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Introducing a Novel Concept for an Integrated Demolition Waste Recycling Center and the Establishment of a Stakeholder Network: A Case Study from Germany

Magdalena Zabek [1,*], Pauline Jegen [2] and Lillith Kreiss [3]

[1] Department of Architectural Engineering and Technology, Delft University of Technology, 2628 BL Delft, The Netherlands
[2] Resource and Energy Systems, TU Dortmund University, 44227 Dortmund, Germany
[3] Baukultur Nordrhein-Westfalen e. V., 45886 Gelsenkirchen, Germany
* Correspondence: m.zabek@tudelft.nl; Tel.: +31-(0)6-4827-2643

Abstract: Using recycled aggregates has many positive environmental impacts because of the conservation of natural resources and minimization of waste. The use of recycled aggregates in downcycling processes is already common in Germany, whereas utilizing them to produce high-quality recycled concrete is rarely applied in practice. The reasons behind this lag have been investigated based on surveys and interviews with stakeholders. Miscommunication and missing information were identified in all stakeholder groups. Therefore, establishing a robust network and facilitating knowledge transfer by specifying the demand for recycled aggregates in the case study region have been considered as prerequisites. Therefore, the paper presents a novel concept of a stakeholder network for an integrated construction and demolition waste center. The conceptualization integrates the recycling companies and construction product manufacturers in one venue with research, service, and educational divisions. The design of the facilities is based on calculations regarding future construction activities and the demand for concrete production. The proposed concept aims to supply the region in the west of Germany with high-quality recycled products while also establishing a robust network that offers benefits in terms of logistical optimization and knowledge transfer.

Keywords: circular economy; recycling system; construction and demolition waste; recycled aggregates; recycled concrete

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1. Introduction

The concept of the circular economy (CE) as a response to finite resources and climate change has been receiving growing attention [1]. In the construction industry, too, CE promises an alternative to the current linear economy in which business is conducted according to the "take-make-use-dispose" principle [2,3]. With the help of CE as a restorative and regenerative model, the consumption of resources, waste production, and emissions generated show potential to be minimized. Anticipated rises in demand and investments within the building sector are foreseen [4], coinciding with a global increase in the extraction of non-renewable resources [5]. Therefore, there is a critical need to shape this transition toward a more circular and resource-efficient building economy. Key factors supporting this transition include the availability of products derived from renewable or secondary raw materials, as well as mechanisms facilitating knowledge transfer.

As mineral material has the highest share of 95% of the total mass in the built environment [6], it is even more important to reduce the extraction of natural mineral resources and provide an infrastructure that recycles mineral material on a high-quality level. As the building sector is a material-intensive industry, millions of tons of raw materials and wastes are generated in Germany every year (e.g., in 2020, natural aggregates = 129.2 Mt, rubble = 60 Mt, road construction waste = 16.9 Mt, other construction waste such as iron, and steel or timber = 13.8 Mt [7]). However, the implementation of a CE is rather new to stakeholders such as planners within the construction industry as energy reduction strategies have been the main focus within the last decades [8].

In order to meet the European Union's requirements by increasing shares of secondary raw material in products [9], using construction and demolition waste (CDW) as recycled aggregates (RA) as a substitute for natural aggregates is gaining importance. This practice shows the potential to further decrease the environmental impact of the construction sector by conserving natural resources and minimizing waste. However, the reduction in CO_2 emission associated with the use of RA compared to natural aggregate is minimal due to comparable emissions generated during manufacturing and processing [10]. With a recycling rate of 91% of mineral raw material, Germany appears to have successfully implemented circular material flows in comparison to, for example, Portugal or Greece with a recycling rate of 5% or Spain with 14% [11–13]. With a mandatory recycling rate of 70% by 2020 [14], only five European countries (Denmark, Estonia, Germany, Ireland, and the Netherlands) fulfill these regulations. However, these numbers are difficult to compare as they include various CDW fractions such as, for example, soil and report on the usage of recycled materials in road construction [13], which, according to the CE definition of the Ellen McArthur Foundation [3], is a downcycling process. Apparently, the usage of high-quality mineral recycled products is not yet a common practice and the possibility to produce recycled concrete (RC) from RA is rarely applied in the industry [15].

The revised European Waste Framework Directive [14] is anticipated to serve as the principal regulatory mechanism for enhancing the recycling of CDW in the forthcoming years. Nonetheless, it lacks provisions for establishing quality criteria for RA and European member states are currently in the phase of integrating the 70% recycling target into their respective national legislations. Consequently, a substantial proportion of CDW is still landfilled, resulting in low recycling rates. The implementation of landfill banns and fiscal measures, such as levies, have demonstrated considerable efficacy in raising recycling rates as, for example, in Belgium. However, the effectiveness of bands depends on appropriate enforcement and control, as well as on the presence of an established infrastructure comprising alternative waste treatment facilities [13].

Today, natural aggregates in concrete can be partially replaced by recycled material, forming RC concrete. Numerous technical analyses have investigated this practice [16–18] and regulations governing its use are available in European countries such as Germany [19,20], Switzerland [21], or the Netherlands [22].

However, major obstacles remain when targeting circular material streams through the application of RC products which include (1) uncertainties within the supply chain of secondary material [23], (2) insufficient investment in innovations of resource recovery technologies and facilities (including storage or marketplaces for resource recoveries) [24], and (3) limited or uncertain availability of material supply and challenges associated with cost-effective material recovery [25]. These challenges can potentially be addressed through innovative configurations of existing recycling systems.

However, the existing literature lacks practical solutions to address these obstacles comprehensively. Therefore, this research primarily aims to identify reasons behind the scarcity of high-value RA products through interviews and surveys.

Additionally, it aims to propose a novel concept for a Demolition Waste Recycling Center (DWRC) as a comprehensive solution to address the above-mentioned obstacles within the construction industry in a specific region of interest known as the Rhenish Revier (RR) in western Germany.

2. Method

2.1. Surveys and Interviews to Determine Barriers and Drivers for the Usage of RC Products

Heading 3 of this paper defines the existing problems within a CE in the construction sector via surveys and interviews conducted in 2020, 2021, and 2022. In total, 2 surveys, 1 qualitative questionnaire, and 12 semi-structured interviews were conducted to examine the acceptance, barriers, and facilitators for the usage of recycled (RC) concrete. In total, a number of 270 individuals participated in the surveys and interviews.

The first survey aimed to assess the current utilization of RA for high-quality products or the willingness to adopt them in the future. A total of 51 individuals were participating in the survey. Predominantly stakeholders from industry (23%) and planning (21%), along with various other parties (research 16%, municipality 12%, NGO 5%, building owners 5%, product manufacturers 4%, and others 15%) participated in the survey. The survey was conducted during an online conference event as part of a project kickoff event named 'ReBAU'.

Additionally, a second survey targeted end-consumers, where 161 residents of a village in the RR of Germany were asked about their willingness to use RC products such as concrete or bricks. The survey was administered through online and postal methods using multiple-choice responses.

A third qualitative questionnaire conducted in 2022 with 46 participants addressed interest and knowledge in regard to aspects of CE in the built environment. The participants consisted of various stakeholder groups (15% municipality, 9% planners, 22% industry, 21% academic, and 33% others). The questionnaire was conducted online.

To further investigate the barriers and drivers for the use of RC concrete in the region, semi-standardized interviews were conducted with 12 stakeholders from recycling companies (25%), concrete producers (33%), and associations (42%). The stakeholders were contacted by mail and were selected due to their expertise in the field of CE. The interviews were held via online meetings between 24.03.2021 and 15.06.2021. The interview transcriptions and qualitative questionnaires were analyzed qualitatively using a category system [26].

2.2. Data Analysis of the Demolition Waste Supply and Demand for RC Concrete

Following the exploration of barriers and drivers for the usage of RC products, Section 4 outlines the potential demand for RA in the RR. Construction activities and the material capacity index (MCI) were calculated for this purpose, considering the average number of buildings constructed in RR between 2015 and 2019. The method was developed and implemented to calculate the German building stock in 2015 by Ortlepp et al. [27].

The MCI calculation is based on the average amount of concrete in relation to the average net floor area derived from the IOER Research Data Centre database. For residential buildings, data on detached, semi-detached houses, and multi-family houses were utilized [28]. Regarding non-residential buildings, the distribution of building types was determined according to datasets from the federal state of North Rhein Westphalia (NRW) [29]. To determine the concrete required for new building construction, the different usable areas were multiplied by the MCI and then by the average concrete density of 2400 kg/m^3 [30].

2.3. Conception of DWRC

Following the investigation of potential demand and supply for RA, Section 5 presents the rationale behind the DWRC and its layout and components. This is based on a technical study [31], namely a Feasibility Study [32], outlining its layout, facilities, equipment, and operational processes. Furthermore, the strategic roadmap in Section 5.2 presents a chronological sequence of key actions for the DWRC's development. This roadmap is developed based on the authors' empirical insights and the developmental process acquired during two projects: "Circularity in the Built Environment" (2016–2018) and its follow-up project "ReBAU" (2020–2022), both funded by the European Regional Development Fund (ERDF). Primarily, the roadmap delineates the objectives, approaches, and outcomes for each phase of the process. Additionally, collaborations with various stakeholders and their respective outcomes are chronologically mapped and visualized in Figure 4. Validation of the proposed conception of the DWRC is pending, as a real-life application has not yet been implemented.

The RR in the German federal state of NRW serves as the region of interest for both the potential demand analysis of RC products and the development of the DWRC concept.

Section 6 discusses the research findings, including complementary measures regarding legislation and policymaking. Section 7 (conclusions and outlook) summarizes the main outcomes and suggests recommendations for adopting a similar strategy in other regions.

3. Results Survey and Interviews about Barriers and Drivers for the Usage of Recycled Products

The survey results indicate a strong willingness among respondents (88%) to utilize RA for high-quality products or to adopt them in the future. However, practical application remains limited, with only 18% reporting previous use of RC products, including 4% specifically mentioning the use of RC concrete. Interestingly, 41% of respondents had not yet used such products and showed no intention to do so.

The survey also highlighted potential knowledge gaps among regional stakeholders, as depicted in Figure 1. Specifically, 18% of respondents expressed a need for information on various products, including RC concrete, reused bricks, or timber. Additionally, 9% of respondents were interested in information regarding the costs associated with CE practices, i.e., an additional 3% in funding opportunities and 3% in the tendering process. Another 6% sought information on regulations related to CE implementation, while 6% were interested in detachable construction methods and the availability of resources for CE practices.

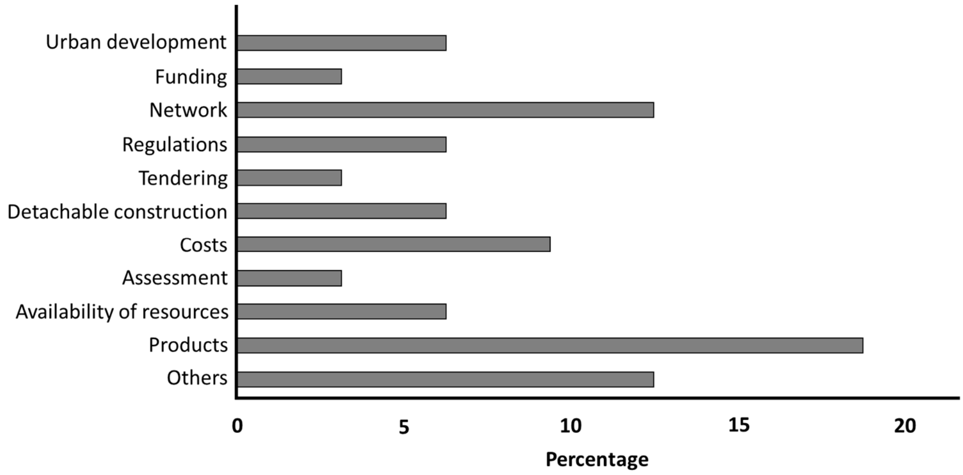

Figure 1. Results from a survey conducted among regional stakeholders demonstrate the demand for information and education on various topics of circular economy (CE).

Furthermore, 13% of respondents expressed a desire for more networking opportunities to facilitate the implementation of CE practices, particularly among clients and municipalities. This suggests a need for increased collaboration and information sharing among stakeholders to advance the adoption of CE practices in the region.

Results from the interviews indicated a general interest among all participants in utilizing sustainable products to address climate change and resource scarcity. While half of the interviewees had experience with RC concrete, they highlighted various challenges and uncertainties regarding the implementation of CE strategies in the construction sector. These challenges included a lack of knowledge regarding legislative aspects, techno-economic feasibility, and acceptance. The interviews also confirmed the limited usage of RC concrete, as only a few participants had used it so far, which aligns with the results of the surveys.

Simultaneously, the interview participants were asked for their suggestions for achieving a successful CE. Several instruments have been suggested as drivers for the usage of RC products by the interviewees. For example, applying recycling quotas and the obligation to use RC concrete in public building projects has the potential to level price differences. Such regulations have already been applied in other European countries such as Switzerland [21].

The participants of the interview also mentioned that the existing regulations for RC concrete production are defined in German regulations (DIN standards [19,20]). Specifically, they suggested loosening restrictions related to the allowable compressive strength classes for RC concrete applications.

Additionally, the introduction of a performance concept akin to the German national technical approval was suggested to allow manufacturers to produce non-standard or innovative products compliant with building codes.

Recycling companies also stated that it would be beneficial if they could also use more fine aggregates (smaller than 2 mm) to produce RA.

The interviewees proposed the integration of new social networks as a tool to boost the utilization of RC products. These networks would facilitate collaboration among stakeholders engaged in demolition and construction projects, creating a marketplace for the exchange of aggregates. Additionally, they suggested establishing registers listing both ongoing demolition projects and upcoming building projects. This would enable stakeholders to track pending projects and foster cooperation between them.

Furthermore, the experts recommended the implementation of subsidy programs to incentivize the use of RC concrete. Such programs could provide financial assistance or other incentives to encourage the adoption of RC products in construction projects.

Another proposed instrument is ensuring equal treatment of RC concrete in the public tendering process. By incorporating ecological criteria, such as quotas for the use of secondary raw materials, into the decision-making process during tendering, the adoption of RC concrete can be promoted. This approach could incentivize companies to include RC concrete in their portfolio, thereby increasing its application in construction projects.

Furthermore, the introduction of certificates, such as those provided by the Concrete Sustainability Council (CSC), could serve as another driver for the increased use of RC concrete. These certificates would validate the sustainability credentials of RC concrete, potentially increasing its attractiveness to stakeholders and facilitating its adoption in construction projects.

Overall, the findings from both interviews and surveys indicate stakeholders' interest in utilizing RC concrete. However, barriers such as a lack of experience and supply of RC aggregates and concrete currently impede its practical application. To address these challenges, the establishment of a center dedicated to the production of RA and concrete, along with opportunities for networking and educational activities, is proposed. This concept, which can be realized through a DWRC, aims to provide a platform for stakeholders to collaborate, exchange ideas, and participate in educational initiatives to promote the use of RC concrete in construction projects.

4. Rhenish Revier as a Region of Interest

The RR, located in the federal state of North Rhine-Westphalia (NRW) in Germany, has been selected as a case study region for both analyzing the demand/supply of RC products and implementing the DWRC concept.

Notably, RR hosts the largest German coal mining area, making it a region of significant interest.

Several factors contribute to RR's selection. Firstly, the coal and lignite power plants in RR are planned to become obsolete by 2038 in line with the coal phase-out plan [33] of the German government. These decommissioned power plants offer a promising source of secondary raw materials for recycling [31]. Additionally, they provide an ideal location for establishing a DWRC [32]. Obsolete power plants are a potential source of high-quality recycled materials for RC production due to their availability, size, and homogenous material supply. These characteristics facilitate material distribution and incentivize industrial partners to explore investment opportunities in DWRC infrastructure.

Moreover, the shift away from coal mining will have a significant impact, including a decline in job opportunities. Consequently, the region is exploring new business models to replace the outdated lignite value chains. Introducing sustainable business models, such as the DWRC, can support the regional transition toward that shift. This approach aims to reduce resource consumption by establishing circular material flows within the building industry while also creating new jobs in the field of CE.

The supply of secondary raw materials for a DWRC extends beyond the material stock of obsolete power plants in the RR. Regional demolition activities, such as those involving residential and non-residential buildings, offer additional potential for supplying the DWRC with material input. To determine the necessary facilities and their sizes, the expected demand and supply of construction waste for secondary raw materials will be investigated in the following section. This analysis will provide insights into the requirements for establishing and operating the DWRC effectively.

4.1. Recycled Aggregates for Concrete Production

Today, RC concrete, which substitutes natural aggregates with recycled material, is recognized as a viable option in construction. RA can technically replace natural aggregates in concrete production by up to 100%. However, not all recycled aggregates can be used for RC concrete production due to regulatory constraints, including limitations on its application if directly exposed to water [19]. Additionally, German regulations limit the substitution of natural aggregates in concrete production to 45% [19].

The uncertainties within supply chains of secondary materials, arising from issues such as incomplete information about material quality and the heterogeneous nature of sources due to conventional demolition processes [34], pose additional challenges to the effective utilization of demolition waste as high-quality recycled materials.

To establish a DWRC, consistent material streams are essential. Therefore, two key aspects are investigated: (i) the construction waste production of the federal state of NRW as a potential material supply and (ii) the demand for RA in the RR.

4.2. Results of the Potential Supply for Demolition Waste Analysis

NRW, one of the most densely populated federal states in Germany, experiences a high frequency of construction and demolition projects. Annual demolition activities in NRW produce approximately 10 million tons of rubble, representing over 17% of Germany's total waste [12,29].

As the RR undergoes transition processes due to the coal phase-out, buildings and infrastructure associated with lignite-power plants will become obsolete, offering opportunities for reuse or recycling [33,35]. Notably, power plants contain substantial amounts of concrete, estimated at over 150 tons per MW capacity [36]. With NRW housing 28 coal and lignite power plants totaling 18.7 GW in capacity, around 3 million tons of concrete are expected to be generated in the coming years solely from power plants.

4.3. Results of the Potential Demand for RC Products Analysis

On average, 4,504 residential buildings (with a total area of 910,000 square meters) [28] and 598 non-residential buildings (with a total area of 600,000 square meters) [29] were completed annually between 2015 and 2019 in the RR.

To calculate the Material Capacity Index (MCI), which signifies the amount of concrete relative to the net floor area, the limitations on RC concrete utilization were investigated. This yields an MCI averaging at 1.1 t/m^2.

Given that RC concrete is limited to strength class C30/37 [19], adjustments were made accordingly. Concrete production data indicate that 81.5% of concrete is produced within or below this strength class [37]. Further reduction in RC concrete usage is applied due to restrictions on exposure classes if only 50% of the concrete produced corresponds to exposure classes permitted for RC concrete. Considering that up to 45% of natural aggregate may be substituted by RA depending on the exposure class, adjustments were made to the aggregate quantity.

The calculations indicate a requirement of approximately 200 kt and 220 kt of aggregates for residential and non-residential buildings, respectively, per year. Based on this estimation, the quantity of RA required was determined. For RC concrete production, two aggregate types can be utilized, differing in the distribution of concrete rubber and masonry/clinker rubble within the RA. An equal distribution of the two aggregate types was assumed in the analysis. The results indicate a necessity of approximately 110 kt of concrete rubble and 25 kt of broken masonry or clinker annually to produce residential and non-residential buildings in NRW with RC concrete.

The estimated 10 million tons of rubble, along with an additional 3 million tons of concrete expected from power plants in the coming years, are projected to fulfill the annual demand for approximately 110 kt of concrete rubble and 25 kt of broken masonry or clinker needed for RC concrete production. However, the data from demolition activities do not specify the type of waste generated (i.e., concrete rubble, broken masonry, or clinker). Furthermore, it is essential to note that only non-hazardous waste is suitable for the production of RC concrete. Such waste materials must undergo appropriate treatment or disposal procedures. Notably, there is a lack of data concerning the quantity of hazardous waste generated from power plant demolitions. This lack of detailed information may present challenges in accurately matching the available waste streams to the specific requirements for RC concrete production.

5. Concept for a DWRC

To address the limitations of current demolition recycling systems and meet the future demand for RA, a novel concept for a DWRC is proposed. Current systems suffer from logistical inefficiencies, such as disjointed operations across multiple locations and communication gaps between stakeholders. For instance, recycling companies typically receive construction and demolition waste from demolition sites and transport it to consumers after recycling, involving multiple intermediate steps [38–41]. This fragmented approach results in high transportation costs and environmental impacts due to repeated material handling and long-distance transportation. Transportation constitutes the primary environmental impact during the recycling of CDW [38], making the selection of an adequate location for a DWRC a key element for the successful implementation of a CE. Situating a DWRC in the RR, where large industrial buildings are expected to become obsolete in the near future due to outdated lignite value chains, offers the availability of high-quality recycled materials for RC production. Anticipated increases in demand and investments within the construction sector in this region, facilitated by funding opportunities [4], enhance the financial viability of the concept.

The proposed DWRC aims to streamline the recycling process by consolidating operations into a single facility. By integrating recycling, production, and distribution functions next to an obsolete power plant ready for disassembly (location is depicted in Figure 2, schematic drawing in Figure 3), the DWRC eliminates the need for multiple transportation stages and reduces associated costs and environmental footprints. This fiscal efficiency enables the investment into recycling strategies of CDW fractions previously overlooked due to economic constraints, such as wood. Moreover, centralizing operations facilitates better coordination among stakeholders and ensures the consistent quality of RC products. Additionally, by establishing a dedicated facility for recycling and distribution, the DWRC can optimize its service area and capacity, improving economic efficiency and reducing environmental impacts associated with transportation.

A novel conceptualization of a high-quality recycling plant for mineral material waste, which forms part of an integrated DWRC comprising additional production sites for other CDW fractions such metals, wood, glass, etc., and educational divisions (see Figure 2). By integrating recycling companies and manufacturers (e.g., precast concrete) within a single venue, the DWRC aims to improve communication among stakeholders.

Furthermore, the absence of knowledge and experience among planners in utilizing RC products has been identified in part 3 of this research as a significant challenge. Therefore, the inclusion of an educational division in combination with research units as part of the DWRC aims at generating and disseminating knowledge to stakeholders. Previous studies [31,32] have primarily focused on the technical aspects of recycling plants, such as mechanical properties. However, establishing a robust stakeholder constellation is crucial for the successful realization of the pilot project. Various best practice projects in different European countries [42–44] have also combined Research and Development (R&D) units at the same location as the recycling plants and have been proven to support economic prosperity [32]. Additionally, numerous best practice projects [45–47] incorporate various industries adjacent to the recycling plant, fostering synergies between material flows [32].

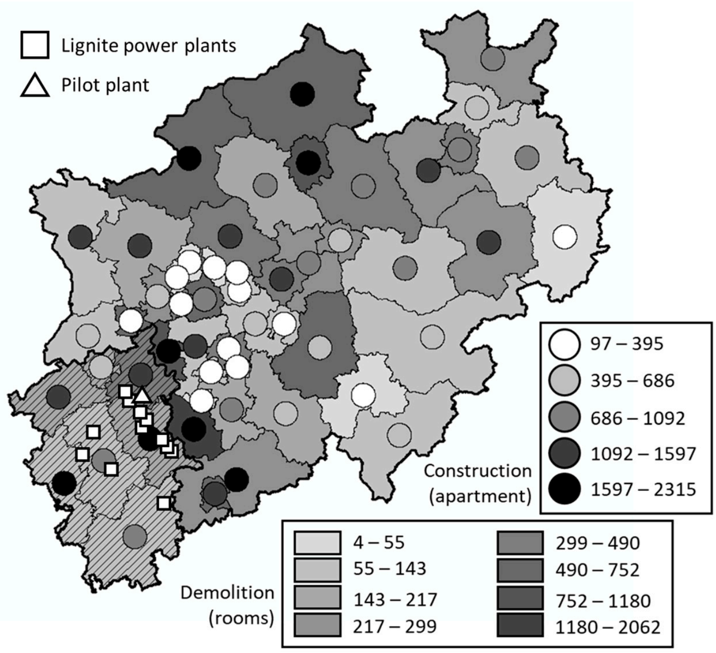

Figure 2. Location of power plants, demolition, and construction activities in the federal state of NRW [29,31,32,35].

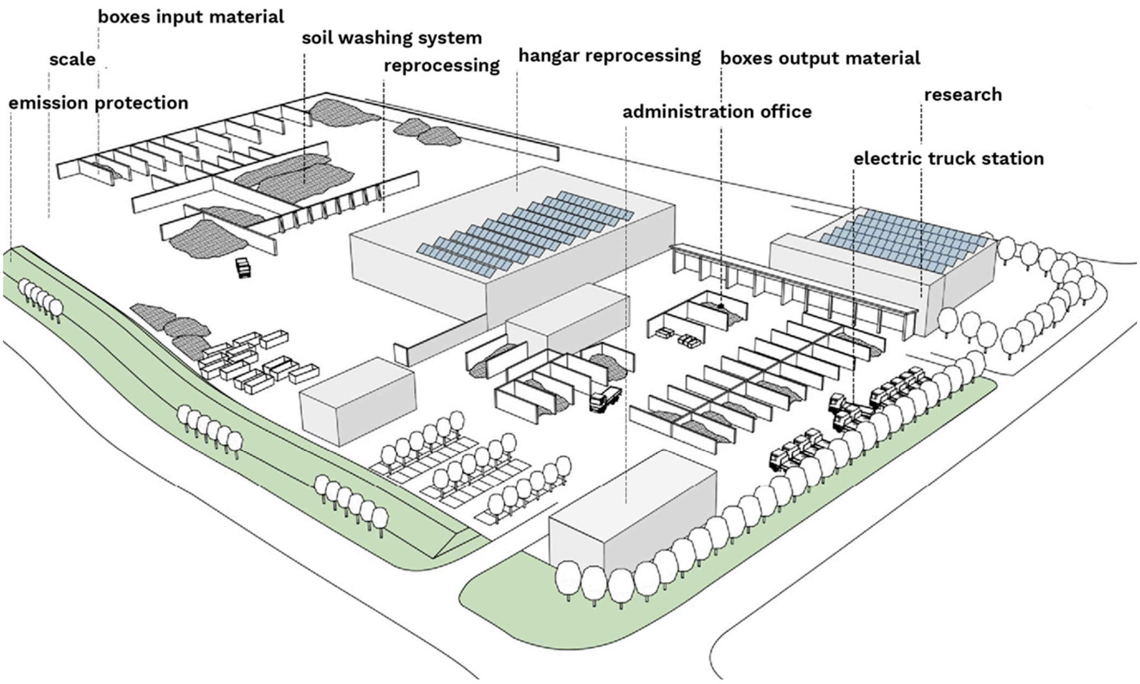

Figure 3. Visualization of DWRC [48] including the location of administrative and research units, next to outdoor and indoor storage facilities (containers for input and output materials), and technical systems, such as a soil washing system and scale. A surrounding berm is incorporated to mitigate acoustic disturbances and potential dust emissions to safeguard the neighboring community.

Additionally, insights gleaned from surveys and interviews were applied to the concept of the DWRC. To address the requirement for enhanced knowledge and research concerning RC products, the DWRC concept envisions the integration of diverse stakeholders from various research fields and incorporates R&D units. Moreover, the concept emphasizes the coordination of different operations, such as production, service, research, and education, to facilitate improved knowledge transfer among stakeholder groups.

5.1. Initiating the Process of DWRC Realization

The development of the DWRC concept was initiated in 2016 as part of the "Circularity in the Built Environment" regional development project, which spanned from 2016 to 2018. During this period, the conceptualization process was conducted [49], resulting in the formation of a stakeholder network comprising the power plant's owner and a potential purchaser of secondary material. These stakeholders tested the power plant's substance to assess its suitability for concrete production.

Subsequent investigations were carried out by academic personnel, including both conceptual [32] and technical studies [31]. Building on the findings and conceptualization, a funding proposal was jointly submitted by the municipality, the power plant owner, and a recycling company in 2020. This proposal aimed to facilitate the successful realization of the DWRC, encompassing research and educational services.

Continuing the initiative, the follow-up project named "ReBAU" was launched, spanning from 2020 to 2022. This phase further refined the funding proposal and culminated in the publication of a Letter of Intent (LOI). This document garnered support from associations, recycling companies, and other stakeholders, including purchasers, affirming their commitment to the establishment of the DWRC [50]. Figure 4 illustrates the initiation process.

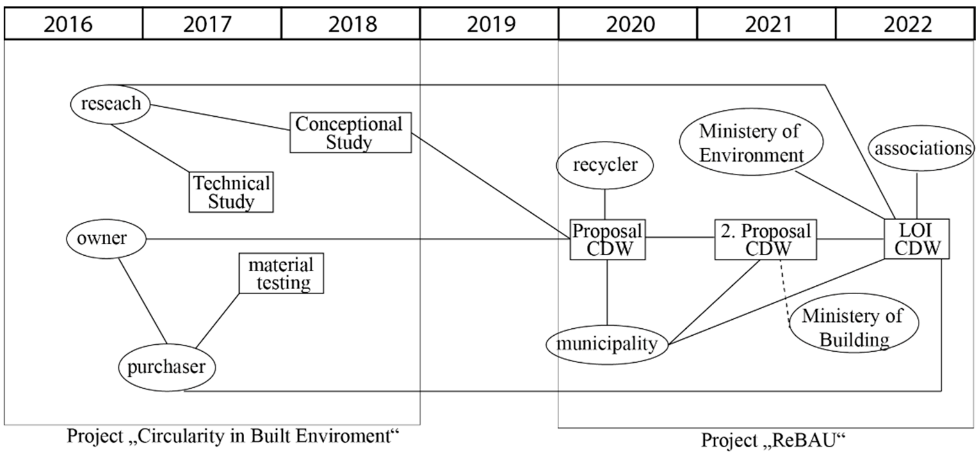

Figure 4. DWRC initiating process was conducted during two projects "Circularity in the Built Environment" (2016–2018) and the follow-up project named "ReBAU" (2020–2022). Various stakeholders were engaged, including owners, purchasers, municipalities, Ministry of Building Affairs (partly involved), Ministry of Environmental Affairs, associations, recycling companies, and research institutions. Several outputs were produced throughout this process, including funding proposals, Letter of Intent [50], technical [31] and conceptual studies [32], and material testing.

5.2. Roadmap for a DWRC Development

To summarize the key steps toward the realization of a DWRC, a phased approach as a roadmap was developed, depicted in Table 1. It begins with the deployment of a mobile recycling plant and progresses toward the establishment of a stationary plant at a former coal power plant site. R&D activities, educational initiatives, and stakeholder engagement are integral components of the roadmap, aimed at ensuring the success and sustainability of the DWRC.

Table 1. Roadmap for DWRC development.

Phase	Objective	Approach	Outcome
Mobile Recycling Plant	Produce high-quality RA for concrete products.	Station a mobile recycling plant near dismantling projects.	Establishment of a reliable source of RA for concrete production.
Stationary Plant	Expand operations to a stationary plant at a former coal power plant site.	Utilize a sensor-controlled system for material sorting of mixed waste.	Enhanced efficiency in recycling processes through sorting of mixed waste, manufacturing of concrete products, and storage for resale.
Research and Development Activities	Focus on developing sorting systems and final products, addressing technological advancements and innovation.	Engage in research activities to optimize sorting processes and improve the quality of recycled products.	Research and development of sorting technologies and testing and validation of final products.
Educational Units	Address the demand for information identified through surveys and interviews.	Develop educational formats to disseminate knowledge about recycled products and processes.	Design and implementation of educational programs, workshops, and training sessions to increased awareness and understanding of recycling practices among stakeholders, fostering adoption and collaboration.
Stakeholder Network	Establish a network of relevant stakeholders and a registry of available secondary resources.	Engage with stakeholders to build collaborative partnerships and facilitate resource sharing.	Networking events, stakeholder meetings, and development of resource databases to strengthen collaboration among stakeholders and optimize utilization of secondary resources.
Realization Process	Proceed with the realization of the DWRC based on thorough investigation and holistic conceptualization.	Implement the DWRC concept derived from previous studies and stakeholder consultations.	Execution of funding proposals, regulatory approvals, and project management.

In the initial phase, high-quality RA for concrete products will be generated using a mobile recycling plant on the site of an obsolete power plant. The position of the mobile plant near dismantling projects secures homogeneous waste streams, which result in high-quality RA. Here, a sensor-controlled system will be employed for the material sorting of mixed waste. Additionally, concrete products will be manufactured and stored for resale purposes.

Following, research activities will be undertaken to refine the sorting systems and enhance the quality of final products. Moreover, educational initiatives will be developed based on the insights gathered from the demand for information identified in previous surveys and interviews.

To complement the concept, a network comprising relevant stakeholders will be established, along with a registry detailing the available secondary resources.

6. Discussion

The comprehensive adoption of RC products encounters several obstacles outlined in Heading 3 through surveys and interviews. However, it is essential to acknowledge that the conclusions are subject to uncertainty due to the restricted number of interviews conducted and the participants' limited experience with the application of RC products.

An important finding from the survey is the recognition by concrete producers of a significant barrier: the absence of manufacturers specializing in producing RA specifically for concrete production. This shortfall contributes to a restricted supply of RC concrete. Additionally, a factor not addressed in interviews but worthy of consideration is the reluctance among companies to invest in new innovations and machinery for producing high-quality recycled aggregate [24,51]. This situation causes a dilemma leading to a lack of demand for RC products and their unavailability on the market. Simplifying regulations and disseminating knowledge about the application of RC products among stakeholders could potentially resolve this issue. However, it remains uncertain whether the establishment of a DWRC can effectively address these obstacles. Therefore, facilitating knowledge distribution and closing communication gaps between stakeholders are crucial steps toward overcoming these challenges. However, such efforts can be operated independently of the concept of a DWRC.

Additionally, the image of RC products as "waste" materials, despite possessing similar properties to conventional building materials, compounds the challenge. It remains uncertain as to whether the establishment of a DWRC alone can address these hesitations toward RC products. While providing educational facilities may aid in overcoming these challenges, raising social awareness about the benefits of RC products, streamlining regulations for their application, and enforcing quotas for RA usage are essential steps toward achieving circular material streams.

Developing a well-designed and meticulously planned facility and technology for a DWRC represents a crucial step toward establishing a long-term solution for addressing the existing gap between supply and demand for RC products. By estimating the anticipated distribution of future demand and supply for RC products, it becomes possible to estimate the appropriate size of DWRC facilities. However, uncertainties persist, particularly regarding the potential impact of new regulations or unforeseen advancements in recycling technologies on the market. For instance, the emphasis on material reuse may introduce new economic opportunities requiring different logistical and technological infrastructures. Therefore, it is imperative to conduct a more comprehensive study encompassing various scenarios for DWRC application, incorporating realistic estimations of economic factors. Additionally, estimations of the anticipated distribution of future demand and supply of other CDW fractions, such as wood, metal, and glass, should be conducted to broaden the CWRC facilities beyond mineral fractions.

Additionally, a validation of the proposed conception of the DWRC after realization is recommended.

7. Conclusions and Outlook

The presented results of interviews and surveys reveal a strong interest among stakeholders in utilizing RA for concrete production to address the environmental impact of the construction sector. However, practical adoption remains limited due to, for example, a lack of information among stakeholders regarding regulations, costs, funding opportunities, and networking opportunities. Several suggestions were made to promote the usage of RC products, including implementing recycling quotas. Additionally, the integration of new stakeholder networks was proposed to facilitate collaboration and information sharing.

To address these barriers, a DWRC concept is proposed, aiming to centralize RA and concrete production while providing networking, research, and educational opportunities for stakeholders to promote the adoption of RC products in construction projects.

To prove the availability and possibility of using construction waste in high-value applications, the use of RC concrete and the demand for RA for new building construction in the RR as a region of interest was calculated by approximately 110 kt waste concrete and 25 kt of masonry rubble per year. These figures are relatively small compared with the potential supply either from the current recycling system or from the demolished power plants in the coming years. The fact that RC concrete is still used on a small scale is due to various reasons. Producing RC products does not depend only on the technical feasibility but also on socio-economic aspects (e.g., acceptance and knowledge of stakeholders) as results show from the interview and surveys, legal aspects such as regulations enabling equal treatment during the tendering process, and logistical aspects such as the materials' location close to the recycling and production plants.

The presented concept of a DWRC, where recycling companies and manufacturers are in close proximity to a demolition object of the size of a power plant, can be a solution to increase the application of RC products. But besides the establishment of an innovative facility, additional interventions need to take place such as, for example, the establishment of a robust network between all relevant stakeholders to facilitate knowledge transfer. It is recommended to moderate and support information exchange by establishing and maintaining a network through an independent institution.

Further investigations on other potential RC products can be also helpful in attracting more investments and stakeholders on the venue of a DWRC.

Transferability and Future Research

The aspect of transferability represents another key aspect in the widespread adoption of CE practices. Hence, there is a pressing need for further investigations into establishing similar pilot projects for DWRCs in other regions across Germany and Europe. The outlined initiation process in Section 5.1 can serve as a valuable starting point for this.

Similarly, decommissioned coal and lignite power plants or other large-scale structures present suitable locations where substantial quantities of construction waste can be available. Within this study, potential future demolition sites for power plants in the RR are outlined in Figure 2, Section 5. To facilitate tracking of upcoming demolition projects, the establishment of a register on a national level detailing the locations, schedules, and nature of pending demolitions would be instrumental. Such a register would enable stakeholders to coordinate and exchange information regarding potential material sources effectively.

Regions that host large-scale industrial structures are likely to become obsolete soon due to transformation processes or shifts in global supply chains. Here, the adoption of the proposed concept can catalyze recycling activities, particularly in states that are falling behind in achieving the recycling goals set by the EU. However, further research on economic analyses will be required to contrast the prospective benefits with the required costs and investments of DWRC concepts.

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