Urban Mining of Mineral Building Materials in the Ruhr Area: A Spatial Analysis

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Abstract

The concrete industry in the Ruhr region faces critical challenges, including primary raw material shortages and the need to reduce anthropogenic greenhouse gas emissions. Immediate action is essential as primary resources remain necessary even with secondary raw materials being used, and cutting emissions is crucial to mitigate climate change. This research proposes that establishing a Resource-conserving Concrete Hub (RCH) can positively affect the image and efficiency of Resource-conserving Concrete by unifying key stakeholders and integrating new participants. The Ruhr region, with its dense population, rich industrial history, and polycentric structure, seems to provide an ideal setting for implementation. Although current data on urban mining is insufficient for precise planning, as a material registry has not been implemented yet, the study identifies promising locations, particularly the Essen city harbor, as prime candidates for advancing the RCH concept and therefore boosting urban mining practices within Germany.

Keywords: Resource-conserving concrete, Urban Mining, Recycling hub, Location-Allocation analysis, Ruhr area

1. Introduction

Concrete, due to its material properties, is an inherent component of modern construction, leading to a global demand for the building material like no other (Miller et al., 2016). In 2020, according to the Global Cement and Concrete Association (GCCA, 2023), approximately 14 billion m³ of concrete were produced worldwide. This trend can be attributed in part to factors such as a growing global population, increasing urbanization, and a continuously expanding global economy (UNEP, 2022). Resulting in a threefold increase in demand over the past 40 years (UNEP, 2021).

However, due to the high demand and therefore production of the mineral building material, challenges such as resource security, as well as climate and environmental protection, are gaining increasing relevance. For instance, during the production process of concrete, approximately 280 kg of CO_2 are emitted per cubic meter of the building material being produced (LANUV, 2021), making the production of concrete responsible for around 8.6 percent of anthropogenic climate potent emissions (Miller et al., 2016). The high amount of climate potent greenhouse gas emissions in concrete production can be attributed mainly to the production process of clinker for Portland cement production - an elemental component of concrete - and partly to the transport of the building material and its primary raw materials (Miller et al., 2016; LANUV, 2021).

Due to the high demand, sand is considered one of the most heavily exploited resources worldwide after water (UNEP, 2022). The extensive extraction of this mineral resource also has negative effects on regional ecosystems and the water cycle (Albrecht-Saavedra and Lippelt, 2015). Consequently, a significant portion of the remaining raw material reserves in Germany has been protected from further extraction efforts by conservation initiatives, leading to potential regional shortages of primary raw materials as the industry has failed to transition early to alternative secondary raw material sources (VDZ, 2022; Elsner, 2018). Such scarcity increases distances to be traveled, further negatively impacting the environmental footprint of the raw material, and consequently of concrete as a building material, while also intensifying the economic and (geo-)political pressure on business and political entities to explore alternative sources of raw materials (Arora et al., 2017; Fluchs and Neligan, 2023; Hilgers and Becker, 2019).

As such, Urban Mining of construction and demolition waste (CDW) can serve as an alternative source within the Circular Economy (CE), being necessary to face upcoming raw material shortages. By utilizing locally sourced recycled aggregates (RA), the demand for primary raw materials can be reduced, thereby lowering extraction levels. Additionally, it helps prevent the landfilling or inferior recycling of materials classified as waste according to the Waste Framework Directive, through downcycling processes. Within the framework of the CE, materials obtained from dismantled structures are sorted and processed before being reintegrated into concrete production and ultimately used in construction (Müller, 2018).

In Germany, mineral CDW constitutes the largest material flow within the national waste balance, amounting to 229.4 million tons (55.4 %). Out of this total, approximately 95 percent (218.8 million tons) are classified as non-hazardous waste and are thus eligible for recycling (UBA 2022c). However, only materials categorized as construction debris, totaling around 59.8 million tons, are suitable as RA in concrete production and therefore eligible for being reused in building construction (bbs 2021; Müller 2018).

A majority of all mineral CDW in Germany undergo further processing (89.7 %). However, the recycling rate of these waste materials is only 33.7 percent (bbs 2021), with the definition by bbs encompassing downcycling processes such as usage in road substructures. Consequently, the use of RA in the production of resource-conserving concrete (R-Concrete), and thus an adequate recycling process in line with the CE, is exceedingly low, at approximately 0.9 million metric tons (VDZ 2021).

While the substitution of sand and gravel can notably alleviate the impacts of the described raw material shortages, reducing climate potent greenhouse gas emissions in concrete production necessitates the substitution of clinker in cement production. This substitution is already practiced on a large scale, resulting in a 30 percent reduction in clinker and thereby nearly the entire greenhouse gas emissions in cement production through the use of fly ash and slag sand (VDZ 2022; VDZ 2020). However, due to the planned coal phase-out in Germany and the transition to hydrogen in the steel industry, a significant reduction in the availability of both substitutes is expected in the near future (Voland and Westendarp 2021; Holcim Deutschland 2021; acatech 2023). Current research and initial practical attempts indicate that the current substitutes can be replaced by RA from construction waste processing; however, further research and experiments are needed to implement this on a similar scale (Kytzia and Stürwald 2021; Müller et al. 2020; Holcim 2023). The VDZ (2022) predicts the share of RA in concrete production to reach around 26 percent by 2050.

Consequently, the concrete industry is currently undergoing a transformation out of necessity. In order to sustainably remain competitive and meet the climate targets outlined in the Paris Climate Agreement, a restructuring of current processes is imperative to transition the linear economic system to a CE.

Thus, this study develops a concept of an Resource-conserving Concrete Hub (RCH), which aims to consolidate relevant stakeholders in one location and thereby enables the utilization of synergies. In doing so, the concept of an RCH is being based on, but not limited to already existing concepts (e. g. Müller and Kurkowski (2017) and Zabek et al. (2024)). Building upon this, the identified location factors of the stakeholders are transferred to the Ruhr area through a spatial analysis to identify an ideal-typical location for its implementation.

2. Methodology

2.1 Development Of A Resource-efficent Concrete Hub (RCH) Based On Expert Interviews And Literature Review

The primary aim of developing an RCH is to achieve high-quality and efficient processing of mineral construction waste of dismantled buildings and the utilization of recycled aggregate in concrete production, which is then used in building construction. Additionally, a modular system is developed, which can be adapted based on existing local requirements as well as site conditions and aims to enhance the hub's accessibility to a broader audience.

This is based on a transformation from the currently limited mineral material cycle in the concrete industry (see Figure 1) towards a circular cycle based on urban mining of secondary aggregates and their usage in concrete and cement production (see Figure 2).

The concept of the RCH is based on three semi-structured expert interviews conducted with representatives from Remex (construction waste processing), Holcim (concrete and cement production), and Madaster (provider of a materials passport) in early 2023. The information gathered from the interviews was compared with existing literature, particularly a feasibility study by Müller and Kurkowski (2017) in the Rhenish lignite mining area, and best practice examples such as those by Feeß (Heinrich Feess GmbH & Co. KG 2023) in southern Germany.

Based on this, a catalogue of requirements for the core businesses was subsequently developed, serving as the basis for the site selection process.

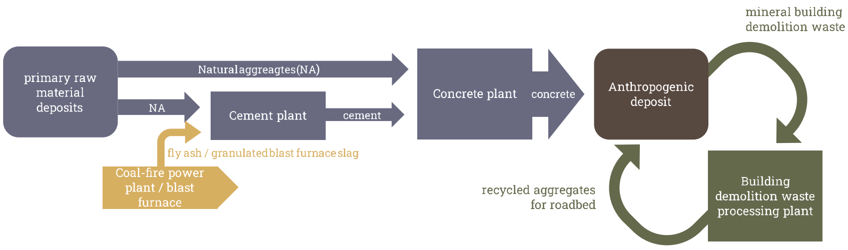

Figure 1: current and primarily linear system of concrete production.

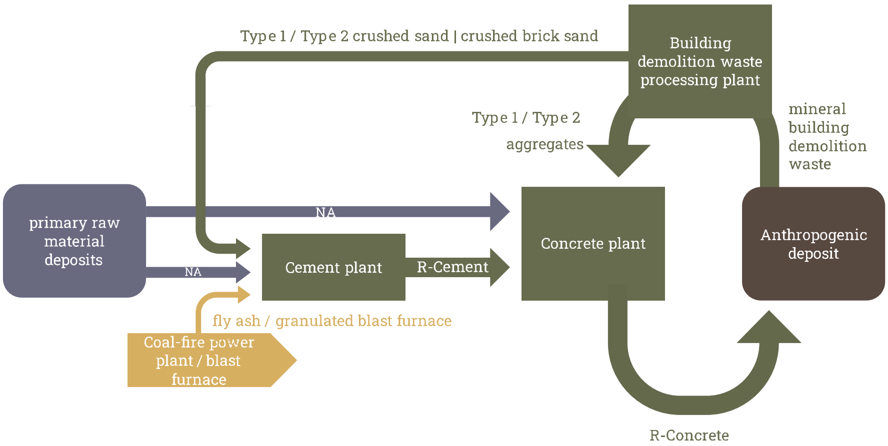

Figure 2: possible circular economy in concrete production.

2.2 Spatial Analysis With Geo Information Systems (GIS)

The objective is to identify specific regions and zones within the Ruhr region as a representative area, conducive to the establishment of an RCH. This entails conducting a Location-Allocation Analysis. Initially, emphasis is placed on the concrete evaluation of hard location factors, namely secondary raw material accessibility for the construction waste processing facility and the market viability for R-Concrete. To prevent peripheral zones within the study area (Figure 3) from being disadvantaged, data within a 20 km radius is also factored in, with the exclusion of areas in the Netherlands due to data limitations. Subsequently, the chosen areas from each category undergo a reevaluation to assess their suitability within the local context, thereby eliminating unsuitable locations like sites being completely surrounded by residential uses or not adequately connected to existing feasible road infrastructure.

Figure 3: Study Area | Data Source: GEOportal.NRW (2023).

The applied network layer is based on a dataset from Geofabrik (2023), which consists of data derived from OpenStreetMap. Further processing of the data regarding intersection points is required.

Based on the identified location requirements described in Chapter 3.2, cement plants, coal-fired power plants, and port areas located in the Ruhr region are considered as potential sites separately. The areas designated in ALKIS as commercial and industrial zones are filtered based on their distance to residential areas (overlaid with a 250 m buffer) and size (3.05 hectares).

For the indicator of secondary raw material availability, there are no data available for the study area regarding material availability or demolition volume. Therefore, the formula proposed by Müller (2018) is employed, where the population serves as an indicator for calculating the amount of construction waste (Figure 4). Census data from the most recent census conducted in 2011 (Statistische Ämter des Bundes und der Länder 2011) are used as the basis for this analysis as they are found to be the most recent data based on their scale. To further refine the respective areas, the data from each one-square-kilometer grid cell are transferred to the built-up areas within the corresponding square. However, due to data limitations, drawing conclusions about the generated construction waste based on population density is not feasible, resulting in only a weighting being considered.

$$Catchment\ Area = \frac{Annual\ \ Capacity}{Population\ \ Density\ * per-capita-volume}$$

Based on

catchment area in km²

annual capacity in t

population density in inhabitant/km²

*per-capita-volume in t/inhabitant*a*

Figure 4: Equation used for assessing the expected availability of secondary raw material based on Müller (2018).

As a demand indicator, construction activity within the municipalities is applied. A high-quality and available information source is the completion of residential and non-residential buildings within the last 10 years at the municipal level in square meters of floor area (IT.NRW 2022). The application of this dataset is based on the assumption that construction activity and concrete consumption are strongly positively correlated, although this correlation is not precisely quantified. By using the average of the data from the last 10 years, possible fluctuations (such as the completion of a new housing development within a rural municipality) within the dataset are expected to be better balanced. These data were also intersected accordingly with the ALKIS settlement areas, open spaces such as cemeteries and parks being excluded beforehand.

To assess a site's suitability for establishing the core elements of an RCH, it is therefore necessary to integrate both of the indicators described earlier. Since the respective values are in different units of measure (people and square meters), a simple multiplication is not appropriate. Therefore, it is necessary to group the values into categories, opting for categorization based on natural breaks (Jenks (ESRI 2023)). The data are standardized on this basis and divided into five groups. The layer containing the census data is considered a suitable scale for this purpose, as it evenly subdivides the entire study area into 1 km² squares. A larger scale is deemed too coarse, while a smaller scale increases the data inaccuracy of the secondary raw material indicator, as the original information is based on the shapefile of the 1 km² parcels used. To increase the weighting of densely populated areas with extensive construction activity compared to regions with low population and below-average construction activity, it is decided to multiply the two categorized indicators (1 to 5) together in a final step. Consequently, the range between "sparsely populated and low construction activity" to "densely populated and high construction activity" is 1 to 25.

3. Results Of Interviews: The Concept Of A Resource-conserving Concrete Hub (RCH) And Its Location Factors

3.1 The Concept

A new proposal for an RCH is suggested to overcome the limitations of current demolition waste recycling systems and to fulfill the future demand for Recycled Aggregates (RA). Existing systems face logistical challenges such as fragmented operations across various sites and communication gaps among stakeholders (Remex 2023; Holcim 2023; Madaster 2023;

Zabek et al. 2024). Typically, a building is being demolished by a demolition company, in the following recycling companies collect construction and demolition waste from demolition sites, then transport it to their recycling plant and to consumers, e. g. concrete mixing plants, after recycling, involving multiple intermediate steps. This fragmented approach leads to high transportation costs and therefore environmental impacts due to repeated material handling and long-distance transportation. Transportation is identified as the primary environmental impact during the recycling of demolition waste (LANUV 2021; Hilgers and Becker 2019). Consequently, consolidating stakeholders at a single location reduces travel distances or even ways and can furthermore improve communication between the different stakeholders.

The core of the RCH consequently consists of processing facilities: the cement plant, the construction waste processing plant, and the concrete mixing plant, as these are essential for the production of R-Concrete. Depending on factors such as the size of the site and demand, this core group of companies can be expanded to include additional stakeholders.

The expansion of the RCH in this work is divided into four categories: *Complementary businesses*, *education and research*, *services and institutions*, and *public stakeholders* (Müller and Kurkowski 2017; Zabeck et al. 2024; Holcim 2023; Remex 2023; Madaster 2023).

The group of *complementary businesses* comprises companies involved in various aspects of the R-concrete recycling process, complementing the functions of core businesses. Benefits of integrating those, who are directly involved into the recycling process, e. g. demolition contractors, is emphasized due to the coordination required among stakeholders (Holcim 2023). The potential for knowledge spill-over in the form of Porter Externalities is expected. However, spatial proximity does not reduce transportation distances in this particular example, as demolition contractors still need to travel to the demolition site and return machinery to their premises after completion. Nevertheless, they do benefit from the central location of the RCH as well. On the other hand, logistics companies specializing in construction waste benefit from proximity due to localization effects, significantly shortening the distance traveled after delivering construction waste, thereby minimizing empty return trips. However, these companies benefit minimally from dynamic agglomeration effects. To further promote the use of RA beyond R-Concrete production, additional businesses should be established to utilize RA as a secondary raw material. The production of brick substrates or precast concrete enables the utilization of those secondary raw materials which, due to their suitability or volume, are not eligible for concrete production, while utilizing industries still benefiting from the same agglomeration effects as the core businesses (Müller and Kurkowski 2017).

Integrating *educational and research* facilities within the RCH is expected to foster collaborations between these institutions and other companies within the RCH, enabling practical education and industry expert involvement. This synergy can enhance expertise and therefore stimulate demand for R-Concrete. For monitoring R-Concrete production, sampling by external entities is essential (Holcim 2023, Remex 2023). This task can be delegated to the university, scientific institutes, or specialized labs, benefitting from efficient oversight due to proximity (Zabek et al. 2024).

The group *service industry and institutions* encompasses architecture, planning, and engineering firms, along with authorities and industrial associations. Integrating these stakeholders can facilitate knowledge exchange within the RCH, potentially increasing the consideration of R-Concrete as a construction material in building projects. Furthermore, the needs of service companies in R-Concrete production can be better addressed and potentially accommodated. As a result, the presence of service companies can enhance the expertise of all involved actors and stimulate demand for the material. Further, establishing reputable service companies within the RCH elevates the site's profile, attracting attention to R-Concrete and enhancing its image as a building material. Soft agglomeration effects, alongside tangible location factors, are crucial for the hub's success as a service destination. Incorporating municipal stakeholders and industry-specific associations demonstrates official confidence in the secondary building material, aids in site profiling, and streamlines quality assurance through simplified monitoring channels.

Including event spaces and gastronomy as services being open to the broader *public* within the hub can have multiple benefits. For example, integrating event spaces, as demonstrated by Feeß (Heinrich Feess GmbH & Co. KG 2023), allows companies within the RCH to showcase their progress publicly. A cooperation with a university is conceivable due to its demand for lecture halls, as both require similarly sized facilities. External events can also attract individuals from outside the field to the RCH, positively influencing public perception of R-Concrete, thereby improving its current negative image (Remex 2023; Holcim 2023; Madaster 2023). To showcase the material's versatility and expertise, the establishment of an exhibition ground for events such as the Solar Decathlon or circular construction-themed fairs is necessary. Likewise, implementing gastronomic offerings can invite external visitors to the RCH, while providing lunchtime benefits for workers and students. The incorporation of green and blue infrastructure can also have a similar effect, enhancing the appearance and sustainable function of the commercial and industrial district, especially during times of climate change.

However, the concept avoids integrating multiple core processing plants of the same type. This assessment is based on the limited operating radii of these facilities, determined by ecological, economic, and technical factors. If the capacity of a plant is exceeded, it is therefore considered more sensible to place additional facilities outside the RCH to maximize operating areas and minimize transportation routes. This can accordingly have a positive impact on the ecological footprint and cost-effectiveness of R-Concrete.

Therefore, the establishment of an RCH can be deemed beneficial. It is important to note that it is a mixed-use high-quality commercial and industrial district, with its conceptual center being the core businesses. However, due to their emitting nature, a certain distance between the industrial and the other areas is necessary to avoid conflicts. Green and blue elements can help create this distance, while elevation differences can also aid in overcoming these challenges.

Concluding, the presented concept of an RCH focuses primarily on stakeholder knowledge exchange, reducing transportation distances, and improving the image of recycled building materials. Therefore, stringent collaboration among stakeholders is essential to realize these aspects fully; otherwise, potential benefits may remain untapped. While the impact of soft location factors on the success of core businesses is considered secondary, they are mandatory for other stakeholders, particularly office and public uses.

Additionally, using recycled building materials during the hub's construction phase can facilitate the establishment of both service and core businesses involved from the outset. It can also create a living laboratory, demonstrating the feasibility of a high-quality district built with recycled materials, thereby helping to reduce reservations about their use.

3.2 The Location Factors

As the design of the RCH entails a modular system centered around the core enterprises of R-Concrete production (construction waste processing plant, concrete mixing plant, cement plant), with the remaining actors being variable, the subsequent discussion focuses solely on the spatial requirements of these core stakeholders.

Given limited impact of globalization on supply chains within R-Concrete production, the selection of processing plant locations aligns with Weber's Industrial Location Theory. This implies that proximity to raw material suppliers and customers predominantly dictates site selection (Farhauer and Kröll 2013). Analyzing various transportation modes and networks aims to minimize transportation costs, thereby mitigating ecological and economic burdens. Figure 5 depicts the salient location factors pertinent to the three involved enterprises, illustrating their mutual complementarity. It underscores that diverse location requirements coalesce rather than conflict, emphasizing the interconnectedness of stakeholders in R-Concrete production. Notably, three pivotal factors in location selection emerge across stakeholders: location within an industrial area, Distance to residential areas and good road connection. Therefore, good street connection sites ideally situated in urban industrial zones yet maintaining distance from residential areas to sustain demand and resource availability while safeguarding sensitive land uses are considered ideal locations.

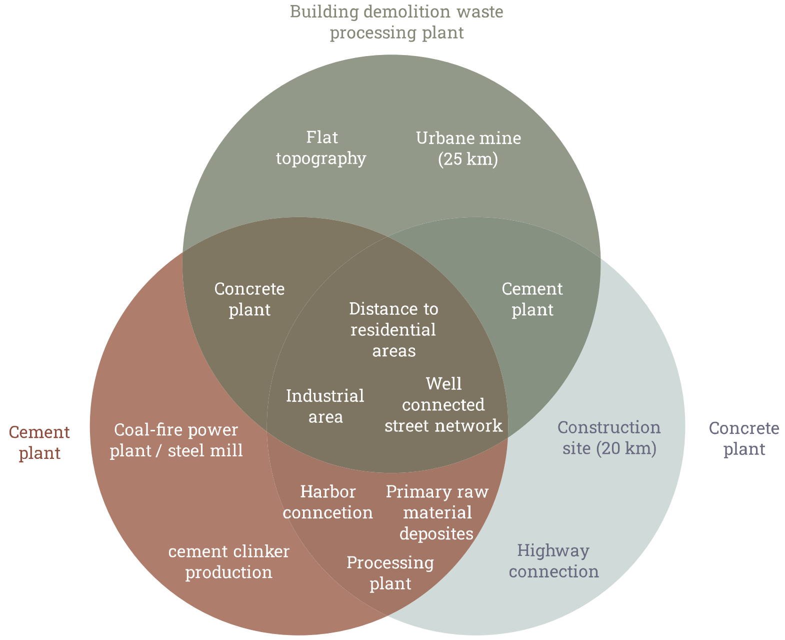

Figure 5: Location Factors of an RCH.

Hence, when selecting a site for the RCH, it is important to consider maintaining a sufficient distance from sensitive land uses, although this distance cannot be universally quantified.

Additionally, high demand for construction materials, a comprehensive supply of construction waste, and good accessibility to the site are fundamental requirements.

Further, economic factors make integration with an existing cement plant highly advantageous. If such a plant is being planned, careful consideration should be given to integrating an RCH, especially the remaining core enterprises. However, establishing a cement plant as part of the implementation of an RCH is considered challenging. Therefore, already existing plants may be a well suited location for being extended by an RCH and hence should be considered within the location analysis.

The establishment of an RCH is particularly suitable in close proximity to water bodies also as these can be used to transport necessary primary aggregates. Although, it might not be as relevant for concrete production today, the region's limited availability of local primary aggregates will likely make importing them from further regions necessary in the future (Holcim 2023; Remex 2023; Elsner 2018). Furthermore, part of the dock area can enhance the site's appearance and be developed into a waterfront promenade, expected to have a positive impact on the other stakeholders. Therefore, port areas and areas adjacent to a canal are considered particularly suitable.

Former power plants and coal-fired power plants, on the other hand, are suitable for the establishment of an R-Concrete Hub due to their large size, high existing sealing rate, and established industrial use. Additionally, many of these plants have established connections to the waterway network. The dismantling of existing structures can also serve as a catalyst to establish the concept further.

In general, consideration should be given to selecting sites that are already sealed. The establishment of an RCH on greenfield sites may be necessary in certain cases but should only be considered as a last resort due to the project's sustainable nature, after all alternatives have been exhausted.

For further site analysis, additional exclusion criteria are applied to narrow down the areas to be considered. Accordingly, only existing industrial areas with some distance to residential use and large enough to accommodate at least a construction waste processing and a concrete plant (about 3.55 ha according to Müller (2018) und Holcim (2023)), cement plants, port facilities, and coal-fired power plants are taken into account.

4. Results Of The Location-Allocation-Analysis

The Ruhr Area is of particular interest as a case study region for implementing an RCH due to various reasons. According to the Geologischer Dienst Nordrhein-Westphalen (2022), the local primary resource reserves of gravel and sand are projected to last for 21 and 33 years, respectively. However, due to extraction limitations, supply shortages emerged as early as 2017, leading to significant increases in primary resource costs (Elsner 2018; Hilgers and Becker 2019). Consequently, the exploration of alternative resource sources through urban mining is attributed particular significance for this region, leading to a higher need for action.

Additionally, the Ruhr Area covers an area of 4,438 km² divided into 53 municipalities with an average population density of 1,149 inhabitants/km² (RVR 2021), making it one of the fifth largest metropolitan regions in the European Union with around 5 million inhabitants (Statista 2022). The region's rapid development during the industrial revolution has resulted in a structurally heterogeneous polycentric region, consisting of independent large, medium, and small towns, which are considered unique in Germany and Europe (Reicher 2022). It is expected that this regional structure will facilitate the implementation of an RCH, as it allows for placement not only in peripheral areas but also in the region's center as well as providing high enough resource flows.

Expanding the study area to include a 20 km radius around the Ruhr Area's borders results in a total area of 11,227 km², encompassing or intersecting 159 municipalities in North Rhine-Westphalia. Of the 2,535 km³ designated as settlement areas according to ALKIS within this expanded area, representing areas eligible for development excluding existing open spaces within municipalities, 52 percent are within the Ruhr Area, despite it occupying only 39.5 percent of the total area. Within the Ruhr Area, the proportion of settlement areas is particularly concentrated in centrally located municipalities, where their share of the total area is particularly high, such as Herne (58.4 %), Oberhausen (56.4 %), Bochum (53.2 %), Essen (52.0 %), Gelsenkirchen (51.6 %), and neighboring municipalities.

The spatial distribution of the population within the study area per square kilometer, based on the 2011 census, is illustrated in Figure 6. Within the Ruhr region, the central residential areas of the municipalities of Duisburg (≤ 14,756 inhabitants/km²), Dortmund (≤ 14,741 inhabitants/km²), Gelsenkirchen (≤ 2,415 inhabitants/km²), Oberhausen (≤ 12,380 inhabitants/km²), and Essen (≤ 11,365 inhabitants/km²) stand out due to their particularly high population density. The northern part of the Ruhr metropolis is comparatively sparsely populated, with larger uninhabited areas noticeable, while in the east, the municipalities of Hamm (≤ 5,672 inhabitants/km²) and in the south, Hagen (≤ 7,793 inhabitants/km²), emerge as local population centers. Outside the Ruhr region, apart from the state capital Düsseldorf (≤ 18,401 inhabitants/km²), the municipalities of Krefeld (≤ 1,791 inhabitants/km²) and Wuppertal (≤ 13,709 inhabitants/km²) are present.

According to available data, of the total approximately 8.73 million inhabitants within the study area, around 5.06 million people are located within the Ruhr region, accounting for 58 percent of the total population.

Figure 6: Inhabitants / km² | Data Source: Zensus 2011 (2011); GEOportal.NRW (2023).

Figure 7 depicts the average annual newly constructed area in square meters per square kilometer between 2010 and 2020. Unlike the population data, these are processed data available only at the municipal level, hence the figure presented shows the overall construction activity reflected on settlement areas and again merged with the raster used in Figure 6. The final step was undertaken solely to establish a consistent visual representation; the calculations were conducted based on the results of the first two steps.

In general, it can be observed that within the Ruhr region, the municipalities of Kamen (520.69 m²/km²), Essen (503.92 m²/km²), and Dortmund (479.11 m²/km²) had the highest average newly constructed areas per square kilometer of municipal area. Conversely, the lowest construction activities occurred in Breckerfeld (31.53 m²/km²), Rheinberg (52.46 m²/km²), and Schermbeck (61.24 m²/km²). Expanding the scope of analysis reveals that the construction activity during the study period in Düsseldorf, with 953.41 m² of newly constructed area per square kilometer of municipal area, was 83 percent higher than in Kamen. Other municipalities with comparatively high construction activity include Neuss (574.97 m²/km²), Straelen (537.82 m²/km²), and Hilden (504.10 m²/km²).

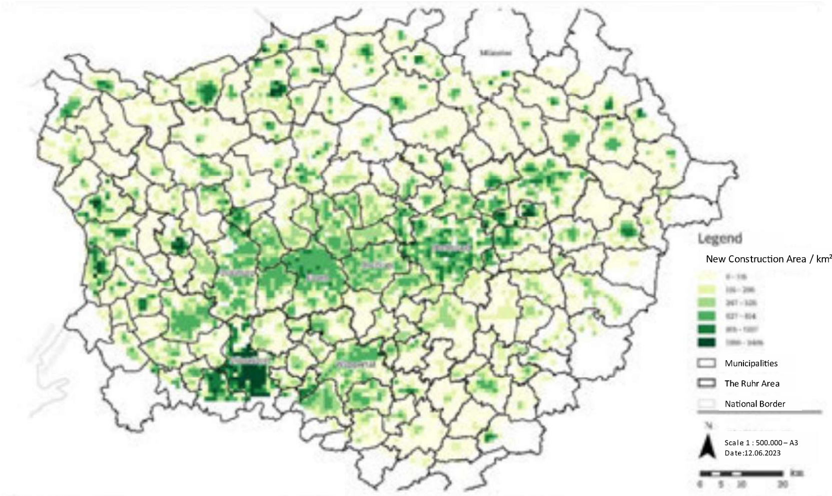

Figure 7: Construction Activity | Data Source: IT.NRW (2022); GEOportal.NRW (2023).

For further computation, the integration of both datasets is mandatory. The derived values, ranging from 1 to 25, are depicted in Figure 8. A total of 9,430 km² grids receive a score equal to or less than 5, of which 7,028 km² grids receive the lowest score of 1. Only 356 km² grids are rated 15 or higher, among which 17 km² grids achieve the maximum score of 25. All top-ranking areas, due to their high construction activity and dense population, are located within the municipal boundaries of Düsseldorf. This analysis emphasizes not only Düsseldorf but also the central Ruhr metropolitan areas, as well as Krefeld and Wuppertal.

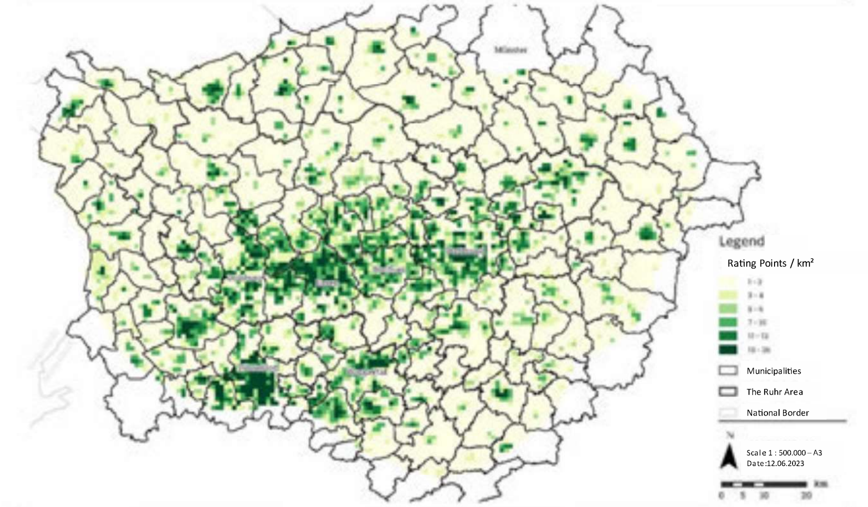

Figure 8: Rating Points / km² | Data Source: Zensus 2011 (2011); IT.NRW (2022); GEOportal.NRW (2023).

Figure 9 illustrates the results of the location-allocation analysis, aiming to identify the region with the highest expression of an indicator within its corresponding catchment area. The focus of the indicator for R-concrete demand (red point) is based on the completed new construction areas per municipality. The catchment area for this analysis spans 20 km, the distance within which the construction material can be transported without losing its qualities. The selected parcel is situated in the southern part of Duisburg, adjacent to the urban area of the state capital, Düsseldorf. The surrounding region exhibits relatively low development but benefits from close proximity to a highway interchange. The catchment area fully encompasses the municipality of Mülheim an der Ruhr, as well as significant portions of Düsseldorf, Krefeld, and the Ruhr metropolitan municipalities of Duisburg, Oberhausen, and Moers. Within the entire catchment area, an average of 336,195 m² of usable area is completed annually, making it the highest value among the points under consideration.

The point within whose catchment area the indicator for the volume of generated construction waste—the 2011 population density—is most pronounced (blue point) is located in Essen. The catchment area for this analysis spans 25 km, the distance within which the transport of construction waste is environmentally and economically more sustainable than the use of primary aggregates. The determined centroid, concerning population density, is in close proximity northwest of Essen's main railway station (1 km). The catchment area of the parcel dominated by commercial use almost entirely covers the Ruhr metropolitan cities of Essen, Bochum, Mülheim an der Ruhr, Gelsenkirchen, Gladbeck, Oberhausen, Bottrop, Hattingen, Herten, and Herne, as well as large parts of Duisburg and Dinslaken. In total, around 2.65 million people lived within the catchment area of the selected location in 2011.

The outcome of the analysis, based on the data from both indicators, identifies a centroid in the western part of Bochum-Wattenscheid (green point). The catchment area for this analysis spans 20 km. Within this area, the mean of the usable area completed between 2012 and 2021 amounts to 307,523 m², and the total population sums up to 1.92 million individuals. Unlike the previous analyses, the indicator values no longer rely on the settlement area but solely on the parcels used for site selection. The sum of the scoring points for the 774 considered parcels amounts to 5,418.

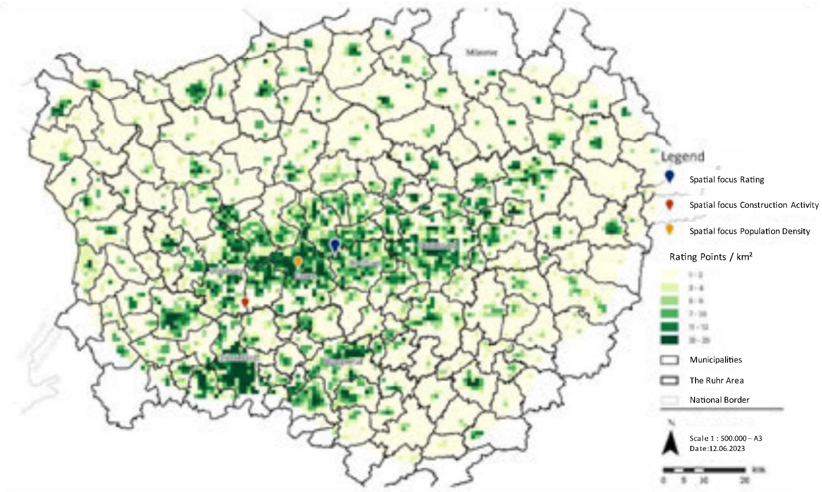

Figure 9: Spatial Focal Points of Population Density, Construction Activity and Rating Points | Data Source: Zensus 2011 (2011); IT.NRW (2022); GEOportal.NRW (2023).

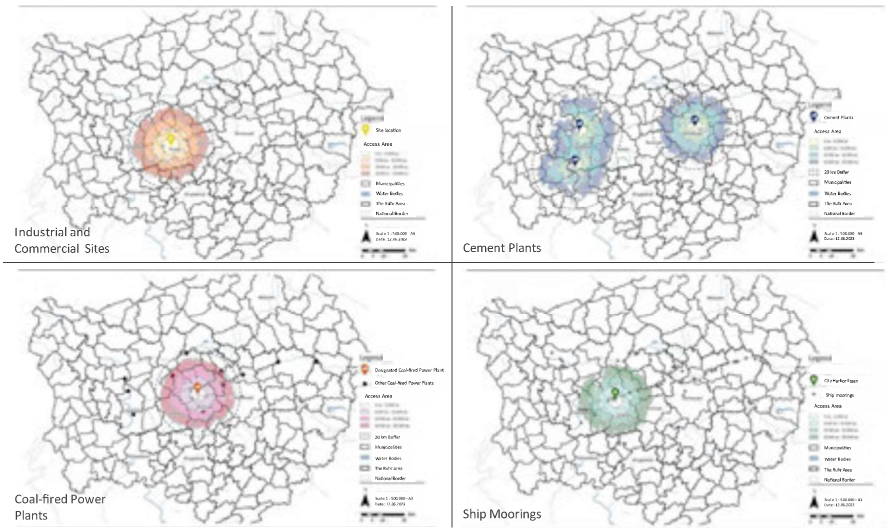

Figure 10: Calculated Catchment Area of Different Locations Performed on the Results of the Location-Allocation-Analysis | Data Source: Zensus 2011 (2011); IT.NRW (2022); Geofabrik (2023); GEOportal.NRW (2023); Bundesnetzagentur (2022).

Designation	Rating (pts.)	Supply (inhab.)	Demand (m²)	Catchment area (km²)
Coal_1	4789	1,85 Mio.	293.749	800

Coal_2	4605	1,70 Mio.	281.001	770
Cement_Do	3847	1,08 Mio.	282.584	693
Cement_DuNo	3368	1,20 Mio.	211.730	602
Cement_DuSu	3253	1,15 Mio.	230.917	616
Ind_Site	5399	2,64 Mio.	313.488	876
Harbor	4929	1,82 Mio.	291.057	739
Supply_max	-	2,65 Mio.	-	-
Demand_max	-	-	336.195	-
Rating_max	5418	-	-	-

Table 1: Comparison of the characteristics of investigated indicators according to identified locations.

Table 1 presents a summary of the findings outlined in Figure 10. Upon direct comparison, the comparatively low population values of the three cement plants, as well as the limited expression of the demand indicator regarding the plants in Duisburg, are striking. Conversely, the values of the prioritized harbor location, as well as the two power plants, are relatively close to each other and form the mean concerning the results of all sites. A categorization into three groups is also supported by the rating system (cement plants | power plants and harbor | commercial and industrial area). However, a detailed examination reveals that the ratings within the groups are not always consistent with the actual expressions of the indicators, albeit the differences are relatively minor. Regarding the research findings, it can also be noted that the average catchment area of the depicted sites is 728 km². Since the utilized distances are 20 km, on average, 57.9 percent of a circle with a radius of 20 km is covered. Here, the catchment area of the prioritized commercial and industrial site is notably large at 69.7 percent, while that of the cement plant in the north of Duisburg is relatively small at 47.9 percent. The average constructed area within the respective catchment areas amounts to 272,066 m², with the area derived from the commercial and industrial areas exceeding the average by 15.2 percent, and cement plant in the north of Duisburg falling 22.2 percent below the average. The population located within the sites' catchment areas averages at 1.63 million people, with values varying significantly between the site in the center of Essen (2.64 million) and the location of the Dortmund cement plant (1.08 million).

5. Identification Of An Ideal Location Within The Ruhr Area: Validation Of The GIS-Analysis

The analysis of demand concentrations within the Ruhr area and its periphery reveals Düsseldorf municipality as a significant influencer in determining the location of the demand hotspot, owing to its notably high construction activity. This influence is particularly pronounced due to extensive urban development projects undertaken in recent years, exemplified by the development of entire urban quarters (cf. Quartier Central). However, indicators in the immediate vicinity (up to 7.5 km) exhibit relatively modest levels. According to Holcim (2023), a substantial proportion of deliveries from a concrete plant occur within a radius of 10 km. Consequently, the region identified as the hotspot appears comparatively unsuitable for establishing a concrete plant. Therefore, the choice of Düsseldorf as a site should seemingly be explored within a different study, and its consideration for a suitable location within the Ruhr area should be tempered accordingly.

The population density, as an indicator of supply, is particularly pronounced within the Essen center based on the analysis results. Within a catchment area of 867 km² around the prioritized industrial and commercial area, 2.64 million people can be reached. This represents 52.2 percent of the Ruhr area's population, despite the catchment area covering only 19.5 percent of its land area. Unlike construction activity, municipalities southwest of the Ruhr area do not appear to play a significant role in this analysis.

The comparative analysis between the region with the highest accessibility – the industrial and commercial zone near Essen's urban core – and the one with the lowest connectivity – the grinding and mixing facility in northern Duisburg – elucidates fundamental distinctions contributing to a diminished catchment radius. Notably, the catchment zone of the top-performing site exhibits a complete absence of unconnected areas within its scope, indicative of exceptional connectivity likely attributed to the absence of significant open expanses such as forests, fields, or protected areas. Conversely, the northern Duisburg area features numerous such expanses, notably the Rhine River and the Kirchheller Heide in the northeast, markedly impeding accessibility. Furthermore, the natural obstacle of the Rhine and the absence of a nearby bridge hinder connectivity, particularly in the northwest region of the site. A detailed examination of the Essen central area also unveils non-concentric catchment zones, with deficiencies in the southern and northwestern sectors, suggesting a rural environment with comparatively limited connectivity, as inferred from population density.

The analysis outcomes reveal substantial variances between the area of a simple 20 km radius circle (1,256.6 km²) and the actual catchment area delineated by a road network (867 km² to 602 km²), even within densely inhabited regions like the Ruhr area. In this instance alone, the actual catchment area represents only 69.7 percent and 48.2 percent of the circle area, respectively, underscoring the intricacies of urban connectivity.

The location-allocation analysis performed to ascertain the requisite number of facilities for comprehensive coverage of the Ruhr area concludes that a total of 15 facilities are necessary. However, uncertainties persist regarding how many of the designated facilities can procure adequate raw materials and demand to ensure seamless and profitable operation. Particularly in less urbanized locales such as the Ennepe-Ruhr district and the Wesel district, the viability of sustaining such facilities is dubious. The resultant map from the analysis distinctly delineates regions featuring significant unconnected areas in the road network, notably the Rhine River in the west and the municipalities of Breckerfeld and Haltern am See.

Upon closer examination of the locations identified through the Location-Allocation Analysis, it is evident that not all areas are suitable for the implementation of an RCH. For instance, due to accessibility constraints and the anticipated heavy traffic from trucks associated with an RCH, the centrally located industrial and commercial area in Essen is deemed unsuitable. Similarly, the area of the cement plant in the north of Duisburg, which is relatively difficult to access, is also excluded. Conversely, the coal-fired power plant in Bochum is excluded due to its direct adjacency to residential areas on multiple sides.

The sites in Dortmund and Duisburg are particularly advantageous because there is already a cement plant located at these sites. Given the high investment costs, it must be considered that implementing an RCH at another location may have to do without the cement plant component. Nevertheless, the evaluation of these sites in the Location-Allocation Analysis is significantly lower compared to other sites. Additionally, these sites lack the address-forming characteristic of the areas in Essen and Herne, which can utilize proximity to water to attract other companies and stakeholders to the location.

For the implementation of a new RCH, however, the Essen city port is perceived as an ideal location. This is attributed to its excellent connectivity and central position within the core metropolitan areas of the Ruhr region, potential integration into existing industrial structures, and the presence of blue and green infrastructure. Additionally, the city's plans for the reorganization of the port (Stadt Essen, 2022) and the development of the Freiheit Emscher (Freiheit Emscher Entwicklungsgesellschaft mbH 2023), which aims to enhance adjacent areas, are viewed positively, as they offer the potential to act as catalysts for the implementation of an RCH.

6. Conclusion

As stated, the concrete industry in the Ruhr region faces critical future challenges, including primary raw material shortages and the necessary reduction of greenhouse gas emissions to meet Paris Climate Agreement targets. Addressing these issues is urgent, as primary resources will still be needed alongside secondary raw materials due to legal and static requirements of Resource-conserving Concrete (R-Concrete), and reducing carbon emissions is essential for mitigating anthropogenic climate change.

The research presented highlights that the formation of a Resource-conserving Concrete Hub (RCH) can substantially enhance the perception and effectiveness of R-Concrete itself. This enhancement is achieved by not only unifying the three primary stakeholders to streamline the R-Concrete production process but also by incorporating additional participants from the construction and planning industry as well as the public sector. Further, the Ruhr region presents optimal conditions for this initiative due to its high population density, industrial heritage, and polycentric structure, making it an ideal location for the implementation of an RCH.

However, due to inadequate data on the extent of the urban mine, the analysis performed does not provide a precise volume estimate that could serve as a foundation for detailed planning. Therefore, in order to facilitate effective reuse of construction and demolition waste and ensure accurate site planning regarding an RCH, the establishment of a material registry is expected to be crucial. Despite this limitation, the study offers new insights into the spatial dynamics of R-Concrete production and identifies specific locations within the Ruhr metropolitan area for further investigation. The Essen city harbor area, in particular, emerges as a promising site, especially due to its connectivity and infrastructure. As this area is currently the subject in a master planning process, it presents a timely opportunity to further develop and implement the RCH-concept developed, thereby boosting urban mining practices within the entire region.

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