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Adapting the ESSENZ Method to Assess the Criticality of Construction Materials: Case Study of Herne, Germany

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Abstract: The steady increase in the world's population combined with the globally growing need for living space by each individual is leading to an ever-faster consumption of limited resources by the construction industry, particularly sand and gravel. While a consensus exists regarding the sand and gravel resource availability on a global level for long-term supply, it is important to note that local supply shortages may still occur. Thus, this study aims to identify critical aspects of both locally and globally traded construction materials by adapting the ESSENZ method, which evaluates the criticality of globally traded abiotic resources. For the specific case of the local availability of construction materials, a new indicator is introduced: The Surface Squared Driven Indicator (SSDI), which is adapted to the specific conditions of the German market. The modified ESSENZ method is applied in a case study of materials needed for maintaining the material stock of the city of Herne, Germany. The results indicate that raw materials for concrete production in Germany, such as aggregates, are expected to be sufficient in the long term, but silica sand for glass production is only guaranteed for a few decades. Concrete poses the highest supply risk due to its high material demand, with steel and concrete dominating the environmental impacts. Limitations include data availability and the exclusion of certain materials. The adapted ESSENZ method allows for the comparison of criticality results for materials traded globally and locally, offering valuable insights for decision-makers seeking to promote sustainable construction practices.

Keywords: supply risk; criticality; construction; ESSENZ; concrete; glass

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1. Introduction

Global resource use has increased in recent decades [1]. This development can be observed in many sectors, especially in the construction industry, as buildings are responsible for around 65% of the world's material flows [1], 35% of the world's energy flows and 38% of the world's greenhouse gas emissions [2]. The two most commonly used building materials in the EU are concrete, i.e., a mixture of different-sized mineral rocks (sand, gravel, natural stone, lime, clay, gypsum and anhydrite), and glass made from silica sand, lime, alt, dolomite and feldspar. Together they account for almost 90% of the raw materials used in construction [3]. In Germany, the per capita annual usage amounts to 137 million tons of concrete and 9 tons of glass [4].

In the construction industry, bulk materials are often traded locally, mainly to reduce transport costs. While sand and gravel for concrete and glass production are rather cheap to purchase [5], their transport costs contribute considerably to their procurement expenses, doubling the gravel price, on average, for every 40 transport kilometers traveled [6]. Short delivery distances are particularly crucial for ready-mixed concrete, as the concrete must be discharged from the mixer truck within a maximum of 90 minutes [7]. However, ensuring short transport routes is only feasible when raw materials are locally available. In regions where distribution is uneven, certain areas may necessitate long-distance transportation of building materials. A well-known example is Singapore, which has expanded its land area by 25% using imported sand [8].

Local uneven distribution and associated challenges in terms of access to resources are addressed in national and international strategies, for example, the German sustainability strategy [9]. Additionally, numerous studies on criticality have been published in recent years. They differ in the scope, time period, objectives, geographical unit, resources considered, specific characterization factors, and whether the approach is static or dynamic [10,11]. The majority of studies focus on the criticality of metals [12,13]. An example is [14], examining the criticality of 42 abiotic materials on the European level and focusing on the three dimensions of sustainability. In addition, ref. [15] estimated the criticality of 62 metals and metalloids on a global level, considering the supply risk, environmental impacts, and vulnerability to supply restrictions. As it comes to building materials, ref. [16] estimated the supply risk associated with selected wood species in various regions using a criticality assessment framework based on [15]. However, the existing methods cannot be easily applied to construction minerals, as they do not sufficiently take into account the specifications of the local trade [16].

While criticality methods evaluate the potential resource availability for a specific user, in the construction industry, Life Cycle Assessments (LCA) are being used more frequently to identify opportunities for enhanced efficiency in products and processes [11]. A number of studies examine the relationship between material stocks in the built environment and their environmental impact [17]. For instance, ref. [18] performed a life-cycle assessment on a single-family house located in Sweden with a focus on the construction materials, their transport distances, and the potential alternatives to mitigate the environmental impact associated with the most significant contributors. Likewise, ref. [19] introduced a comprehensive multiscale framework for evaluating the environmental performance of the built environment. This framework incorporates Life Cycle Assessment (LCA), nested system theory, and dynamic modeling of material stocks and flows. In a similar vein, ref. [20] developed a model that integrates Life Cycle Assessment (LCA) and dynamic material-flow analysis (MFA) for evaluating the environmental impact and material efficiency across the entire lifespan of a building. The authors further validated the model by testing it at a neighborhood scale.

In addition, ref. [21] extended the analysis beyond the environmental impact typically associated with the built environment and developed a methodological framework for Dynamic Life Cycle Sustainability Assessment (D-LCSA). The authors integrate environmental, economic, and social parameters in order to assess the sustainability performance of buildings from a life-cycle perspective. The study considers factors such as energy consumption, greenhouse gas emissions, resource depletion, and waste generation.

These studies led to the implementation of measures aimed at reducing energy consumption, particularly in heating during the usage phase. However, it is worth noting that the current research predominantly focuses on the environmental impacts, specifically greenhouse gas (GHG) emissions resulting from construction usage, omitting the social and economic aspects associated with them. To strike a balance between energy and material efficiency, it is crucial to expand our perspective and place greater emphasis on the raw materials extensity employed within the built environment as well as consider their supply chain and extraction location.

The integrated method to assess resource efficiency (ESSENZ) was developed to assess resource criticality at a product level [12]. ESSENZ focuses on economic criticality but also includes environmental and social aspects. In its current version, ESSENZ mainly provides factors for metals and fossil fuels. However, the methodological framework allows the inclusion of mineral resources like sand and gravel in the assessment. To better reflect the unique challenges of these materials, additional aspects like logistic limitations should be added [12]. In the construction industry, the raw materials for concrete and flat glass are locally traded, and therefore their assessment requires a methodological adaptation. For example, 93% of the raw materials sand, gravel and crushed natural stone come from national sources [22], with an average transport distance of 30 km [23]. Considering the global view of ESSENZ does not account for local criticality aspects, because domestic production is assumed to be risk-free.

To account for aspects of local trade Ioannidou et al. [24] developed an area-based indicator (called Surface Squared Driven Indicator (SSDI)) to assess the quarry's availability of materials used in the construction sectors. The SSDI was adapted and integrated into criticality analysis for Switzerland and France based on the approach of Graedel et al. [25]. However, the case study does not provide an integrated assessment of construction materials incorporated into the built environment.

Based on the identified research gaps, this paper aims to enhance the existing body of knowledge by developing a comprehensive framework for assessing the criticality of both locally and globally traded building materials, along with globally traded construction materials integrated within the built environment at a city level. To accomplish this, we modify the ESSENZ method, enabling an integrated evaluation of these materials, providing valuable insights, and fulfilling the need for a more holistic approach. In order to evaluate the effectiveness of the newly developed approach, we apply the adapted ESSENZ to a case study conducted in Herne, Germany, to assess the criticality of locally traded materials used in the city's building stock, with a particular focus on building materials that contain sand, such as concrete and glass.

The following section describes the adaptation of ESSENZ (Section 2), followed by a presentation of the adapted method and its categories and indicators (Section 3). Then we illustrate how we determined the anthropogenic stock of the city of Herne and present the case (Section 4). Subsequently, the method and results are presented and discussed (Section 5) and a conclusion is drawn (Section 6).

2. Method

The construction materials analysed in this study are steel, copper and aluminium, and the minerals used to produce concrete and glass. For concrete, the considered raw materials are sand, gravel, cement, limestone, blast furnace slag, clay, gypsum and anhydrite. The materials assessed for glass production are silica sand, salt, limestone and dolomite. To evaluate the criticality of the selected materials, the ESSENZ method was chosen, as it evaluates the criticality of the resource use of abiotic materials considering the three sustainability dimensions: economic, environmental and social. Further, ESSENZ is among the recommended methods to assess the criticality of products [26,27] and has been applied in several case studies [28–30].

ESSENZ assesses abiotic resources considering the three sustainability dimensions within categories quantified by corresponding indicators. Each category has a specific target value based on a stakeholder survey; thus, the calculated category results are set in relation to the target, leading to the distance-to-target (DtT) value. The further normalized DtT results are used as characterization factors specific to the studied materials, which are then multiplied by the material quantities within the system. A detailed description of the original ESSENZ method can be found in Supplementary Information (SI), Section S1. In the adaptation of ESSENZ, we aimed to keep the modifications to a minimum to ensure comparability to globally traded materials. The modifications are partially specific to the German case study, as the data availability was evaluated for Germany. In Figure 1, the steps of this adaptation are visualized.

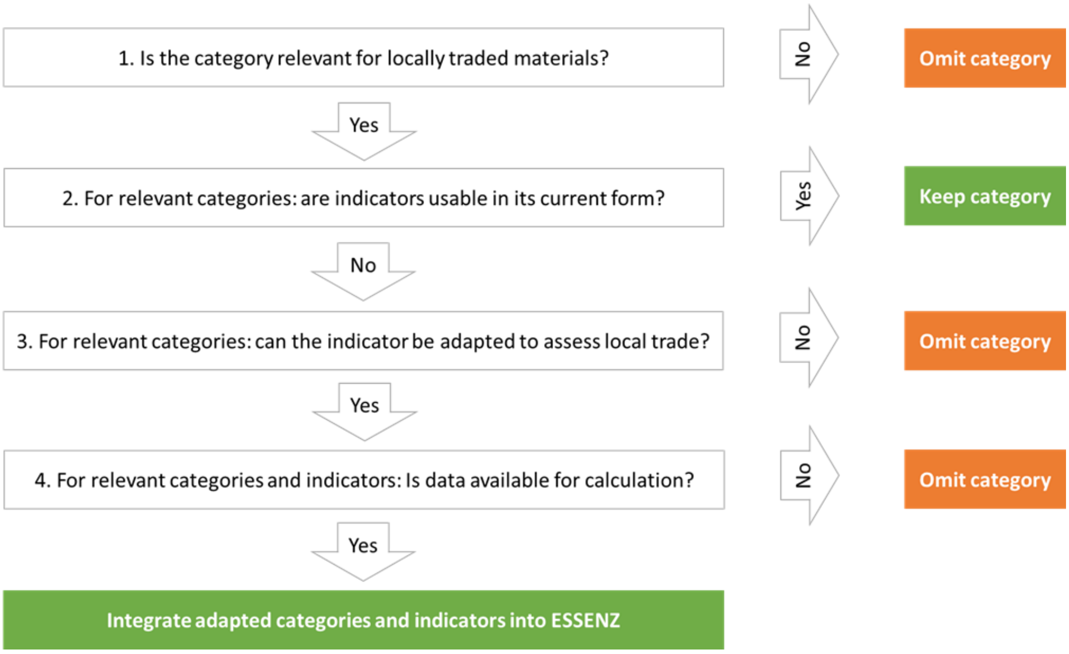


Figure 1. Steps to modify the ESSENZ method for the assessment of building materials.

These steps are explained in detail in the following:

1. In the first step, the categories were examined regarding their ability to assess resource criticality in the local context. Categories that quantify aspects, which do not occur in the local context are omitted. For example, trade barriers describe restricted trade across borders. Since trade barriers exist mostly in border regions and do not play a considerable role in accessing locally traded building materials, the category is excluded from the analysis. The categories relevant to local trade are further evaluated in the next steps.
2. In the second step, the not-omitted categories were analysed regarding the used indicators and their suitability to assess the local context. For example, one category that was not omitted was the feasibility of exploration projects, as the category assesses the situation regarding the overall investment settings in the mining sector within a country. The conditions for exploration projects are highly influenced by the political framework [31], which is assumed to be similar to the local markets of a country, as it is strongly influenced by a national government. Thus, the indicator is used in its original form and not modified.
3. For the remaining categories not omitted but requiring adaptation, the associated indicators were adjusted to reflect local markets in the third step. For example: in the original ESSENZ method, there are three categories quantified by the Herfindahl–Hirschmann Index (HHI) [32] regarding market concentration at a global level (company and country concentration of global reserves and global production). The calculation of the HHI was adapted to consider the concentration of domestic and local production, e.g., regionally active quarries.
4. In the fourth step, the data availability of the reconceptualized indicators was evaluated with a focus on the case study of Germany. For example, to calculate indicator values for the category concentration, global production data were replaced by data from the individual German federal states.

The resulting adapted method is presented in the following chapter. The categories' compliance with social and environmental standards was not considered, as the focus was on criticality. However, the environmental impacts are assessed with a Life Cycle Assessment (LCA) [33,34].

3. Case Study—City of Herne

The adapted ESSENZ method was applied to the selected construction materials (concrete, glass, steel, copper and aluminium) within the building stock of Herne, Germany. For concrete, the considered raw materials are sand, gravel, cement, limestone, blast furnace slag, clay, gypsum and anhydrite. The materials assessed for the glass production are silica sand, salt, limestone and dolomite.

Calculation Procedure

The functional unit is defined as the material demand to maintain the building stock in two urban districts in Herne in one year. The two districts are Strünkede with approx. 8153 inhabitants and a surface of 2.21 km^2, and Pantringshof with 2502 inhabitants and a surface of 1.19 km^2. Both are located in the medium-sized city of Herne in North Rhine Westphalia [35]. The building stock of the districts includes the materials used for residential and commercial (non-residential) buildings. Informal dwelling types like garages, sheds and infrastructure materials were excluded from the study.

Recycled building materials and industrial by-products make up a relevant share of the aggregates used in Germany. Given that the market for these materials is particularly complex and cannot be compared with that of the other materials, they are addressed in a qualitative analysis only. The composition of cement includes many components. Raw materials that make up less than 1% as well as additives and admixtures adding up to about 2%, were ignored. In the float glass market, the refining step plays an important role. Due to the lack of data on the quantities of raw materials for flat glass processing and the relatively small amount of resources, only the input for float glass production is considered in this study. Complex market structures with several product levels are presented in this study in less detail. For example, no distinction is made between in-situ concrete and ready-mixed concrete.

The building stock was determined based on the database and model provided by Marinova et al. [36] and its companion study by Deetman et al. [37]. The database contains quantities of steel, concrete, aluminium, copper, wood, and glass per m^2 of Useful Floor Area (UFA) for the residential building stock and per Gross Floor Area (GFA) for the non-residential buildings. The values of the residential stocks are determined based on the building stock and the material quantities for four different building types in rural and urban areas: detached houses, row houses, apartment buildings and high-rise buildings for 26 world regions. The region-specific values for Western Europe were used in this analysis.

To determine the material stock, the UFA of each building type for both residential and commercial buildings was determined. This was performed using statistical data from the city of Herne and the Geoportal NRW [38]. Based on this information, the GFA for the residential buildings was estimated. To determine the usable floor area, factors from the study by Vujicic [39] were applied. The factors represent the ratio between the UFA of the building and the total area (GFA) of the building. They are estimated as a mean value for each of the building types included in this study and are based on different criteria, such as construction method, building standards, occupancy etc. For more information, please refer to SI. For the non-residential buildings, the values were calculated accordingly.

In the final step, taking into consideration that the existing building stock is not static, the annual material input is calculated based on the stock growth and its demolition rate. The required quantities are determined according to Wiedenhofer et al. [40], which estimates that the annual demolition rate for Germany is 0.12% of the total stock, while the growth rate equals 0.5%. We assume that the structure of the building stock remains the same; thus, the above-mentioned rates are used for all materials and building types.

4. Results

4.1. Adapted ESSENZ Method

An overview of the adapted ESSENZ method is given in Table 1. The calculations of the indicator values are generally carried out according to the ESSENZ method. Minor deviations are explained in SI, Section S3.

Table 1. Overview of the dimensions and categories and their consideration in the adapted ESSENZ method.

Dimension		Category	Status in Adapted Assessment Title 4	
Economic Dimension	Physical Availability	Abiotic Depletion Potential (ADP)	≈	Omitted in step 4 due to limited data availability; only qualitatively assessed
		Anthropogenic Stock Extended Abiotic Depletion Potential (AADP)	χ	Omitted in step 4 due to missing data
	Socio-economic Availability	Concentration of Reserves, Production, and Companies (HHI)	≈	Omitted in step 4 due to limited data availability; only qualitatively assessed
		Mining Capacity	°	Omitted in step 4 due to limited data availability; category is assessed with SSDI
		Feasibility of Exploration Projects	√	Kept category with original indicator and data source applied
		Trade Barriers	χ	Omitted category in step 1, as trade barriers are not occurring in the local market
		Occurrence of Co-Products	√	Kept category with original indicator and data source applied
		Political Stability	√	Kept category with original indicator and data source applied
		Price Fluctuations	√	Kept category with original indicator and data source applied
		Demand Growth	√	Kept category with original indicator and data source applied
		Primary Material Use	√	Kept category with original indicator and data source applied
Environmental Dimension	Environmental Impacts	The Global Warming Potential (GWP)	√	Kept category with original indicator and data source applied
		Acidification Potential (AP)	√	Kept category with original indicator and data source applied
		Eutrophication Potential (EP)	√	Kept category with original indicator and data source applied
		Photochemical Ozone Creation Potential (POCP)	√	Kept category with original indicator and data source applied

√ Category and indicator are applied as described in ESSENZ. ≈ Category and indicator of ESSENZ are adapted. χ Category and indicator of ESSENZ are not applied. ° New Indicator is applied for kept category data.

In the following, the modified categories and corresponding indicators are described in more detail. Only the categories where changes were made are presented in the main paper.

Abiotic depletion reflects the geological availability of resources, which is relevant for globally as well as locally traded materials. To calculate the indicator, production and ultimate resource data are needed. For construction materials, only production data are available, while data on ultimate resources are lacking for most considered construction materials on a global and local level. As the data are insufficient for a quantitative assessment, the physical availability is assessed qualitatively by a semi-quantitative score (between 0 and 1). If the local reserves are sufficient in the long term, a score of 0 is given. For short-term available resources, a score of 1 is assigned. If the reserves are sufficient for several decades, a score of 0.33 is assigned and, for the medium term, a score of 0.67. Via desk research, qualitative information about resource availability is determined, as shown in Section 4.

Anthropogenic stock extended abiotic depletion is relevant for the assessment of locally traded materials, as it accounts for the ultimate reserves as well as resources of anthropogenic stocks. Buildings and infrastructure have the highest share of anthropogenic material stock in Germany, the majority of which are aggregates and concrete [41]. The reuse of material from anthropogenic material stocks might relieve pressure on natural stocks. However, due to missing data—not only for building materials but also for many metals—the calculation of the indicator is challenging [30]. The category is therefore excluded from the adapted ESSENZ method.

Concentration of reserves, production, and companies: The concentration of resources, production and companies is significant for supply security at the local level. As stated before [28–30], the calculation of company concentration is especially challenging due to the lack of data. However, since this category is relevant on a local level, data were also gathered for company concentration as well as for reserves and production concentration. The concentration of production is measured at three levels (raw material, intermediate product and product level). The final result is obtained, and a weighted average is calculated based on the individual values (for details see SI, Section S6).

Mining capacity: The category mining capacity evaluates how long a resource can still be mined, considering the current technological state of the art and stable demand. The indicator for the mining capacity—the static reach—compares the annual extraction in relation to the reserves and thereby provides the number of years until new mines have to be developed. Due to data lacking for sand and gravel reserves in Germany, the applied calculation is not possible. Thus, the *SSDI* indicator by Ioannidou et al. [24] is applied (see Equation (1)). The concept is that although sand and gravel can be found in both urban and rural areas, access to them is limited in urban areas due to conflicting land usage. To measure the competition between the areas, the ratio of mining area to urban area is compared with the ratio of urban area to the total area under consideration.

$$SSDI = \frac{\frac{S_Q}{S_C}}{\frac{S_C}{S_T}} \tag{1}$$

where S_Q stands for quarrying surface, S_C stands for urban settlement surfaces and S_T for the total surface of observations.

A requirement for the calculation of the indicator is that the quarrying surface S_Q only includes mines in which building materials are extracted. To calculate the *SSDI* for building materials in Germany, statistical data on mining surfaces [42,43] had to be modified as it is not material-specific. To ensure that the considered surfaces only represent mining areas for building materials, the data are corrected by subtracting the areas for coal mining (for details see SI, Section S3).

To account for the availability of materials from the anthropogenic stock as well (as this was not possible within the category of anthropogenic abiotic depletion), the potential of urban mines is included. In Germany, it is estimated that approximately 12.5% of the annual production of aggregates comes from the urban mine, and this figure is expected to increase [44]. Thus, the building stock has a relevant impact on overall availability. Further, Ioannidou et al. [45] introduce strong (see Equation (1)) and weak locality (see Equation (2)). Weak locality considers the potential of materials in old buildings, except for listed historic buildings that are not expected to be demolished. To account for the fact, that mines are operated for many years, while buildings can only be demolished once; an average operating time of 50 years for quarries is integrated into the formula.

$$SSDI_{weak} = \frac{50 * S_Q + S_{old}}{S_C^2} S_T \tag{2}$$

where S_{old} stands for Surface of buildings that are more than 60 years old, S_Q stands for quarrying surface and S_C stands for urban settlement surfaces.

Equation (2) thus compares opencast mining surfaces with building surfaces, without taking the quarrying thickness or the building height into account. The comparison of material density between the mining areas and old buildings is untenable due to the difference in expected material per square meter, hence the formula has been adjusted. The output quantity for mineral construction waste is used as a starting point. The data are taken from a study on the anthropogenic stockpile in Germany by Schiller et al. [46], which is distributed to the German federal states according to their building surface. A fictional quarrying surface (S^*_Q) is determined by comparing the ratio of the surface area of quarries to their output to the output of the building stock (see Equation (3)).

$$S^*_Q = \frac{S_Q}{Output_Q} \times Output_{\ Stock} \left[\mathrm{km}^2\right] \tag{3}$$

where S_Q stands for the actual quarrying surface, $\mathrm{Output_Q}$ stands for the output of mineral material from the quarrying surface, and S^*_Q stands for the fictional quarrying surface, which corresponds to the actual output of mineral material from the building stock $Output_{Stock}$. The output of mineral raw materials from the anthropogenic stock is 72 million t, and the output of the mines (input to the stock) is 564 million t per year (2010) [46].

Since the waste statistics are recorded at a national level, an exact breakdown of the waste is not possible. The assumption is made that the demolition is proportional to the existing building stock in terms of quantity. Thus, a fictitious surface is assigned to each federal state based on the expected annual output of recycled material.

The new indicator *SSDI** (see Equation (4)), which includes the real and fictitious mining surfaces, is calculated to assess mining capacity from geological and urban sources.

$$SSDI^* = \frac{(S_Q + S^*_Q)/S_C}{S_C/S_T} \tag{4}$$

As the data on reserves for construction materials are missing, only the mining capacity of sand and gravel is calculated. In addition, since no validated target value for the *SSDI* is available, it is excluded from the quantitative analysis and only evaluated qualitatively. The highest value for a federal state is set to 100% and the values of the other states are considered in relation to it. As in ESSENZ, higher values refer to higher criticality, and the SSDI was scaled and reversed.

The category **trade barriers** was omitted because it refers to restrictions on trade across borders. There are no cross-country borders in the local context. The categories "feasibility of exploration projects", "occurrence of co-products", "political stability", "price fluctuations", "demand growth" and "primary material use" remain unchanged in terms of their original indicators and data sources.

Regarding the **environmental impacts**, the categories and corresponding indicators from the original ESSENZ method can be applied without adaptations. The five environmental impacts considered are climate change (Global Warming Potential (GWP) expressed in kilograms of carbon dioxide equivalents (kg CO_2-eq)), acidification (Acidification Potential (AP) expressed in kilograms of sulphur dioxide equivalents (kg SO_2-eq.)), eutrophication (Eutrophication Potential (EP) expressed in kilograms of phosphate equivalents (kg $PO_4{}^{3-}$-eq.)), and the formation of photochemical substances (Photochemical

Ozone Creation Potential (POCP) expressed in kilograms of nitrogen oxides equivalents (kg NOx-eq.)). The data on these materials were taken from the Gabi database [47] (see SI, Section S7 for details).

4.2. Results of the Case Study

In this section, we present the main results from the case study. The total mass to maintain building stocks of the two districts for 2019 adds up to 354.024 tons. Concrete is the main building material with a 90% share. The actual building material share is probably lower since the data do not account for all building materials, e.g., bricks. However, if the entire built environment is considered, the share of concrete might rise due to its extensive use in infrastructure. Steel has the second largest share of the building stock with a 9% share, followed by glass (0.7%), aluminium (0.2%) and copper (0.2%). More details can be found in SI, Section S5.

The physical availability of raw materials for concrete in Germany is sufficient in the long term for aggregates, such as sand, gravel and natural stone, limestone, and clay (see Table 2). The overall result for concrete adds up to 0.02. Thus, adequate supplies of the ingredients required for concrete (cement, water, sand, and aggregate) are expected to be sufficiently available in the future.

Table 2. Quantitative results for the physical availability of the raw materials for concrete and glass production in Germany and calculation of semi-quantitative average indicator values.

Material			Share	Raw Materials	Physical Availability	Weighted Average
Concrete	Aggregates		33.8%	Gravel and sand	Long term	0.0204
			29.8%	Natural stones		
			9.6%	Recycled building materials		
			4.3%	Industrial by-products	Long term	
	Cement	Clinker	9.6%	Limestone, marl and chalk		
			0.27%	Silica sand	Decades	
			0.15%	Clay	Long term	
			0.06%	Fly ash		
			0.04%	Foundry sand		
			0.04%	Input materials from the metal, iron and steel industries		
			0.04%	Other input materials		
			1.7%	Blast furnace slag	Short term	
			0.1%	Gypsum from flue gas desulphurisation (REA-Gips)		
			0.4%	Natural gypsum and anhydrite	Medium	
			0.1%	Others (kaolinite, bentonite, oil shale, iron, etc.)		
	Additives		7.5%	Water		
			2.6%	Additives		
Glass	Soda		7.0%	Salt		0.2376
			7.0%	Limestone		
			72.0%	Silica sand		
			9.0%	Limestone		
			4.5%	Dolomite		
			0.5%	Alumina/feldspar		

In Germany, the long-term availability of salt, limestone, and dolomite, which are raw materials for glass production, is guaranteed. However, silica sand, which is identified as the most critical component, is only guaranteed for the next few decades. The weighted average availability factor for building materials is 0.23, ensuring that there will be no shortage of building materials in Germany and Herne in the short term but might occur long-term. Therefore, the availability of building materials in both Germany and Herne is expected to remain secure. For more detailed information and sources, see SI, Section S5.

The weighted average values are then multiplied by the mass of the materials, as required by the original ESSENZ method (see Figure 2).

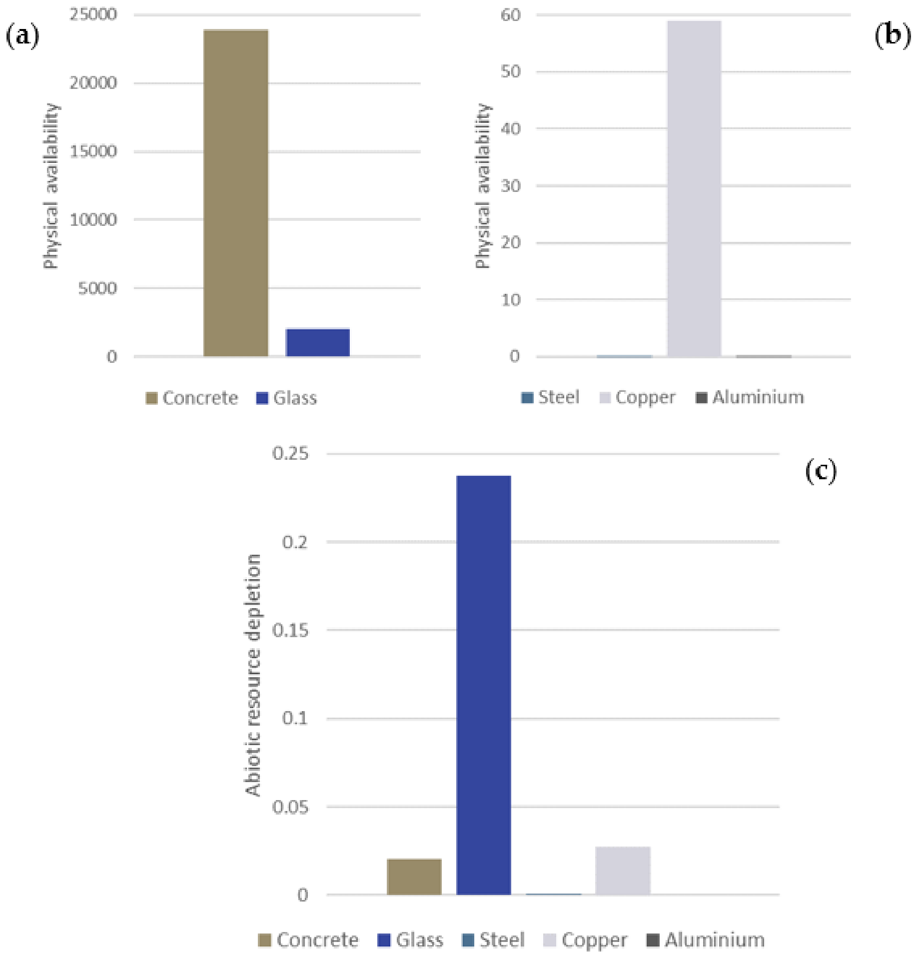


Figure 2. Results of physical availability for concrete and glass (**a**), as well as steel, copper and aluminium (**b**); abiotic resource depletion for considered materials (**c**).

The assessment shows that the raw materials that are relevant for concrete production have a higher risk of restricted physical availability than the raw materials for glass. This result is also influenced by the high demand mass of concrete, even though the physical availability of glass is higher. Copper has the biggest risk of depletion among the building metals.

The **concentration of reserves, production and companies** for the raw materials needed for concrete and glass is assessed. For concrete and glass, the category is determined at all production stages (raw material, intermediate product, and product level) and a weighted average is calculated. Thus, the indicator value for concrete is 0.38 and, for glass 0.5 (on the scale, 0 is low concentration and 1 is high concentration). More detailed information can be found in SI, Section S6.

As explained in the previous section, the urban mining potential is assessed together with the quarry mining potential by a modified SSDI* indicator. Further methodological notes can be found in Section S2 in SI. The results for the different federal states in Germany are presented in Figure 3 and Table 3. In the ranking, Brandenburg, including Berlin, performs best because it has large mining areas combined with a small proportion of urban areas in relation to the total area. Saarland ranks last because it has a high proportion of urban areas combined with a medium proportion of extraction areas.

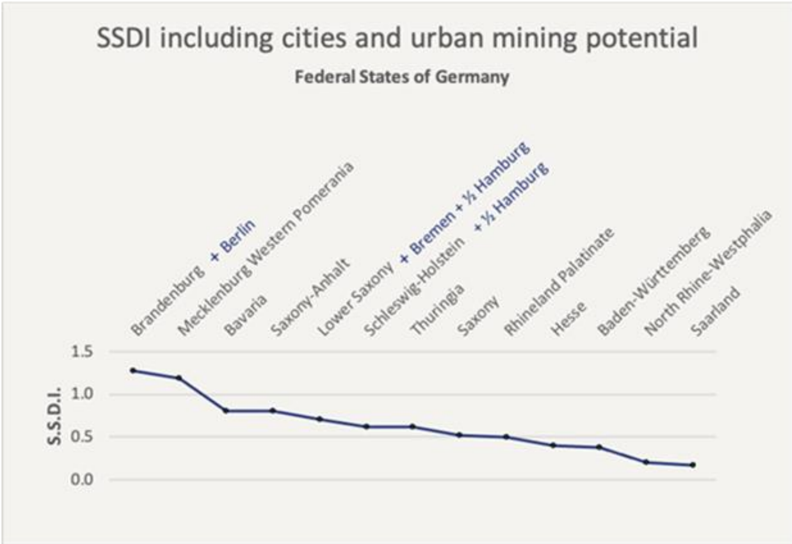


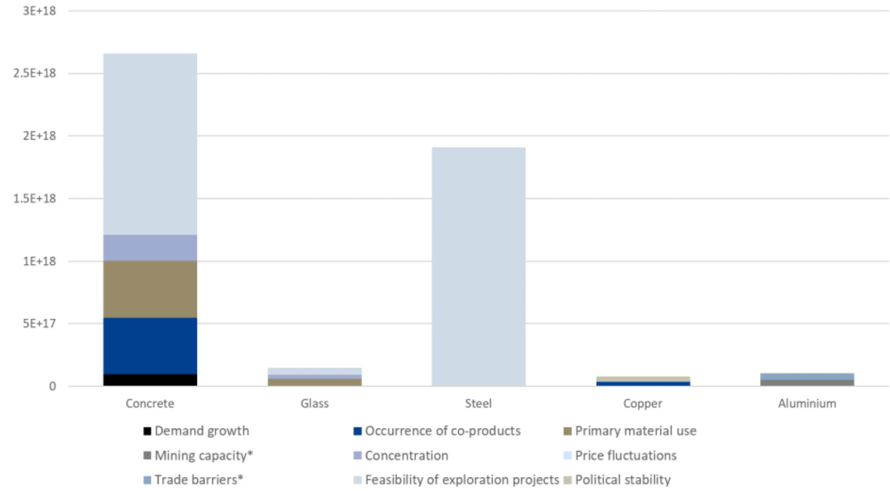
Figure 3. Results of the modified SSDI indicator to assess the availability of sand and gravel at the federal-state level in Germany based on Ioannidou et al. [24].

Table 3. Results of the modified SSDI indicator to assess the availability of sand and gravel at the federal-state level in Germany based on Ioannidou et al. [24].

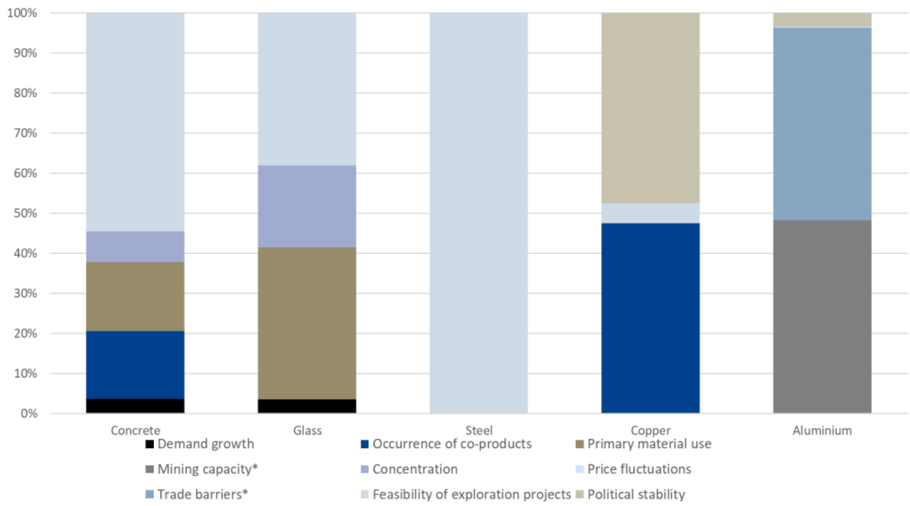
Federal State	Rank	SSDI	Demand Growth	Result ESSENZ
Brandenburg + Berlin	1	1.27	92.31	0%
Mecklenburg Western Pomerania	2	1.19	84.62	6%
Bavaria	3	0.81	76.92	36%
Saxony-Anhalt	4	0.80	69.23	37%
Lower Saxony + Bremen + $\frac{1}{2}$ Hamburg	5	0.71	61.54	44%
Schleswig-Holstein + $\frac{1}{2}$ Hamburg	6	0.62	53.85	51%
Thuringia	7	0.62	46.15	51%
Saxony	8	0.52	38.46	59%
Rhineland Palatinate	9	0.50	30.77	61%
Hesse	10	0.40	23.08	69%
Baden-Württemberg	11	0.38	15.38	70%
North Rhine-Westphalia	12	0.20	7.69	84%
Saarland	13	0.17	0.00	87%

In a nationwide comparison, North Rhine-Westphalia and thus the federal state that is relevant for the case study in Herne has a comparatively low value of 0.2 and is ranked in the penultimate place. Although there is a relatively sizeable opencast mining surface, it also has the largest share of urban areas that need to be supplied with building materials. The analysis of the indicator shows that federal states with little settlement area perform better. In these regions, there is less competition for land and less resistance to the opening of quarries.

As shown in Figure 4a, concrete has, by far, the highest value for all the assessed categories followed by steel, with a higher contribution solely to the feasibility of the exploration projects category. The values for glass and aluminium are relatively similar while copper displays the lowest risk. The characterization factors for the socio-economic categories of local building materials are higher for glass than for concrete in all the categories. However, in the final results, concrete has a higher indicator value because it represents almost 90% of the material demand. Its socio-economic risk is rated higher than that of the other materials assessed. For concrete, the categories of highest risk are the feasibility of exploration projects, primary material, co-product, concentration and demand growth. For glass, the categories with the highest indicator values are the primary materials, feasibility of exploration projects, concentration and demand growth. For copper, the main contributors are the categories of political stability, feasibility of exploration projects and occurrence of co-production, while, for aluminium, trade barriers, political stability and mining capacity. Most of the characterization factors equal zero, which means that the calculated indicator did not exceed the corresponding DtT value, and the category is not considered critical for the material and is therefore not shown in the graph. The analysis shows that the risk of physical availability is moderately too low for all building materials and that supply is geologically sufficient for at least the next few decades. Potential risks lie in the socio-economic dimension.



(**a**)



(**b**)

Figure 4. Results for locally traded concrete and glass, as well as globally traded metals steel, copper and aluminium in the dimension of socio-economic availability: (**a**) absolute scale, (**b**) displayed by percentage. The categories marked with asterisk indicate that they do not consider locally traded materials.

The **environmental impacts** are displayed in Figure 5, which shows that steel dominates the overall value, followed by concrete, copper, aluminium and glass. As it comes to the individual categories, for climate change and eutrophication, the dominating materials are steel and concrete, the third most critical material is copper, and the material with the lowest value is glass. As for the eutrophication category, the contribution is similar, except the less critical material is aluminium. Steel is again the dominating material within the acidification category. The material with the second-highest contribution is copper, followed by concrete, aluminium and glass. When it comes to the formation of photochemical substances, steel is again the main contributor and concrete the second. Glass and aluminium have the smallest contribution.

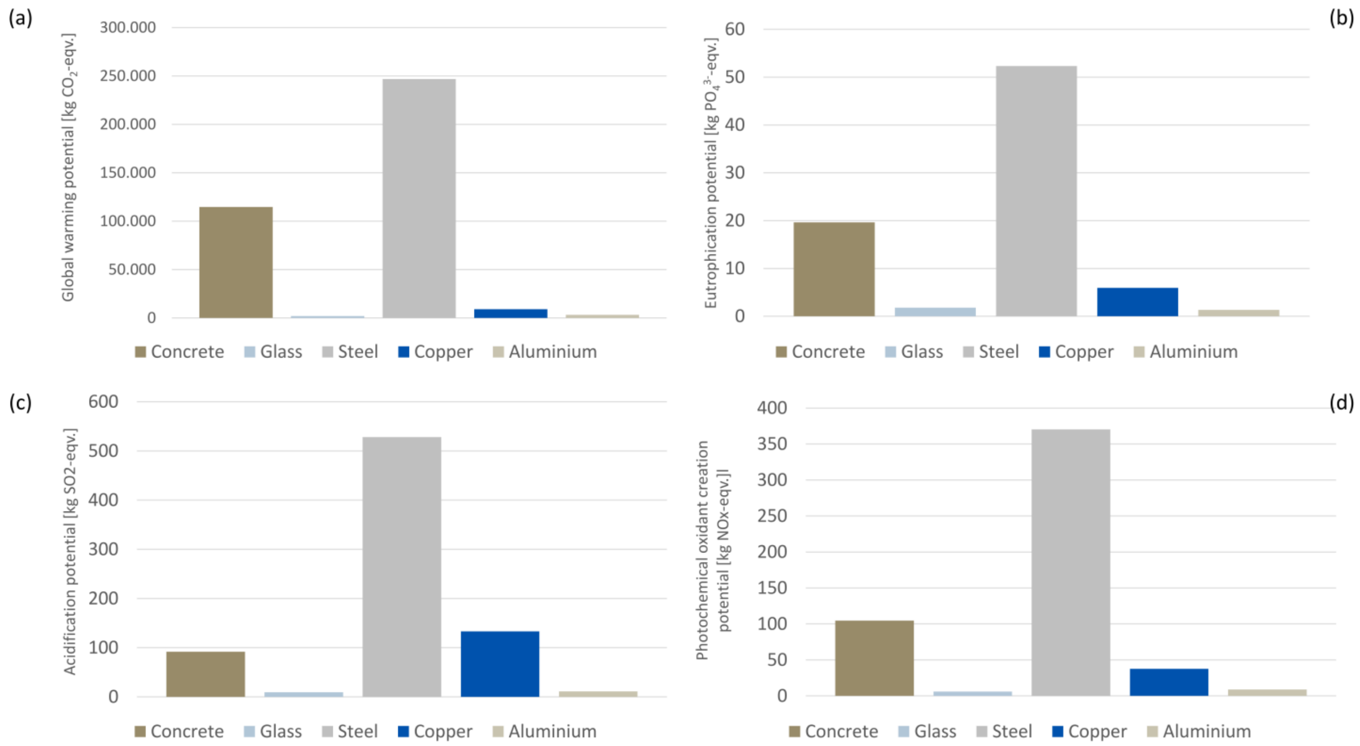


Figure 5. Results for the environmental impacts (global warming (**a**), eutrophication (**b**), acidification (**c**) and photochemical oxidant creation (**d**)) of concrete and glass and the metals steel, copper, and aluminium.

In conclusion, the annual material input needed to maintain the building stocks in two districts in Herne, Germany, amounted to 354,024 tons. Concrete was found to be the predominant building material with a 90% share, followed by steel at 9%, glass at 0.7%, aluminum at 0.2%, and copper at 0.2%. The availability of raw materials for concrete has a higher risk of restricted physical availability compared to glass, with copper facing the most significant risk of depletion among the building metals. The concentration of reserves, production, and company concentration for the raw materials necessary for concrete and glass production were assessed, resulting in weighted average values of 0.38 and 0.5, showcasing increased socio-economic risks for these materials. Lastly, the environmental impact analysis revealed that steel had the highest overall impact, followed by concrete, copper, aluminum, and glass, with steel and concrete contributing the most to climate change and eutrophication categories.

5. Discussion

This study enables the evaluation of the criticality of locally traded building materials with the ESSENZ method and thus expands the scope of the approach to include the most important resources for the German economy in terms of mass. The results show that, despite the generally moderate criticality of building materials, socio-economic availability in relation to available quarries can be an obstacle. This study can be seen as a first step for measuring availability at the federal-state level and lays a foundation for an integrated criticality assessment of non-metallic minerals and metals used in construction. In addition, the results obtained from these assessments not only provide a better understanding of the supply situation of building materials but also offer actionable recommendations for future material decisions. Moreover, by quantifying the building stock and considering the three pillars of sustainability, the assessment method makes a valuable contribution to the implementation of the circular economy in the built environment.

Despite this added value, there are some limitations to the method and case study. The listed uncertainties in the original publication of the method, ESSENZ, also apply to the presented work. It should be noted that the quality of the results is highly dependent on the quality of the data. Some data was not available, which limited the scope of the assessment.

Unfortunately, not all relevant materials could be taken into account, as the data basis for the calculation of the material stock does not include materials such as bricks, natural stone or clay. Additionally, raw materials needed for cement production with a very low share (less than 1% of the raw material) were ignored in the quantitative analysis. This can be challenging, as raw materials with a small mass share can be indispensable for the manufacture of a product. Moreover, the adapted method and results only apply to the conducted case study in Germany. To analyse the criticality of another country or region, additional studies and potential methodological adaptations (due to data availability) need to be carried out.

Assessing the physical availability of building materials with the original ESSENZ method was not possible, as the corresponding indicators could not be used due to limited data availability. The physical availability was determined with qualitative data and mining capacity was considered with a new indicator that was adapted for the study. The quantification of the mining capacity was only possible for aggregates. The results for aggregates were evaluated qualitatively, as the DtT value was not available. The main adjustment in the method is the focus on local markets. However, there are large differences in the average transport distances of raw materials within the building materials sector. For example, sand and gravel are transported 30 km on average, and most other raw materials for cement are about 100 km. Due to the availability of data and the effort required for the analysis, it is not possible to introduce different locality levels here. The distinction is not necessary, as there is a comparable situation for most indicators within the German market, and the SSDI* indicator is explicitly considered at the federal-state level.

In the original approach to the SSDI, the author ignores the city-states Basel and Paris, as there are no mine areas within their territory and therefore the SSDI value would be zero [24]. However, it could be argued that the high demands of the city-states have to be met by the quarries of the surrounding states and thus the city area should be included in the calculation of the SSDI of the bordering states. This approach was chosen for this paper.

The goal of SSDI is to enable a quick assessment with limited data availability. In this context, the simplicity of the indicator is compromised because the lignite areas in Germany still have to be excluded from the official statistical opencast mining areas. Apart from the excluded coal areas, the indicator does not distinguish between different opencast mining areas. This adds a certain amount of uncertainty, but the shares of quarries that mine for materials beyond sand and gravel are very small.

Another uncertainty might be caused by the fact that more areas would have to be approved to cover the supply of building materials in the long run as reported by several industries. The raw materials are usually available in sufficient quantities, but the operation of the mines can be hindered due to the difficulty to obtain a permit. The permit procedures for quarries are time intensive and often take 10–15 years in Germany [48].

In this study, the category “societal acceptance” is not considered for two reasons. On one hand, some of the indicators are not available for Germany, on the other hand, the risk of, e.g., forced labour or child labour is considered low in Germany. When interpreting the results of the environmental impacts, it should be emphasized that only the manufacturing phase, and not the construction phase, is considered in the analysis. Also, the data sets of raw materials were used, not those of final products. Thus, accounting for the whole life cycle emissions of buildings will result in higher values.

The environmental results for steel and concrete are due to the large volumes of these materials. The aggregates used for concrete production are characterized by lower embodied emissions compared to steel; however, the extensive amount of concrete in the built environment leads to the higher contribution of the material to the overall result. In addition, the comparison of the characterization factors shows that different building materials have high impacts in different categories, e.g., for the global warming potential category, the material associated with the higher carbon emissions is copper. The goal should be to reduce the use of concrete and steel and consider alternative raw materials.

Wood was not assessed, as the original ESSENZ method is not designed for biogenic materials. Research on adapting the BIRD method [12] to assess the criticality of wood in the same context would be helpful. Wood is often discussed as an alternative material that can at least partially replace concrete [49]. It would be worthwhile to compare its availability with other building materials. Furthermore, the applied method could be integrated into an overall planning and development plan for neighbourhoods such as the Resource Plan [50]. Additional insights could be generated by comparing different areas, either within Germany with a different material structure or a similar area in another country with different criticality factors. Future research could focus on the integration of the SSDI* indicator into the quantitative structure of the ESSENZ method and the assessment of building wood in Germany to enable a holistic assessment. Moreover, the different criticality dimensions could be compared for primary and secondary building materials.

6. Conclusions

In this study, the ESSENZ method for assessing resource efficiency was adapted to enable the assessment of locally traded building materials. By applying the adapted ESSENZ method to the city of Herne, Germany, we achieved a comprehensive assessment of both locally and globally traded construction materials. This enabled the comparison of criticality results for globally traded metals, such as steel, copper, and aluminum, with the criticality of locally traded raw materials used in concrete and glass production. The integration of these resources in one method allowed for improved comparability of results. The comprehensive assessment improves the understanding of the supply risks of various construction materials and can thus be of help for future decision-making processes regarding the desirable material composition of buildings and consequently increased resource efficiency. The key improvements of our proposed method refinements lie in their ability to consider locally traded materials, facilitating a more accurate evaluation of material criticality. This refinement addresses a crucial research gap and provides a more holistic approach to assessing the sustainability implications of construction material choices. In addition, by exploring the material quantities embedded in the build environment and integrating the three pillars of sustainable development, our study contributes to the field of the circular economy in the construction industry. Furthermore, the results of the case study show that, although there are several risk factors, there are no predominant risks to be identified for the criticality of concrete and glass in Germany. This finding emphasizes the need for further research in this area to refine the ESSENZ method and deepen our understanding of the sustainability implications of building material choices in the construction industry.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources12080092/s1, Figure S1: Relationship between department population and the surface of urban settlement; Figure S2: Detailed calculation steps of the ESSENZ method for assessing resource efficiency and in blue adaptations for assessing locally traded building products based on Bach et al., 2016b; Table S1: Overview of materials used in Pantringshof and Strünkede; Table S2: Quantitative results for the overall concentration in Germany, including company, resource, and production; Table S3: Sand and gravel production volumes in Germany 2008/2009 with production volumes from Börner, 2012 [51]; Table S4: Volatility of building raw materials [52–71].

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