports of the cases, and then they were classified into four groups, see Table 2. Moreover, the database provided a checklist of stakeholders' roles and responsibilities, which helped map them against the identified factors. The client and designer exhibit greater engagement in strategy and planning with a critical role in initiating the idea of steel reuse in their projects. The designer shows extensive involvement in both the conceptual and practical aspects of steel reuse, as evidenced by the highest number of factors involved. It is also worth noting that, for demolishers, the repurpose or retrofit of end-of-life buildings should be first considered before demolition, given the more favourable environmental implications. Moreover, early engagement, cost, and time are shared concerns for all stakeholders. Most of the case projects have demonstrated early engagement across the supply chain partners to establish the viability of steel reuse. While reused steel typically costs less than new steel, a potential increase may result from design iterations, testing, reconditioning, transportation, and additional labour which may also extend the timeline. Nonetheless, the uptake of reused steel in the case projects has either yielded economic savings or reached a cost-neutral outcome, and not caused any delay because of the early engagement that secured the availability of reused steel.

Table 2: Factors Affecting Stakeholders' Consideration of Steel Reuse

Category	Factors	Client	Designer	Fabricator	Stockist	Demolisher
Strategy and Planning	Early engagement	x	x	x	x	x
	Pre-demolition audit	x	x			
	Circular economy goal	x	x			
	Low-carbon solution	x	x			
	Local development strategy	x				
	End-of-life building repurpose					x
Supply Chain Operation	Availability of reused steel	x	x	x	x	
	Storage		x		x	x
	Demand for reused steel				x	x
	Effective communication		x			
	Transportation		x			x
	Recondition			x	x	
Project Management	Cost	x	x	x	x	x
	Timeframe	x	x	x	x	x
	Test and certification				x	
	Health and Safety					x
	Material record		x		x	
Design and Technology	Aesthetics	x	x	x		
	Specify steel reuse		x			
	Design with reused steel			x		
	Technical capability		x	x	x	x
Number of Factors Affecting Considerations		9	14	8	10	10

Causal Relationships among Factors

Figure 3 reveals the causal relationships between the identified factors concerned by stakeholders. Echoing previous discussions, timeframe, cost, and availability are the key effect factors connected with a range of causal factors. An extension in timeframe incurs an escalated cost, whereas it potentially improves the access to reused steel that becomes progressively available following demolition activities over time. The main causal factor is technical capability in terms of design, material salvage infrastructure, and material reprocessing. Its significance has been demonstrated in the case projects, where a digital tool was developed by the designer that facilitated matching the available reused steel with design requirements and enhanced communication with the stockist. This corresponds to existing research endeavours to promote the technical ease of steel reuse, e.g., integration of new technologies (Ness *et al.,* 2015), and demountable connection systems (Kitayama and Iuorio, 2023).

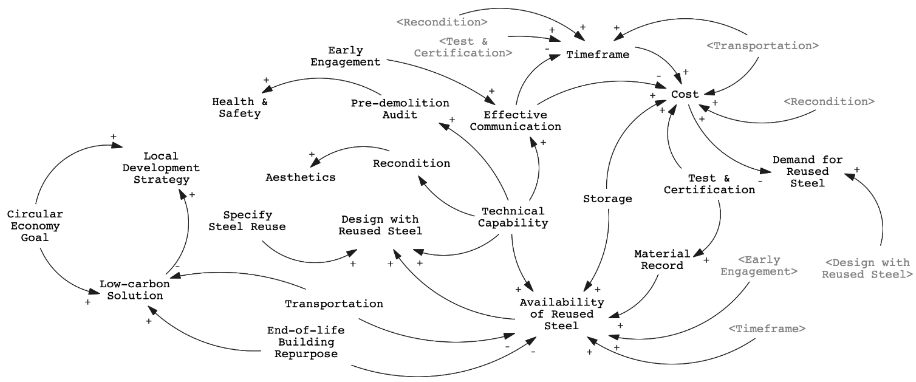


Figure 3: Cause-and-effect Relationships among the Factors

Feedback Loops in Steel Reuse Supply Chain

The circulation of reused steel presented in Figure 1 is regulated by the flow of information in terms of supply and demand across the supply chain. Figure 4 depicts the flow of information and the structure of the interactions between the key actors in the supply chain, representing the supply and demand sides, concerning steel reuse opportunities. It shows five reinforcing loops: R1 denotes the main loop of information flow, while R2-R4 represent supporting loops. These loops indicate a synergistic cycle where actors' growing considerations amplify supply and demand, thereby strengthening the overall process of steel reuse, and vice versa. R2 and R3 emphasize the stockist's pivotal role in boosting demand from steel fabricators and supply from demolishers, further supported by R4 and R5 respectively. This corroborates the suggestions by Dunant *et al.,* (2018): Steel fabricators take on some functions of the stockist to hold and recondition steel from reuse, thus raising the demand (R4) and hurdling opportunity cost; steel stockists store large amounts of steel for long periods to prolong availability (R5) and allow exploiting the fluctuations of steel price. In short, the success of steel reuse stems from the collective willingness and a tightly integrated supply chain.

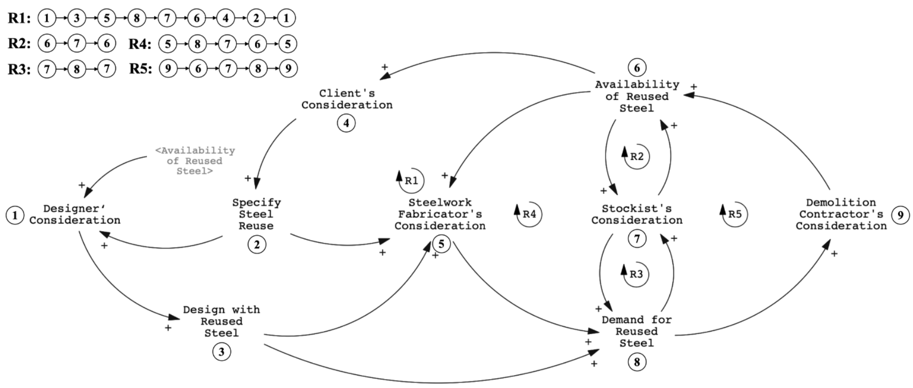


Figure 4: Information Loops Driven by Supply and Demand

Reflecting on previous sections, a holistic picture is formulated using VensimPLP based on: Table 2 that connects the identified factors with stakeholder considerations; Figure 3 that maps the causal relations among the factors; Figure 4 that visualises the connections between stakeholder considerations. This reveals the systemic and complex nature of encouraging steel reuse initiatives. However, there were no additional major feedback loops identified from the intricate structure, indicating that the leverage point for promoting steel reuse resides at the supply chain level as represented by R1-R5. It conforms with the interview results of Densley Tingley *et* *al.,* (2017) where supply chain dynamics is the most frequently mentioned barrier to steel reuse. A coordinated set of activities thus become imperative to strengthen communication and collaboration across the whole supply chain for consolidating steel reuse as a common practice (Dunant *et al.,* 2017; Kanyilmaz *et al.,* 2023). Despite recognising its significance, supply chain coordination remains hindered by the fragmented nature of the industry, with numerous SMEs operating independently on a project-by-project basis. Addressing this issue requires high-level interventions from authorities to influence the broader industry environment.

Policy Implications

Policy governance is a potent catalyst to create a demand-pull environment and shape circular construction supply chains (Abadi *et al.,* 2023). The feedback loops identified can be reinforced with policy intervention by addressing different factors. As informed by Huang *et al.,* (2023), policy instruments can be enacted in four main forms, including economic incentives, legislative control, public leadership, and supporting activities. First, fiscal tools may involve tax relief on the procurement of reused steel, subsidising design for deconstruction, investment into small businesses to stock and recondition reclaimed steel, and research funds for advancing technical capabilities. Second, design for deconstruction can be incorporated into local planning regulations to cultivate a market conducive to steel reuse. Third, the authority could mandate a certain percentage of steelwork comprising reused steel in public procurement and undertake demonstration projects to exemplify the role of steel reuse in the gravitation towards net-zero commitments. Fourth, industry-wide workshops targeting steel reuse could be arranged in collaboration with research institutes to increase knowledge sharing, foster communication across supply chain stakeholders, and develop best-practice guidelines. An official register could be created for reused steel suppliers, powered by digital platforms to match the available stock with design specifications, such as the HTS Stockmatcher.

CONCLUSIONS

This paper investigated the factors influencing stakeholders' considerations for steel reuse initiatives through the lens of system thinking. It draws upon secondary data provided by the DISRUPT project database to develop causal relationships among the factors relevant to different stakeholders. Twenty-one factors were identified and classified into four groups with four types of intervention policies proposed. Early engagement, cost, and time are the shared concerns for all stakeholders, with early engagement demonstrated in all successful case projects, and cost and time being the key effect factors influenced by other causal factors. The major causal factor is technical capability in terms of design, material salvage infrastructure, and material reprocessing. Analysis of stakeholder considerations exhibits reinforcing feedback loops, revealing that the leverage point for promoting steel reuse resides at the supply chain level. Early involvement of all relevant stakeholders should be encouraged in the planning and design phases to ensure that reuse considerations are integrated from the outset and that all parties are aligned towards the same goal. This collaboration could be fostered by interventions from authorities by providing economic incentives, introducing regulations, and leading demonstration projects and industry-wide workshops. The main contribution of this study lies in its visualisation of the complexity involved in promoting steel reuse, thus equipping policymakers with a holistic understanding that recognises the interrelationships among various factors which is essential in devising high-leverage policies. However, other potential factors or causal relationships could have been overlooked. Future research could consider conducting interviews to supplement the factor list, validate the interrelationships, and use surveys to assess the causal relationships to develop the stock and flow diagram for simulation underpinned by the qualitative causal-loop diagram. The simulation will reveal the level of the interplay among factors within the system and their aggregate influence on the overall system behaviour, based on which the factors can be prioritised and addressed with relevant intervention policies.

REFERENCES

Abadi, M, Huang, J, Yeow, J, Mohandes, S R and Zhang, L (2023) Towards a complex push-to-pull dynamics in circular construction supply chains: A systematic literature review, *Engineering, Construction and Architectural Management*, [ahead-of-print].

Anderson, V and Johnson, L (1997) *Systems Thinking Basics from Concepts to Causal Loops*, MA: Pegasus Communications.

ASBP (2024) *Delivering Innovative Steel Reuse Project Steel Reuse Toolkit*, Available from: https://asbp.org.uk/toolkit/disrupt-steel-reuse [Accessed 28 July 2024].

Bajomo, M, Ogbeyemi, A and Zhang, W (2022) A systems dynamics approach to the management of material procurement for Engineering, Procurement and Construction industry, *International Journal of Production Economics*, **244**, 108390.

Densley Tingley, D, Cooper, S and Cullen, J (2017) Understanding and overcoming the barriers to structural steel reuse, a UK perspective, *Journal of Cleaner Production*, **148**, 642-652.

Dunant, C F, Drewniok, M P, Sansom, M, Corbey, S, Allwood, J M and Cullen, J M (2017) Real and perceived barriers to steel reuse across the UK construction value chain, *Resources, Conservation and Recycling*, **126**, 118-131.

Dunant, C F, Drewniok, M P, Sansom, M, Corbey, S, Cullen, J M and Allwood, J M (2018) Options to make steel reuse profitable: An analysis of cost and risk distribution across the UK construction value chain, *Journal of Cleaner Production*, **183**, 102-111.

Ghufran, M, Khan, K I A, Ullah, F, Alaloul, W S and Musarat, M A (2022) Key enablers of resilient and sustainable construction supply chains: A systems thinking approach, *Sustainability*, **14**(19), 11815.

Gorgolewski, M (2008) Designing with reused building components: Some challenges, *Building Research and Information*, **36**(2), 175-188.

Hartwell, R, Macmillan, S and Overend, M (2021) Circular economy of façades: Real-world challenges and opportunities, *Resources, Conservation and Recycling*, 175, 105827.

Hatmoko, J U D and Scott, S (2010) Simulating the impact of supply chain management practice on the performance of medium-sized building projects, *Construction Management and Economics*, **28**(1), 35-49.

Hopkinson, P, Chen, H.-M, Zhou, K, Wang, Y and Lam, D (2019) Recovery and reuse of structural products from end-of-life buildings, *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, **172**(3), 119-128.

Huang, J, Abadi, J and Yeow, J (2023) Policies for the transition to circular construction: A systematic literature review *In:* Tutesigensi, A and Neilson, C J (Eds) *Proceedings of the 39th Annual ARCOM Conference,* 4-6 September 2023, University of Leeds, Leeds, UK, Association of Researchers in Construction Management, 741-750.

International Energy Agency (2021) *Global Steel Demand for Building Construction, 2000-2020 and in the Net Zero Scenario, 2025-2030*, Available from: https://www.iea.org/data-and-statistics/charts/global-steel-demand-for-building-construction-2000-2020-and-in-the-net-zero-scenario-2025-2030 [Accessed 28 July 2024].

ISO (2020) *ISO 20887:2020 Sustainability in Buildings and Civil Engineering Works—Design for Disassembly and Adaptability-Principles, Requirements and Guidance*, Available from: https://www.iso.org/obp/ui/en/#iso:std:iso:20887:ed-1:v1:en [Accessed 28 July 2024].

Kanyilmaz, A, Birhane, M, Fishwick, R and Del Castillo, C (2023) Reuse of steel in the construction industry: Challenges and opportunities, *International Journal of Steel Structures*, **23**(5), 1399-1416.

Khalifa, A A, Ibrahim, A-J, Amhamed, A I and El-Naas, M H (2022) Accelerating the transition to a circular economy for net-zero emissions by 2050: A systematic review *Sustainability*, **14**(18), 11656.

Kitayama, S and Iuorio, O (2023) Disassembly and reuse of structural members in steel-framed buildings: State-of-the-art review of connection systems and future research trends, *Journal of Architectural Engineering*, **29**(4), 03123006.

Knoth, K, Fufa, S M and Seilskjær, E (2022) Barriers, success factors and perspectives for the reuse of construction products in Norway, *Journal of Cleaner Production*, 337, 130494.

Li, Z, Shen, G Q and Alshawi, M (2014) Measuring the impact of prefabrication on construction waste reduction: An empirical study in China, *Resources, Conservation and Recycling*, **91**, 27-39.

Ness, D, Swift, J, Ranasinghe, D C, Xing, K and Soebarto, V (2015) Smart steel: New paradigms for the reuse of steel enabled by digital tracking and modelling, *Journal of Cleaner Production*, **98**, 292-303.

Sansom, M and Avery, N (2014) Briefing: Reuse and recycling rates of UK steel demolition arisings, *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, **167**(3), 89-94.

Sterman, J D (2002) *System Dynamics: Systems Thinking and Modelling for a Complex World*, Massachusetts Institute of Technology Engineering Systems Division, Working Paper Series.

World Steel Association (2021) *Climate Change and the Production of Iron and Steel*, Available from: https://worldsteel.org/wp-content/uploads/Climate-policy-paper-2021-1.pdf [Accessed 28 July 2024].

World Steel Association (2024) *The Uses of Steel*, Available from: https://worldsteel.org/about-steel/steel-facts/ [Accessed 28 July 2024].

WRAP (2008) *Practical Solutions for Sustainable Construction Reclaimed Building Products Guide*, Available from: https://storage.googleapis.com/www.bioregional.com/downloads/Reclaimed-Building-Products-Guide_WRAP_2008.pdf [Accessed 28 July 2024].

Yeung, J, Walbridge, S and Haas, C (2015) The role of geometric characterisation in supporting structural steel reuse decisions, *Resources, Conservation and Recycling*, **104**, 120-130.