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Scaling Recycled Concrete in Sweden - Technical Advances, Supply Chains and Optimized Logistics for a Circular Flow

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ABSTRACT

This study examines the benefits and limitations of different supply chain models for recycled concrete aggregates (RCA), a highly resource- and CO_2-intensive material. Focusing on Sweden, it combines material science insights with policy analysis and logistics modelling to assess the potential of RCA in construction. RCA demonstrate strong reuse potential in both bound (new concrete) and unbound (road and backfilling) applications, with life cycle assessments indicating lower climate impacts than virgin aggregates. However, barriers to achieve circularity persist, including fragmented regulations, limited infrastructure, and weak market demand. Using qualitative data from industry actors and quantitative modelling, three scenarios are developed: high-utility reuse of elements, consolidated recycling into bound and unbound applications, and low-utility recycling for backfilling. Results highlight the importance of selective demolition, traceability, procurement models, and strategic placement of concrete material terminals. The study concludes that coordinated policy, logistics planning, and procurement practices are critical to scaling RCA adoption.

Key words: Concrete recycling, Crushed concrete aggregates, Recycling, Supply Chain Management, Procurement, Material terminals, Sustainability, Circularity

1. INTRODUCTION

The European Green Deal is expected to boost construction activity across the EU, driven by ambitious energy efficiency targets [1]. These efforts are closely linked to circular economy (CE) principles, which have gained traction in both industry and academia. Reusing products and materials can significantly reduce greenhouse gas emissions and improve resource efficiency [2]. The construction sector, as a major consumer of raw materials and generator of waste, is central to advancing CE strategies. However, widespread implementation of CE remains challenging.
Aggregates, the most used bulk material in Sweden, are vital for asphalt, concrete, railway ballast, and fill material. In 2022, Sweden produced 96.2 million tonnes of aggregates, mostly from crushed rock (88.7 million tonnes), with road construction consuming 54.9 million tonnes and concrete production 11.1 million tonnes [3]. Licensed quarries supply 18% natural gravel, 69% rock, 4% moraine, and 10% mixed sources [3].

Crushed rock is increasingly used in urban areas like Stockholm, but construction and demolition waste (CDW) could further substitute virgin materials. Recycling concrete into recycled concrete aggregates (RCA) offers a major opportunity to reduce environmental impacts and secure material supply, though current recycling rates remain low due to logistical and policy barriers [4] even though recycling concrete reduces the need for virgin materials, conserves resources, and limits waste. Swedish research shows that recycled concrete can match the strength of conventional mixes [5]. The Swedish cement and concrete industries are targeting climate-neutral concrete by

2045, exploring alternative binders like slag and ground glass, as cement accounts for about 4% of Sweden's CO_2 emissions [6]. These targets align with both Swedish national policy and the EU Circular Economy Action Plan [6, 7].

The construction sector's transition to CE is slow due to complex regulations and diverse stakeholders [8-10]. While policies can drive change, they have at times slowed CE adoption [4] through their, at times, opposing focus' [11]. In Sweden, climate policy requires carbon reporting for new buildings but lacks equivalent circularity mandates. The EU CE Action Plan [7] prioritizes construction but binding national rules are still missing. Municipal procurement and public demand, as seen in the Netherlands, can stimulate markets for recycled materials [12].

Barriers to circular material use in construction include regulatory, organizational, logistical, and quality issues [13-15]. Technical challenges [15], weak markets for recycled materials, inconsistent regulations [16], and limited supply chain collaboration [11] further hinder progress. Logistics and supply chain management are critical for CE adoption [17, 18].

Persistent barriers include entrenched business models and policy uncertainty. Although Sweden's technical reference guide (AMA) now includes CE criteria [19], adoption is still limited. Some municipalities procure reused CDW, but broader progress requires policies that challenge linear practices [20]. Efficient supply chains and logistics are essential for scaling up CE. Demolition design and accurate material data can improve reuse and reduce costs [21-23]. Overcoming these barriers requires coordinated, multi-actor approaches and proactive planning [4].

A key challenge is inconsistent policy implementation, which hampers proactive planning and efficient logistics. As a step towards a wide-spread transition towards CE, this study examines the benefits and limitations of different supply chain models for RCA, a highly resource- and CO_2-intensive material. The research addresses four research questions:
RQ1: What is the potential for recycling concrete waste, and what best practices exist?
RQ2: How do barriers and enablers interact to influence RCA scale-up?
RQ3: What supply chain and logistics configurations support circular RCA use?
RQ4: What strategies enable industrial-scale RCA adoption in Sweden?

RQ1 is addressed through a literature review on concrete materials and circular supply chain management. **RQ2** draws on qualitative insights from workshops and field observations. **RQ3** is answered by developing scenarios for optimized RCA supply chain configurations, while **RQ4** is addressed in the discussion through guidelines for scaling up RCA use in Sweden.

The main contribution of this study is an integrated understanding of stakeholder perspectives and the presentation of three feasible supply chain scenarios for RCA in construction. By linking technical advances in recycling with organizational and logistical perspectives, the paper clarifies how RCA can be mobilized within circular construction value chains and identifies the conditions necessary for successful adoption.

The paper is structured as follows: first, the literature review (**RQ1**) sets the background for **RQ2** and **RQ3**. Next, the methodology for data collection and analysis is described. Then, results for **RQ2** and **RQ3** are presented. Finally, the discussion addresses **RQ4** and offers recommendations for scaling up RCA use.

2. CONCRETE WASTE RECYCLING – STATE OF ART

This section addresses RQ1: the potential for concrete waste recycling and current best practices. It first places RCA within the broader context of concrete waste management, focusing on legislation, end-of-waste criteria, and material certification. Technical possibilities for circular concrete are then explored through previous studies, emphasizing aggregate supply from CDW, volumes, regulations, and recycling practices. These insights reveal key structural and policy drivers, as well as barriers to scaling high-value recycling.

The second part examines supply chain management (SCM) in circular contexts, highlighting how logistics, planning, and coordination affect RCA feasibility. Given the complexity and fragmented nature of construction supply chains, integrating circular flows is challenging but applying SCM principles can enhance efficiency, traceability, and collaboration.

2.1 Management of concrete waste

CDW represents over one-third of all waste generated in the EU, arising from the construction and demolition of buildings and infrastructure, as well as road planning and maintenance. CDW components, notably metals, bricks, and glass, have high resource value and established recycling chains, often supported by producer responsibility schemes. Separation and recovery of CDW requires selective demolition and on-site sorting, as mandated by the European Waste Directive (2008/98/EC), into six fractions including concrete and other mineral waste. Concrete is the largest CDW fraction and, together with mineral waste from mining, accounts for about 60% of all CDW in Europe [24].

Waste statistics in Europe and Sweden often omit mineral waste due to data gaps (Swedish EPA, 2020). The EU Waste Framework Directive targets 70 wt% recycling/recovery of construction and demolition waste (CDW) by 2025 [24]. In Sweden, mineral CDW mainly from demolition, spills, and concrete plants totals 2.9 million tonnes annually. Of the 14.2 million tonnes of construction waste in 2020, this included 8.7 million tonnes of excavated material, 2.7 million of metal, and 1.6 million of wood. Concrete volumes are not separately reported, grouped instead with bricks, glass, tiles, and mixed CDW. In 2020, 62,000 tonnes of mineral/mixed CDW were recycled conventionally, 779,000 tonnes reused as construction material, 355,000 tonnes used for backfilling, and 310,000 tonnes were landfilled [25].

End-of-Waste criteria and certification
In order to recycle a waste material it has to cease being waste and fulfil the End-of-Waste criteria according to the Swedish Environmental Code chapter 15 [26] based on the joint EU provisions. The four End-of-Waste criteria are: (1) there is a specific purpose, (2) there is a market demand, (3) technical claims are achieved and (4) it has no harmful effect on humans and environment. **Certification** is made after End-of-Waste criteria are fulfilled and makes the basis for recognizing waste as a product for a unified marketing of a circular aggregate.

Sweden is planning to introduce national End-of-Waste criteria in the near future [27]. This process is comprehensive and needs special attention and legal information for those actors who are working with waste management so that the process does not hinder the recycling of materials and the transition towards circular economy.

Recycling and reuse of concrete

Circular business models aim to continually reuse products and materials, ideally using renewable resources [28]. These models include:

- **Slowing**: Extending product life through repair, reuse, and refurbishment [29] such as the repair or reuse of structural elements and building fixtures. A strong trend is design for prolonged technical life of the structural concrete elements from 50 years to 100.
- **Closing**: Recycling or remanufacturing materials post-use [30] such as in the case of recycling concrete waste in bound and unbound applications
- **Narrowing**: Reducing resource use before the point of sale [28, 31] such limiting use of virgin aggregates in concrete

Reuse of concrete respectively reuse of precast concrete elements is a way of slowing the loop as it is aimed at a second technical life. As many buildings from the 1960s and onwards are reaching the end of their technical life it enables the possibility of reusing concrete elements. Framed structure buildings specifically enable the possibility of reusing elements by selective demolition [32].

Recycled Aggregate Concrete (RAC) is coming up when concrete is crushed to fractions and reused as aggregates in new concrete. RAC processes are the most value preserving process for the concrete waste. When concrete is crushed and used as aggregate it is called **Recycled Concrete Aggregate (RCA)** and is used in road applications generally [5]. The sources of concrete waste are demolition sites, concrete industries like ready-mixed concrete plants and prefabricated element plants.

Using recycled concrete aggregates is more environmentally beneficial than using natural aggregates due to reduced resource depletion, landfill avoidance [33], and less impact on geology and biodiversity [34]. Life Cycle Assessment (LCA) shows RCA production has 1% less CO_2 footprint than natural aggregates [35]. This small difference is due to the crushing process being the same for virgin aggregates and RCA. What differs is the blasting process in virgin aggregates which is not needed for recycled aggregates. Additionally, Pradhan *et al.* [36] show that the main contributors when using either RCA or virgin aggregates lay in the transport needed and the cement used. While transport distances can be shorter when using RCA, it may also increase the cement needed, averaging out the gains from shorter transports with lower emissions impacts [36, 37]. Thus, arguing only from an emissions perspective may not give the full impact. Instead, to emphasize material circularity, Kadawo *et al.* [35] use the **circularity index** based on the economic value of recirculated material relative to the product's value which helps distinguish recycled from virgin materials, especially when CO_2 differences are minimal. Circularity index allows the concrete producer to make a clear discernment between virgin and recycled alternatives especially when little differences are seen in CO_2 emissions.

The circularity index can be interpreted in relation to the actor roles in the value chain. For real estate owners, possible circularity indexes suggested are the share by weight of recycled material used in a building or circularity related to generated waste sorted for recycling respectively landfill. Another indicator can relate to the recycling of excavation materials in construction projects, by documenting the amount of excavated materials used for refill at the same object or transported to material terminals. These indicators could provide the statistics and active database for available recyclable and reusable materials at the local, municipal level for all supply chain actors [38].

An agreement on common circular economy indicators will benefit the development of the value chain locally and by putting it in relation to neighbouring municipalities would ensure a sustainable material supply on a regional level.

Production technology for aggregates from concrete waste
In Sweden, most concrete waste is recycled for unbound infrastructure uses like road subbases, where aggregate requirements are limited to particle size, density, and wear resistance [39, 40]. For concrete claims are stricter, including water absorption, freeze-thaw resistance, and shape for pumpability and flow [41]. RCA must be assessed for suitability to ensure it is used appropriately, either in road construction or concrete. Based on its properties evaluated by relevant standard. Aggregate production involves crushing and sieving large rocks into granular fractions, see Figure 1a. For RCA, a washing step removes stone flour from the concrete to enhance adhesion [42] before going through the crushing steps (Figure 1b). The crushing process is versatile as it generates aggregate fractions for both road and concrete applications.

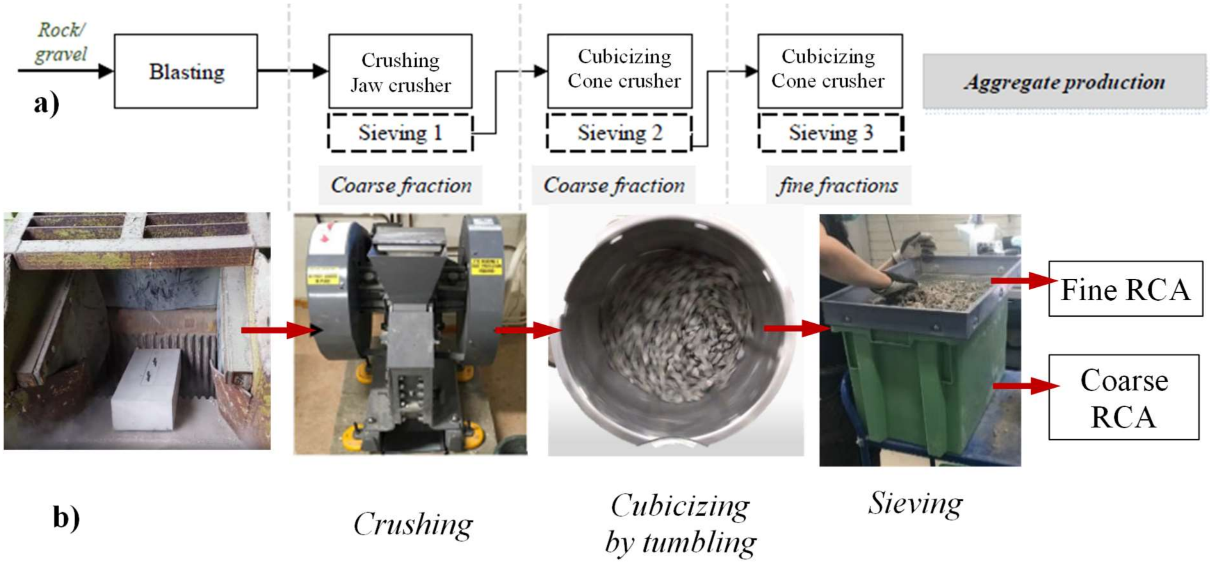

Figure 1 – Aggregate manufacturing process a) crushed rock in industry b) RCA in lab

RCA have very similar properties to crushed rock aggregates which enables virgin aggregate producers to use their existing rock crushing infrastructure to produce RCA along with virgin aggregates. This combined with the shorter transport distances seen for recycled concrete will lead to attractive pricing for these products [43].

There are small differences between virgin aggregate and RCA. The remains of concrete waste are attached as cement paste to the aggregate, see Figure 2. This adhered cement adds to porosity of the aggregate, influencing its density and water absorption property [44]. Removal of the paste results in better concrete strength and durability; removal is possible by abrasion followed by washing, seen in Figure 1.

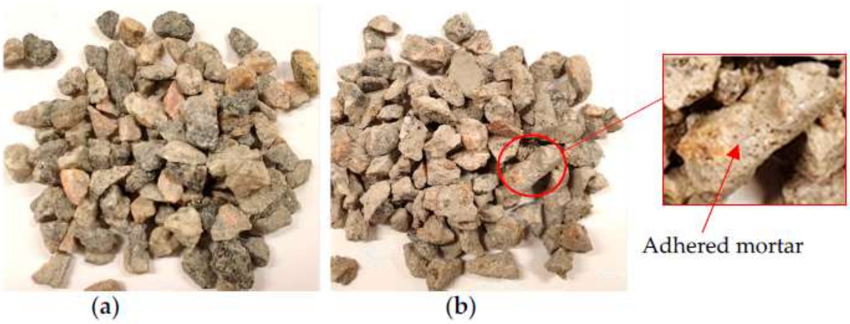

Figure 2 – Aggregate fractions a) crushed rock b) RCA

2.2 Supply Chain Management and Circularity in Construction

Supply Chain Management (SCM) aims to improve coordination and communication among actors to reduce inefficiencies in material flow and planning [45]. SCM involves the strategic alignment of business functions across organizations to enhance both individual and collective performance. In modern supply chains, firms do not compete as isolated entities but as part of interconnected networks [45].

Strong supplier–customer relationships built on trust, commitment, and shared goals are essential for achieving a supply chain orientation (SCO) [46]. Key enablers include organizational compatibility, top management support, and clearly defined roles [47]. SCM comprises three core elements: actors (e.g., suppliers, manufacturers, customers), resources (e.g., materials, equipment, information), and activities (e.g., procurement, production, delivery) [48-51]. Effective communication and trust-based collaboration are critical for synchronizing activities and reducing risk [45, 52].

The construction sector is a project-based, engineer-to-order (ETO) industry, characterized by the production of unique structures at fixed locations. Each project relies on the timely delivery and removal of materials and resources [53]. Temporary project organizations generate fragmented and short-term supply chains, where actors form ad-hoc networks to coordinate production inputs [54, 55]. This fragmentation, combined with siloed operations and sequential processes, creates coordination challenges across subcontractors and suppliers [56]. The construction logistics system involves multiple actors operating across several layers, and weak interconnections hinder system integration and data sharing [57, 58].

Coordination between on-site and off-site operations is often impaired by unclear responsibilities, lack of standardized procedures, and inadequate management tools [59-61]. These issues complicate the implementation of efficiency measures and limit the potential for systemic improvements.

Circular Supply Chains in Construction
The transition to a circular economy (CE) introduces new demands on procurement and purchasing practices. While municipalities refer to this as procurement and private firms as purchasing, both must adapt to circular principles [62]. Circular purchasing emphasizes closing

material loops through reuse, remanufacturing, and recycling, going beyond traditional sustainability goals [63, 64]. Circular procurement has been shown to deliver environmental and social benefits, including reduced climate impact and job creation [65].

Supply chain design plays a critical role in enabling circularity. Closed-loop systems recover products within a single firm but may have limited scope and higher emissions [66, 67]. Open-loop systems, more common in construction, involve independent actors managing reverse logistics [29]. Despite their relevance, open-loop systems remain underexplored in CE research, which has largely focused on closed-loop models in sectors such as electronics and textiles [68]. Concrete recycling illustrates this duality. Road construction has traditionally relied on open-loop recycling, while technical advances now enable closed-loop recycling in new concrete applications, e.g., as aggregates in new concrete elements. To maintain materials at the highest level of the waste hierarchy, purchasers must be equipped to identify and source pre-used materials effectively. Scaling circular supply chains requires applying SCM principles, particularly coordination and information sharing, to manage product complexity [68]. Without structured approaches, ad-hoc solutions risk inefficiencies and increased costs. Wilhelm Lund [68] outlines the key operational steps in circular material flows:

1. On-site demolition
2. On-site sorting
3. First pre-processing
4. Landfilling of non-recyclables (with potential for future reuse)
5. Second pre-processing
6. Material recycling
7. Post-processing
8. Material refining and application

Fredriksson *et al.* [69] similarly elaborate on these operational steps for circular use of excavated soil and rock materials (see Figure 3).

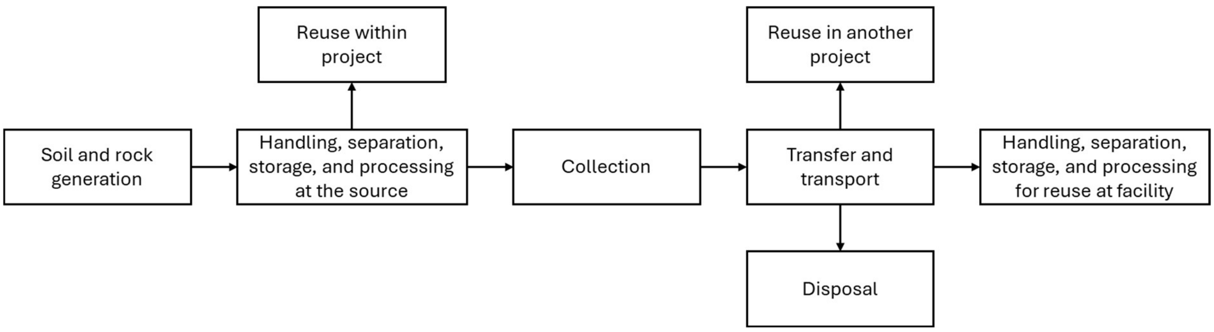

Figure 3 – Process map for reusing excavated soil and rock materials (based on Derrible [70], Magnusson et al. [71], and Fredriksson et al. [69]).

In concrete recycling projects, early-stage trust-based collaboration improves performance. Under producer responsibility, concrete waste producers must inform other actors of available recycling options. Successful examples in bricks [32] and glass [72] demonstrate how transparent communication fosters efficiency and market uptake.

Logistics Setups in Circular Flows
Circular supply chains in construction involve both forward and reverse flows. This section outlines logistical scenarios for organizing recycled concrete aggregate (RCA) supply chains.

Scaling circular markets in construction require both theoretical and practical support, with key challenges including balancing supply and demand, ensuring material quality and traceability, and coordinating actors who often lack established relationships in linear systems.

Effective coordination demands intermediaries, such as terminals, that facilitate collection, storage, processing, refinement, digital tracking, and sales. Terminals serve as logistical hubs, enabling material flow and actor interaction across fragmented value chains [73]. These facilities may be organized openly or internally, on a permanent or project-specific basis, influencing their function and business logic. Longer contracts and larger sites encourage investment in processing and storage infrastructure, subject to regulatory permits. Terminal location is critical for reducing transport costs and improving efficiency through proximity to demolition sites and full-load transport in both directions [74].

Currently, the number of facilities licensed for interim storage, such as quarries and terminals, is limited. Prioritizing interim storage in urban development and municipal spatial planning is crucial. Regional material supply plans are needed to ensure long-term availability of aggregates and to support infrastructure development.

Optimizing logistics in concrete recycling involves modelling material flows, transport and recycling costs, and carbon emissions. Theoretical foundations include the Vehicle Routing Problem (VRP) and its variants, such as Capacitated Vehicle Routing Problem (CVRP), which aims to minimize transport costs while respecting vehicle capacity constraints [75] and the Stochastic VRP (SVRP), which accounts for uncertainties in demand or service times [76-78]. In concrete recycling, these models can incorporate multiple depots, diverse fleets, and waste-specific constraints. SVRP is particularly relevant given the uncertain demand for recycled concrete due to cost, quality, and value chain limitations.

Identifying actors capable of combining multiple roles, such as crushing, recycling, and storage with appropriate permits, can help establish efficient short supply chains. Logistics infrastructure, particularly transport and terminal capacity, is essential for building viable circular value chains and increasing the recyclability of construction and demolition waste (CDW) [32].

3. METHODOLOGY

This study applies a **sequential exploratory mixed methods design** [79], combining qualitative and quantitative approaches in two phases. In the first phase, a qualitative study was conducted to identify the present status of CDW and RCA supply chains, the practices of key actors, and the dependencies shaping their interactions. Insights from this phase form the basis for the design of three quantitative optimization scenarios, which is developed in the second phase to evaluate alternative logistics solutions. According to Pluye and Hong [79], mixed methods research enables both a deeper understanding of new or underexplored phenomena through qualitative inquiry, and the measurement of their impact through quantitative assessment.

The work builds on collaboration between two research groups: one specialising in **concrete and cement materials**, and the other in **construction logistics**. To strengthen the cross-disciplinary understanding, two internal workshops were held to discuss theoretical frameworks and working methods across the groups. This integration was considered essential for analysing RCA supply chains, where material quality requirements and logistics efficiency are interdependent.

The qualitative phase combined workshops, interviews, and field observations. Industry participants included (number of interviewees in brackets): demolition contractors (2), a waste management company (1), developers (2), a main contractor (1), a concrete producer (1), and software developers (2). While the number of interviews is small, the interviews alongside the stakeholder workshops gave a representation of the challenges the industry is facing. Two multi-actor workshops were organised to explore perspectives on RCA management, challenges, and opportunities. In addition, semi-structured interviews were conducted with representatives from demolition and waste management companies to capture practices in handling RCA.

Fieldwork was conducted at two demolition projects, each visited on two separate occasions, to observe material handling practices, logistics setups, and interactions among actors. These observations were used to identify organisational models that might enable more effective reuse or recycling of RCA, as well as to highlight existing barriers.

Findings from the qualitative study provide the foundation for the design of **three quantitative optimization scenarios**. These scenarios will explore alternative ways to organise RCA supply chains, focusing on minimizing storage and recycling costs, transport costs, and carbon emissions, while maximising overall economic viability. The integration of qualitative insights with quantitative modelling allows for a more comprehensive analysis of how RCA supply chains can be made efficient, competitive, and environmentally sustainable.

4. RESULTS

This section first presents the answer to **RQ2:** How do barriers and enablers interact to influence the scale-up of RCA use? and then answers **RQ3:** What supply chain and logistics configurations can support circular use of RCA?

4.1 Barriers and enablers in present day organisation of CDW and RCA flows

We have assumed that all materials resulting from demolition must be managed and processed. One of the largest demolition contractors in Sweden operates a system in which nearly all materials received at their terminal are reprocessed and repurposed for other uses, such as road surfacing, fuel mixtures, agriculture, and metal recycling. A key enabler of circularity in this context is operational flexibility – the capacity to adapt processes and outputs to varying material flows.

The demolition companies operate single facilities each, which are not licensed to handle hazardous waste. As a result, they collaborate with waste management actors to ensure the management of all types of waste. The type of permit held by a facility determines the materials it is authorised to receive. The permit for hazardous waste is the most comprehensive, but it is crucial to match the appropriate contaminants with the corresponding permits. Permits also regulate the annual tonnage a facility is allowed to receive, and capacity limits are frequently reached. Crushed concrete, for example, is typically deposited at a non-hazardous waste designated landfill.

One reason for the limited on-site crushing and immediate reuse of materials during demolition projects is the lack of available space. Crushed material must often be stored temporarily before it can be reintegrated into new construction. Moreover, projects inevitably generate material surpluses, regardless of how efficiently they are managed. Therefore, it is essential to integrate reuse and recycling strategies from the earliest planning stages -specifically during detailed development planning. Municipalities such as Uppsala close to Stockholm are setting a precedent by requiring that all material be either reused or recycled. The availability of interim storage facilities is also crucial, as they enable the aggregation of sufficient material volumes for reuse.

Procurement processes for demolition projects are, in essence, the planning and execution framework for the circular handling of materials. We have identified three typical procurement models to the most usual contracting forms in construction:

1. **Separate Contracting:** The real estate owner procures the demolition contractor, transporter, and construction contractor separately. From a circularity perspective, this model offers advantages, as the demolition contractor can identify and broker opportunities for material reuse across different sites. The real estate owner needs vast competence across different technical fields and legal aspects. The real estate owner must have the prerequisite knowledge for recycling/reusing of material from the object and have it as a claim in the procurement for those sub-contractors involved in the circular processes. The demolition contractor may be one of the initiator sub-contractors for reuse and recycling. The key actor for circularity achievements is the real estate owner or its project leader.
2. **Collaborative Contracting:** The real estate owner procures a construction contractor, who in turn subcontracts the demolition and transport services. This often results in a division of project leadership between demolition and construction phases, making it harder to coordinate reuse efforts effectively. If this contracting form is not used with the intention of collaborating with a common focus, which might be circularity, then the division of the project leadership will come up. If the common intention of circularity is in place, then there are also claims on competence, experience and earlier collaboration that may improve collaboration between actors for recycling or reuse. Once the real estate owner has intention for circularity, all the actors play a key role for a successful circular project.
3. **Manufacturer-Led Model:** The real estate owner procures a materials manufacturer, who then subcontracts the demolition and transport, followed by the real estate owner's procurement of the construction contractor. This model facilitates full transport loads to and from the construction site and supports the development of closed-loop material flows. In this contracting model the real estate owner, with the intention of recycling, is procuring the consultants for planning and design and procures a main contractor who executes with help of subcontractors. This would mean that for a beneficial recycling of the material, the consultants should be knowledgeable of circular design. Once the real estate owner has intentions for circularity, the key actor in this contracting form is the consultant.

The demolition process usually begins when a client, contractor, or manufacturer requests removal of structures or materials. Contractors then quantify materials to prepare a cost estimate and plan of action. Hazardous substances are assessed and costed, though concealed materials are often disclaimed. After completion, documentation details material types, quantities, and destinations. Hazardous substances are first removed by subcontractors through competitive quotations, with handling notifications (e.g., asbestos) submitted to safety authorities three weeks in advance. Contractors may use framework agreements with waste handlers, but materials can go to several stations depending on permits. An environmental sampling map and lab tests determine material types and reuse potential.

Physical demolition proceeds interior-to-exterior and top-to-bottom, with materials segregated and loaded into containers or trucks. Calibrated weighing systems provide accurate, legally verified data, overriding truck measures and ensuring compliance with strict weight limits, especially for 74-tonne vehicles.

Transitioning to RCA requires early collaboration, committed stakeholders, research, EU policy tools, standardisation, reporting, digital passports, and external drivers like carbon pricing and supply risks. Yet barriers remain such as inconsistent regulations across jurisdictions, fragmented industry structures, weak local markets, and limited logistics know-how and operations mean recyclable materials often end up in landfill. Procurement models shift risk downstream, while reuse, especially of prefabricated components, demands specialised expertise. Research on concrete recycling also lags. To improve outcomes, clearer regulation, incentives, standardisation, and regional planning are needed for effective storage, quality assurance, and local material use.

4.2 Supply chain scenarios of optimized logistics of CDW for circular use

We explore the circular logistics material flows in CDW recycling and examine the problem of optimizing logistics flows. The goal is to minimize storage and recycling cost, transport costs, and carbon emissions, which will serve to maximize profit. The following aspects are integral to optimizing the logistics flows:

- Determination of optimal locations for concrete material terminals (CMTs) and demand points (e.g., new construction sites) based on the spatial distribution of CDW generation and demand [80, 81].
- Allocation of demolition sites to CMTs and allocation of the same to demand points to minimize transportation distances and costs, and CO_2 emissions [82].
- Integration of time-varying parameters, such as CDW generation rates, market demand, and transportation costs, to capture the dynamic nature of the logistics and material flow problem [83].
- Incorporation of storage and recycling capacities of CMTs, and transportation capacities of transport vehicles [84].
- Consideration of multiple transportation modes (e.g., trucks, rail, waterways) and their respective CO_2 emission factors and costs [85].
- Inclusion of economic factors, such as RCA revenue, storage and recycling costs, and transportation costs, to maximize profitability [86].

We consider three scenarios for examining the circular logistics material flows in CDW recycling in the Swedish context. These are discussed in detail below.

Scenario 1

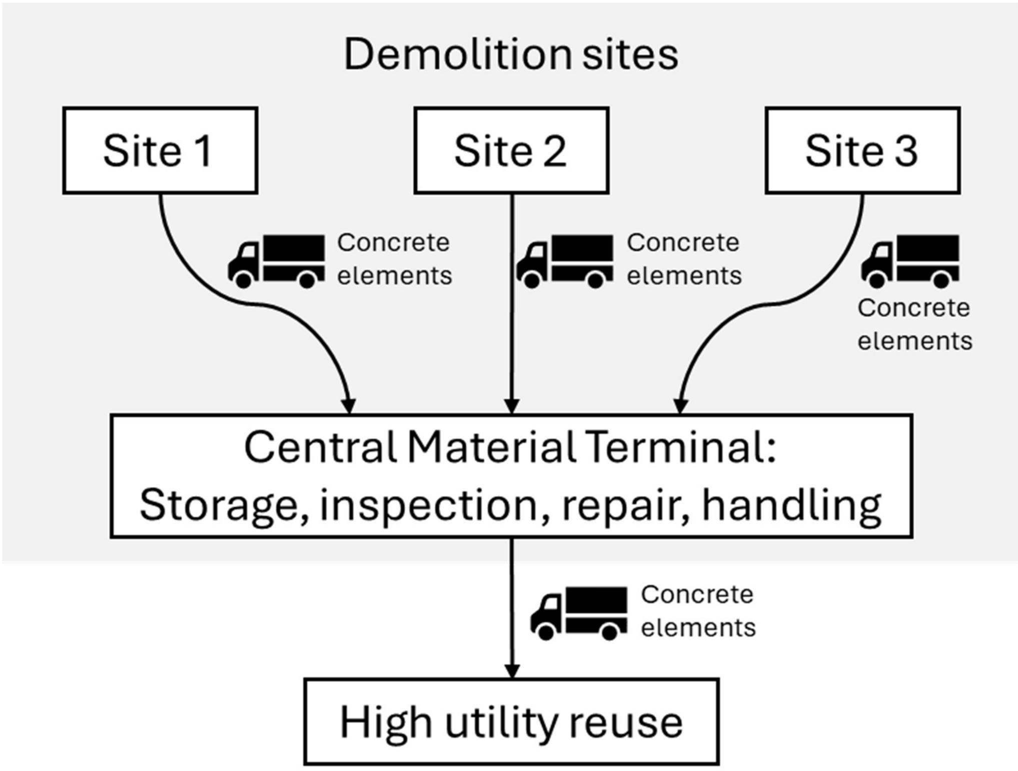

Figure 4 – High-utility reuse of concrete elements and other components

This scenario involves several stages from demolition sites to a terminal and then to high-utility applications. First, elements are collected and transported from multiple demolition sites to the CMT for storage, inspection, repair, and handling, modelled as a many-to-one problem aiming to minimize transportation costs or carbon emissions. Next, elements are distributed from the terminal to building sites, framed as a one-to-many routing problem to optimize transport from a single source to multiple demand points.

In both stages, key parameters include transportation costs, carbon emissions, and potential revenues from high-utility applications. The overall objective is to maximize profit or minimize costs while keeping emissions within limits.

Scenario 2

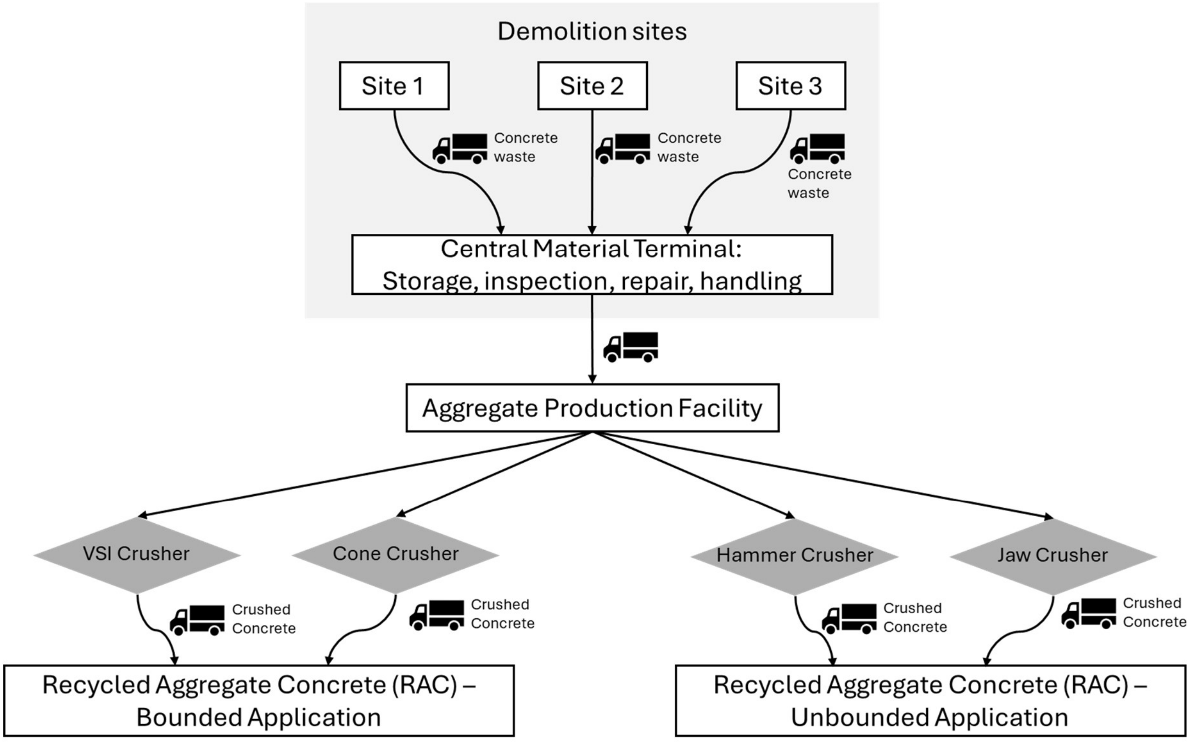

Figure 5 – Scenario for recycling concrete waste to bound and un-bound road construction

Concrete waste from demolition, building, and ready-mix production sites is collected and stored at a CMT. There it is processed through crushing stages before being sent to aggregate production facilities. Recycled aggregate concrete (RAC) is then used in bounded applications like new concrete, while recycled concrete aggregates (RCA) are applied in unbounded uses such as backfilling and roads.

Consolidating CDW at a CMT creates economies of scale, lowering costs and emissions from multiple dispersed trips. The crushed aggregates are then distributed to production facilities for applications including road construction and new concrete, representing a classical transportation problem (TP) [87].

Scenario 3

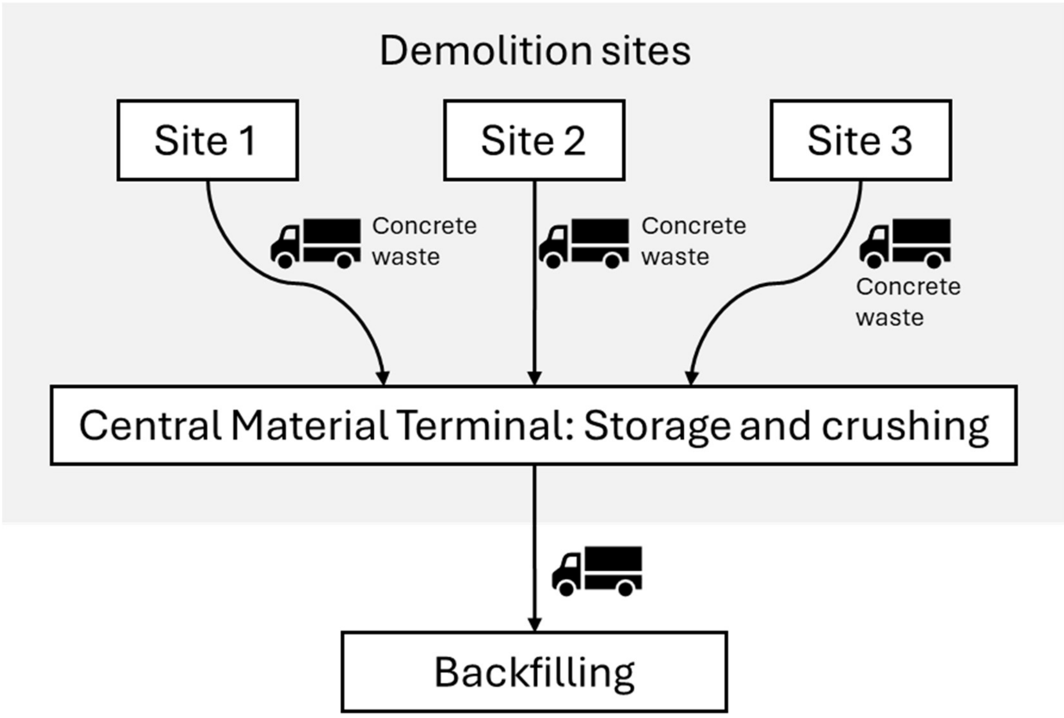

Figure 6 – Scenario for low-utility recycling, RCA for backfilling

This scenario reflects recycling of concrete waste to aggregates for road construction and backfilling; managed by real estate owners of construction sites. Waste is transported from multiple demolition sites to a CMT for storage and crushing, after which the resulting RCA is sent to backfilling applications.

The first stage can be modelled as a many-to-one transportation problem, aiming to minimize costs or carbon emissions from dispersed sites to the CMT. The second stage, transporting RCA from the CMT to backfilling projects, represents a one-to-many distribution problem, where routing and delivery from a single source to multiple demand points are optimized. The logistics challenge involves coordinating transport services under uncertain demand, while minimizing costs and emissions and ensuring efficient delivery of CDW for RCA production.

5. DISCUSSION

This study examined the benefits and limitations of different supply chain models for RCA. To respond to this aim, we combined knowledge of concrete materials to capture technical feasibility, assessed policy implications among CDW actors and developers, and developed logistics scenarios to evaluate the economic feasibility of scaling reuse and recycling.

Sweden generates 60–80 million tonnes of excavated soil and rock annually, particularly in urban centres such as Stockholm. At present, this material largely substitutes natural gravel in low-value applications such as road fill and landfill cover. Although recycled aggregates are often produced at demolition sites or in prefabrication facilities, these flows are not captured in official statistics (SGU). Life cycle assessments show that RCA has comparable or lower climate impact than virgin aggregates, particularly due to shorter transport distances in urban areas [35].

RCA has particularly strong potential for reuse and is a material applied both as backfilling and as a main component in concrete and asphalt [5]. Quality is, however, decisive, and both the use and disposal of CDW are subject to multiple legal frameworks covering environmental, construction, and waste law. International comparisons show substantial variation in CDW management. Mollaei *et al.* [88] demonstrate that instruments such as landfill taxes and diversion schemes strongly influence the degree of reuse. Policy therefore plays a central role at national, regional, and local levels, as aggregate flows cannot be governed solely by private actors. In Sweden, national agencies such as the National Board of Housing, Building and Planning, the Swedish Environmental Protection Agency, and the Swedish Transport Administration provide frameworks and regulations [cf. 25, 89, 90]. These are implemented regionally by County Administrative Boards and environmental courts while municipalities, holding the planning monopoly, act both as environmental authorities and as developers or landowners. This scattered policy landscape complicates implementation of CE and thereby the use of RCA in the industry. Strategic planning of treatment, geolocation, and transport is crucial to minimise sustainability risks in circular CDW management [91]. On-site reuse should be prioritised to achieve sustainability targets, and traceability is essential when combining materials of different origins. Selective demolition facilitates cleaner aggregates without contamination from other materials, enabling their use in new concrete [32, 92]. Yet, all demolition materials must be managed, which restricts RCA utilisation if limited to what concrete producers are willing to accept in closed-loop supply chains.

Demolition practices are therefore pivotal in shaping construction material flows and the sector's transition toward a CE. Whether materials are reused, recycled, or landfilled depends on regulatory frameworks, operational practices, and procurement models. Swedish demolition contractors' practices reveal that facilities, permits, and collaborations with waste management actors largely determine reprocessing potential. Barriers to on-site reuse include space constraints, capacity limitations, and fragmented logistics. Early planning, interim storage, and municipal requirements emerge as critical to enabling circular handling. Procurement models further act as levers for circularity by defining roles, responsibilities, and collaboration across real estate owners, contractors, manufacturers, and consultants.

To address the economic dimension, we developed three supply chain scenarios for RCA. The optimisation model considered storage, recycling, and transport costs, carbon emissions, and profitability. Key factors included the location of CMTs, allocation of flows between demolition sites, terminals, and demand points, time-varying CDW generation and demand, processing capacities, and multimodal transport with differing costs and emissions. Revenues from RCA as stand-alone aggregate products for road, concrete applications and RAC products were incorporated.

Scenario 1 examined high-utility reuse of concrete elements, where materials from demolition sites are transported to CMTs for storage, inspection, repair, and handling before redistribution to new projects. Scenario 2 addressed recycling into both bound (new concrete) and unbound (roads, backfilling) applications, with consolidation at CMTs enabling economies of scale and reduced costs and emissions. Scenario 3 represented the prevailing practice of low-utility recycling, where RCA is used mainly for backfilling, but where uncertain demand and fragmented logistics reduce efficiency. Together, these scenarios provide a structured framework for comparing alternative supply chain configurations and highlight trade-offs between economic and environmental outcomes. They also form a foundation for optimisation models that can guide policy, industry decision-making, and infrastructure planning for circular construction in Sweden.

A further finding is that waste streams from different sources and applications often share process steps and infrastructure. This implies that actors may either own multi-purpose infrastructure usable across several value chains or employ mobile infrastructure shared among multiple actors. Such arrangements increase system flexibility and lower overall costs. As an example, an aggregate producer with crusher facility can work with different material sources to produce aggregates for road construction (infrastructure) and concrete.

In summary, the study demonstrates that large-scale use of RCA requires coordinated action across technical, policy, and economic dimensions. Early stakeholder engagement, supportive regulatory frameworks, effective logistics, and procurement models that align incentives with circular outcomes are all critical to scaling reuse and recycling in line with CE objectives.

6. GUIDELINES FOR CIRCULAR CONCRETE

Here we return to the final research question of this paper, RQ4: What strategies are effective for enabling industrial-scale adoption of RCA in Sweden?

- **Right recycled concrete at the right place:** Use of the right recycled material related to specific application area is seen to be contributing to a wide adoption of recycling and ensuring that the environmental assessment on recycling by municipalities is manageable.
- **Infrastructure and economy of the use of recycling aggregate are important:** Use of recycled concrete products is more economically attractive as they share common infrastructure with crushed rock aggregates and are sourced in proximity to waste management plants. Using the right recycled concrete in the right application leads to a differentiation in pricing due to differences in processing of materials.
- **Commitment and collaboration at several levels** are essential especially at the project initiation stage. If governmental procurement is happening in the project, recycling may be initiated by circularity indicators on share of recycled materials in the building. If private real estate owner procurement is happening, circularity indicator is measured on use of excavated materials or waste sorted for recycling.
- **Commitment and collaboration for recycling** are assured by collaborative contracting as they make all the actors in the supply chain play a key role for a successful circular project.
- **Clarity in policy** is one of the key factors for successful implementation of circularity in concrete. A suggestion is that existing municipality planning documents such as the detail plans include descriptions on circularity in buildings or communities. This can lead to an easier contracting environment instead of having the circularity claims in the procurement.
- **The local governmental actors** are in the forefront and contribute to the demand and use of recycled materials in large scale construction projects.

7. CONCLUDING REMARKS

This study highlights that large-scale adoption of recycled concrete aggregates (RCA) in Sweden requires coordinated efforts across technical, policy, and economic dimensions. While RCA offers clear environmental benefits and strong reuse potential, its integration into construction practices depends on quality assurance and certification of the product, supportive regulatory frameworks, and efficient logistics. Strategic planning for crushing infrastructure, transport, and storage, combined with selective demolition and traceability, is essential to enable high-value applications such as new concrete production.

Policy clarity and procurement models play a pivotal role in aligning incentives for circular outcomes. Collaborative contracting and early stakeholder engagement, particularly by municipalities and governmental actors, emerge as key enablers for scaling RCA use. Economic viability is strengthened when RCA leverages shared infrastructure and proximity to waste management facilities, reducing costs and emissions. Ultimately, successful implementation of circular construction requires commitment at multiple levels, clear planning documents, and integration of circularity indicators into both public and private projects.

While the study integrates material science, policy analysis, and supply chain modelling, several limitations remain. First, the empirical scope is restricted to Sweden, and although many insights are transferable, differences in regulatory frameworks, market conditions, and infrastructure may limit broader generalisation. Second, the optimisation scenarios are based on assumed parameters for CDW generation, market demand, and logistics costs, which may vary in practice; dynamic and stochastic factors such as fluctuating material qualities, seasonal demand, and policy shifts are only partially captured. Third, the analysis focuses primarily on technical and economic feasibility, with less attention to social acceptance, behavioural factors, and labour market dynamics that may influence large-scale RCA adoption. Finally, while procurement is highlighted as a lever for change, the study does not provide detailed empirical evidence on contracting practices or governance innovations, which require further investigation.

These findings are based on ongoing innovation projects and literature findings for other material flows than recycled concrete. Further research work is needed to assess the findings for the Swedish construction industry.

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