Supplementary Information:

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

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This supplementary material contains:

1 ESSENZ Method

The first element in the ESSENZ method is the economic dimension. It describes the availability of raw materials in two respects: on the one hand, the physical availability and, on the other hand, the factual socio-economic availability.

The long-term supply of a resource is fundamentally depending on its physical availability. This is assessed within the ESSENZ method by looking at two indicators: *Abiotic Depletion Potential (ADP)* and the *Anthropogenic Stock Extended Abiotic Depletion Potential (AADP)*.

The sub-dimension socio-economic availability in the ESSENZ method is looking at different factors along the supply chain, which might influence markets and therefore ultimately the supply of resources. The evaluation starts with the concentration on reserves in the stocks, continues with several wide-ranging factors e.g., political stability or occurrence of co-products in the mining phase and goes on to economic factors e.g., demand growth and price fluctuation for the trade of raw materials.

For a comprehensive resource valuation in the context of sustainable development, social aspects are also included in the ESSENZ method. The categories compliance with social standards and compliance with environmental standards are considered in the social dimension.

The third dimension of resource efficiency is the environmental impact. The categories are assessed using the methodology of life cycle assessment according to the ISO 14044 standard. The five environmental impacts considered are climate change, acidification, eutrophication, ozone depletion and the formation of photochemical substances (smog).

2 Mining Capacity—SSDI

The area of the city is defined according to the model study to include all types of buildings, parking areas, railways, unexploited urban areas, and parks/sports facilities. Whereas areas such as power plants, forests or water areas are not included.

The application of the indicator SSDI was tested by the author of the underlying study within a case study for the countries Switzerland and France. One of the basic assumptions of the method is that areas are populated in proportion to their size. This assumption is made for

European cities and validated for Switzerland and France. This assumption also applies to Germany and was tested on the federal state level.

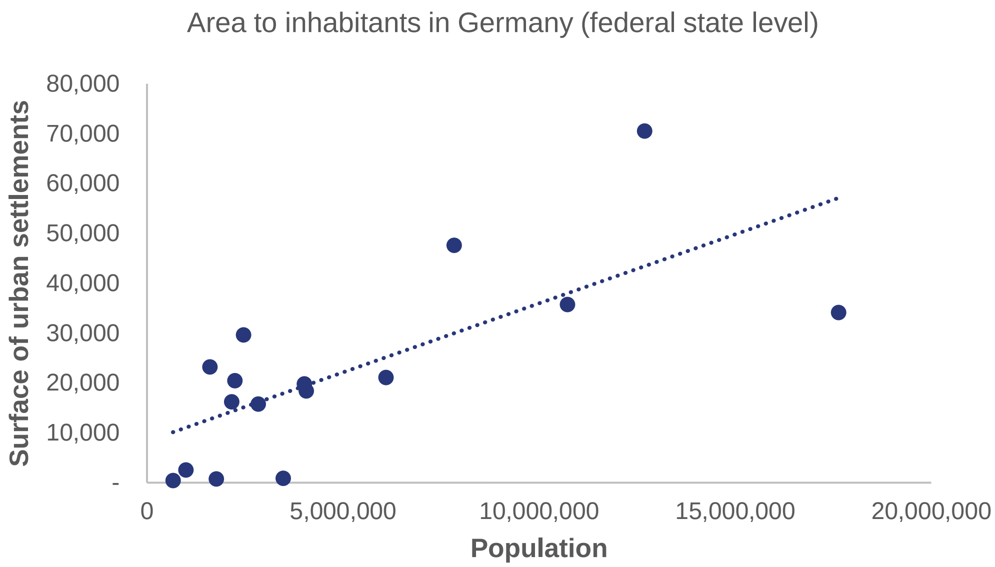

Figure S1. Relationship between department population and surface of urban settlement.

In 2008, the shares of construction minerals of total material production in France and Switzerland were over 90 %, whereas in Germany this figure was just 60 %. This is mainly due to the large quantities of coal extraction in Germany, which still had a share of 25 % at that time [1]. In the meantime, the situation in Germany has changed; the mass share of coal was down to 4 % of the domestic mineral production in 2019 [1]. Therefore, the corresponding areas of opencast coal mining need to be subtracted from the total mining surfaces for every federal state, as they still account for a relevant share.

The coal mining areas are not evenly distributed across the German federal states, they are mainly concentrated in central Germany. The surface data of the lignite areas are available at the level of the mining districts, but in two out of three cases these extend across federal state borders. The precise separation of areas by federal state must therefore be based on less consistent data.

3 Changes in Calculations within ESSENZ

The previous changes in the assessment result in small adjustments in the calculation (see Figure S). In calculating the nDtT values, the German annual production was used as the standard for the local building materials, while the global production was considered for the metals. The characterisation factors depend on the maximum values within a category. Here, too, the metals were considered separately from the construction raw materials, i.e., their own maxima were calculated.

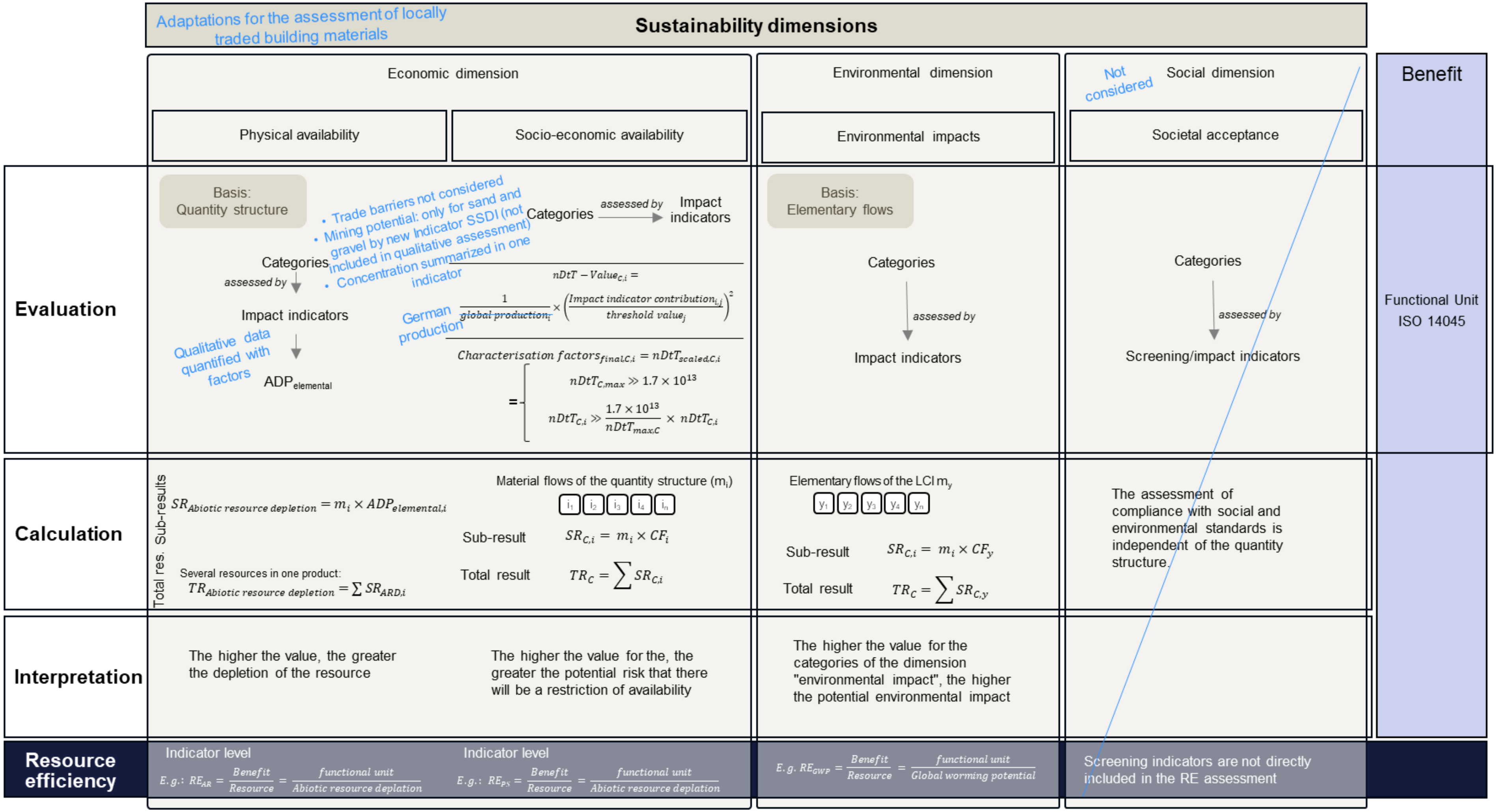

Figure S2. Detailed calculation steps of the ESSENZ method for assessing resource efficiency and in blue adaptations for assessing locally traded building products based on Bach et al., 2016 [2].

4 Materials of Herne's district

In Table S1 the total mass to of the building stocks presented.

Table S1. Overview of materials used in Pantringshof and Strünkede.

	Pantringshof						Strünkede					
	Steel [t]	**Concrete [t]**	**Wood [t]**	**Copper [t]**	**Aluminium [t]**	**Glass [t]**	**Steel [t]**	**Concrete [t]**	**Wood [t]**	**Copper [t]**	**Aluminium [t]**	**Glass [t]**
Commercial												
Hotel & restaurant	44.26	379.79	9.70	1.84	2.31	2.05	26.03	223.38	5.71	1.08	1.36	1.20
Office	-	-	-	-	-	-	7746.08	60,964.99	451.29	262.69	323.31	437.82
Other	925.37	9345.41	231.57	30.88	52.67	131.68	1437.83	14,520.82	359.81	47.97	81.84	204.60
Retail & warehouses	545.52	4865.23	77.83	15.98	16.68	41.00	4363.55	38,916.20	622.57	127.85	133.41	327.96
Sum	**1515.15**	**14,590.43**	**319.10**	**48.69**	**71.66**	**174.72**	**13,573.49**	**114,625.39**	**1439.38**	**439.60**	**539.92**	**971.58**
Residential												
Row house	1322.09	42,728.84	1920.07	0.54	12.35	57.44	774.02	25,015.69	1124.11	0.31	7.23	33.63
High-rise building	3003.96	17,958.31	569.97	0.21	46.44	100.27	2934.64	17,543.93	556.82	0.21	45.37	97.96
Detached house	300.34	9449.49	484.63	19.50	5.83	15.74	857.04	26,964.51	1382.90	55.65	16.64	44.91
Apartment building	518.91	3865.92	339.50	1.02	3.13	76.30	4764.77	35,497.63	3117.35	9.37	28.75	700.59
Sum	**5145.31**	**74,002.56**	**3314.16**	**21.27**	**67.75**	**249.75**	**9330.47**	**105,021.76**	**6181.17**	**65.54**	**97.99**	**877.09**

5 Physical Availability

C	Building sand	Sand reserves are spread throughout the territory of Germany. Despite some areas without sand deposits, no supply constraints are expected in the long term (enough for centuries) [3–5]
C	Building gravel	The geological supply of construction gravel is very large and should last for several more centuries [6]
C	Natural stone	Natural solid rocks such as granite, basalt or gneiss occur in the German low mountain ranges and the Alps. They are most frequently used in the form of crushed natural stones as a gravel substitute in concrete. The reserves of natural stone in Germany are so large that long-term self-sufficiency is assured [5].The minor share of exports of the raw material exceeds imports.
C	Lime	The reserves of limestone are so large that no shortage is expected [5,7]. Limestone is frequently statistically recorded with dolomite and marl or burnt gypsum. The boundaries are blurred, so the figures should be interpreted with caution. Germany has a relevant share in the production of limestone and a positive trade balance. Nevertheless, exports have only a small share of the production.
	Slag sand	Due to the change in energy sources in steel industry and power plants, in the future the blast furnace slag or fly ash supply will shrink and eventually stop. Already today, the import quota for blast furnace slag is fairly high. As long as this is possible, imports from neighbouring countries will continue and grow, ultimately the use of limestone or pre-calcined clays as a clinker substitute will increase [8]
C	Gypsum and Anhydrite	More than half of Germany's plaster resource demand (55 %) is covered by FGD gypsum, a by-product of flue gas purification in coal-fired power plants. Due to the increasing shutdown of coal-fired power plants, an important source of resources will be lost, which will have to be covered by mining gypsum or imports. The current total

		gypsum demand of approx. 10 million t can be covered by domestic raw materials [8] According to the USGS global gypsum reserves are large, but there is no data for Germany [9] . A study from 2011 concluded that gypsum is not a critical resource for Germany and that there is a low supply risk [10]. Another study estimates the reserves of specific extraction sites in Germany to be 20–50 years [11].
C	Clay, Kaolin	The reserves of clay in Germany are so large that long-term self-sufficiency is assured [5].
G	Silica sand	The stocks of silica sand in Germany should last for many decades if production remains constant [6]. Most sources only give qualitative assessments of the reserves of silica sand, but one study values the reserves of quartz sand in Germany in 2012 at 1000 million t. In the same table, the annual production is given as 31.8 Mio. T [12]. This would correspond to a range of only 31 years. However, other sources show that only 10.1 [Mio. t] were extracted in 2012 [5], which would mean a static reach of almost 100 years.
G	Lime for Soda	*See Above*
G	Salt for Soda	Germany has many high-quality salt deposits that secure the supply of the commodity in the long term [13].
G	Dolomite	The reserves of dolomite in Germany are so large that long-term self-sufficiency is assured [5].
G	Feldspar	Feldspar is a common mineral, which is part of most stones. But not every rock that contains feldspar is automatically suitable as a feldspar raw material. There are sufficient reserves in the relevant regions to ensure the supply of German industry for decades, if not centuries. However, this does not apply to all types of feldspar. Although there are many feldspar deposits in Germany, the high-quality raw material is only mined in three locations in the country. In order to meet the needs of German industry, raw material is imported to supplement

domestic mining [5]. According to the USGS the world reserves are more than sufficient to meet the expected demand.

6 Socio-Economic Availability

6.1 Concentration of Reserves, Production, and Company Concentration (HHI)

For the assessment of the concentration, the analysis is looking at the three factors: resources, production, and enterprises. Furthermore, the different product levels are considered individually as shown in Table S2.

Table S2. Quantitative results for the overall concentration in Germany, including company, resource, and production. For the raw materials for concrete and glass production and calculation average indicator values overall product levels. low = 0, medium = 0.33, high = 0.67, very high = 1.

Material			Share	Raw material	Product level	Level 3	Level 2	Level 1	Average
Concrete	Aggregates		33.8%	**Gravel and sand**	medium			**low**	0.378
			29.8%	**Natural stones**				**medium**	
			9.6%	Recycled building materials				medium*	
			4.3%	Industrial by-products					
	Cement	Cement clinker	9.6%	**Limestone, Marl and Chalk**		medium	high	**low**	
			0.27%	**Silica sand**				**medium**	
			0.15%	**Clay**				**medium**	
			0.06%	Fly ash					
			0.04%	Foundry sand					
			0.04%	Input materials from the metal, iron and steel industry					
			0.04%	Other input materials					
			1.7%	**Blast furnace slag**				**medium**	
			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			72.0%	**Silica sand**	high			**medium**	0.496
	Soda		7.0%	**Salt**			high	**high**	

			7.0%	**Limestone**				**low**	
			9.0%	**Limestone**				**low**	
			4.5%	**Dolomite**				**low**	
			0.5%	Alumina/feldspar					

C Building sand and Gravel

The reserve concentration cannot be measured with the HHI due to the lack of data. In general, the reserves are widespread in Germany.

→ The reserve concentration of building sand and gravel is low

The recommended source for the company concentration in the ESSENZ method is the SNL-Database [14]. This database does not contain relevant data for the building material market.

The analysis is complex not only because of the many small companies, but also due to the fact that the companies usually also generate turnover in the subsequent construction industry, which has to be deducted from the data. In addition, the statistics do not necessarily distinguish between quartz sand for industry and sand for the construction sector. The market analysis company IBISWorld has published an industry report on "Quarrying of gravel, sand and clay" for the German market. The sector under consideration includes the extraction and cleaning/first processing of gravel, sand, clay, and kaolin. The extraction of natural stones and the extraction of bituminous sands are not included. The four leading competitors make up less than 30 % of the market share. And of these, Quarzwerke GmbH currently generates the highest industry-specific turnover with a market share of approximately 8.4 %. This company specialises in the quarrying of industrial sand (silica sand) and would be excluded from a specific consideration of construction sand. The next biggest players are HeidelbergCement AG (5.4 %) and Hülskens Holding GmbH & Co. KG (5.3 %). Small companies dominate the industry. 93.3 % of all companies have less than 50 employees and generate 68 % of the turnover together [15]. Theoretically, despite a nationally diverse market structure, there might be a high concentration locally. To rule this out for the considered area, the gravel pits within a radius of 50 km around Herne were considered. Within this range there are 9 different quarries from different companies.

→ The company concentration of building sand and gravel is low.

The quantitative measurement of the concentration of production in Germany is possible by looking at the volumes in the federal states and their shares of the total national production volume. The calculated HHI is 0.145 and thus smaller than the limit value of 0.15.

Table S3. Sand and gravel production volumes in Germany 2008/2009 with production volumes from Börner, 2012.[16]

	Number of active extraction sites	Production volumes per year [Mio. t]
Baden-Württemberg	256	36,6
Bavaria	1120	85
Brandenburg/Berlin	184	14,4
Hesse	77	10
Mecklenburg Western Pomerania	170	14,5
Lower Saxony/Bremen	460	36
Northrhine-Westphalia	328	65,6
Rhineland Palatinate	98	8,8
Saarland	38	1,4
Saxony	178	14,4
Saxony-Anhalt	152	16
Schleswig-Holstein/Hamburg	280	15,5
Thuringia	80	8,5
Total	**3421**	**326,7**

→ The concentration of production in Germany is low.

C Natural stone and Recycled materials

Natural stone and recycled aggregates can serve as a substitute for sand and gravel. Natural stones such as granite, basalt or gneiss, are found in the German low mountain ranges and in the Alps in a high quantity [5] recycled aggregates can be obtained everywhere where buildings are demolished. The use of recycled aggregates in concrete is only economically and ecologically beneficial if the transport distance is less than 30 km. The concentration of these materials is considered together with sand and gravel because they do not have to be a part of the concrete mix. The materials increase the supply, so the already low concentration is further reduced.

C Cement

The cement production in Germany is relatively evenly distributed along the domestic limestone deposits. Limestone is with 77 % of the raw material input the main component of cement. In 2019, 21 companies produced around 34.2 million t of cement in 54 plants [17].

In an extensive investigation of the German cement industry by the Bundeskartellamt, the structure of the market is examined in detail. It should be considered that concentration is particularly high at the intermediate level of clinker production. Throughout Germany, there are only 12 plants in which clinker is burned. There are six cement producers without their own clinker capacities, which consequently have to source all their requirements externally. The Federal territory is examined in five regional markets (South, North, West, East, and Southwest). It is shown that the market shares differ strongly from region to region. In all submarkets, the largest five market participants hold between 76 and 90 % of the shares. Herne is located in the West district, which has the lowest concentration at 0.15. The market is particularly concentrated in the North region. Here the largest market participant has almost 60 % of the market shares and the HHI is 0.36 [18].

Overall, the concentration of cement is medium.

C Lime

Limestone reserves are found in many parts of Germany, especially in the southwest. The lime industry in Germany is predominantly characterised by small and medium-sized enterprises. An average of 6.4 million t of lime are produced at about 75 locations in Germany [19]. There is little concentration in the rock quarrying market.

The concentration of lime is medium.

C Clay

Clays can be found in many parts of Germany. Most of the clay in Germany is extracted in Bavaria and Saxony, other quarries are located in Hesse, Rhineland-Palatinate, North Rhine-Westphalia and Saxony-Anhalt [8].

The concentration of clay is medium.

C Blast furnace slag

Total crude steel production was 39.6 million t in 2019. Blast furnace slag is a by-product of steel production at 8 locations in Germany. The largest steel producers in Germany include thyssenkrupp Steel Europe AG with a production of around 12 million t and a share of 30 %, ArcelorMittal Germany Holding GmbH with around 8 million t (20 %) and Salzgitter AG with around 6.6 million (17 %) t of crude steel [19].

The concentration for blast furnace is medium at the intermediate level and the raw material level.

C Natural gypsum and Anhydrite

Gypsum is calcium sulphate, which occurs in various hydrate states. The water-free form of calcium sulphate found in nature is called anhydrite [19]. Statistically, both forms are often recorded together, which is why they are treated as a unit in this paper. The natural gypsum produced in Germany in 2018 was obtained from around 50 quarries and ten mines [8].

The concentration for natural gypsum and anhydrite is medium.

G Quartz sand

The main component for glass is silica sand (>70 %). Mining sites of industrial silica sand are spread over Germany, the flat glass industry is concentrated in the east and west of middle Germany, close by high quality resource deposits.

The HHI indicates a concentration of 0.33 and thus an elevated concentration for silica sand in Germany.

The concentration of silica sand and gravel is medium.

G Lime — See above.

G Salt for Soda — In Germany, the companies Solvay Chemicals GmbH and CIECH Soda Deutschland GmbH & Co. KG extract brine for the production of soda [22].

The concentration of soda production is high.

G Dolomite — Carbonate rocks consisting mainly of calcite/aragonite and dolomite are mined at 210 sites in 2010 in Germany. Particularly many extraction sites are located in North Rhine-Westphalia [3]. No figures are available on the production of the federal states, so the HHI is calculated using the number of extraction sites per federal state. The result is a figure of 0.21, i.e., a moderate concentration of reserves.

The concentration of dolomite is low.

G Feldspar — Feldspar is extracted from various rocks. In Germany there is one quarry where aplite is extracted as a feldspar raw material, one where volcanic rock is mined, five quarries where pegmatite sand is extracted and four quarries where quartz sands are extracted as a feldspar raw material. Feldspar is not traded locally, over 60 % of domestic demand is imported and 40 % of production is exported [5].

The concentration of feldspar is medium.

G Flat glass — The flat glass manufacturing market is highly concentrated. The four largest companies hold a share of 72 % of the industry's turnover in 2020. The largest producers are Compagnie de Saint-Gobain S. A., Glas Trösch Euroholding AG & Co. KgaA, Pilkington Deutschland AG and AGC f glass GmbH [15].

The company concentration of flat glass is high.

In the calculation concrete achieves a total concentration of 0.38 and glass a total of 0.50.

6.2 Feasibility of Exploration Projects

Considering that this study is looking at local markets of Germany or within Germany this country contributes a share of 100 %. It is the same for all considered building products. The calculated FEP for Germany in 2020 is 96 (see (6.1)).

$$FEP_i = \sum(100\,\% * 96) = 96 \tag{6.1}$$

6.3 Occurrence of Co-Products

The recommended source does not consider the raw materials relevant for the construction minerals. Aggregates are usually obtained as main products without the presence of by-products. In contrast, recycled materials are 100 % by-products, as the reason for demolition is not the extraction of the material [23].

6.4 Political Stability

When considering locally traded resources, only the value of Germany is considered, as 100 % of the production of the raw materials under consideration is located here (see (6.2)).

$$PS_i = \sum(100\,\%\, of\ the\ local\ resources_i \times 1{,}04)^2 = (1 \times 1{,}04)^2 = 1{,}0816 \tag{6.2}$$

6.5 Price Fluctuations

The price volatility of the construction products under consideration is comparatively low. While other commodities, such as oil, show strong fluctuations – annual volatilities of around 100 % and five-year values of over 30 % – building products are between one and five percent [24].

Table S4. Volatility of building raw materials. Calculations are based on data from Statistisches Bundesamt, 2021 [23].

		5 Year Volatility (2015-2019)
Concrete	**Building sand** (GP09-081211 natural sands)	1.78%
	Building gravel and Natural stones (GP09-081212 Field stones, gravel, crushed natural stones)	1.87%
	Cement (GP09-23511 Cement clinker, Portland cement, alumina cement and other cement)	1.41%
	Lime (GP09-235210 Slaked, unslaked and hydraulic lime. Lime)	1.77%
	Slag sand (GP09-08112 Gypsum stone, anhydrite, limestone as blast furnace slag)	1.25%
	Plaster (gypsum), Anhydrite (GP09-235220 Gypsum, from burnt. Gypsum stone or calcium sulphate)	1.85%
	Clay, Kaolin (GP09-081221 Kaolin a.o. kaolinh. Clay and loam, raw or fired)	1.27%
	Recycled materials	-
Glass	**Glass** (GP09-23121 Refined and processed flat glass)	1.01%
	Quartz sand	-
	Lime	1.77%
	Salt (GP09-089310 Salt, pure sodium chloride (without table salt))	4.57%
	Dolomite	-
	Feldspar	-

6.6 Demand Growth

In ESSENZ the data sources for the demand are the BGS and the USGS. The reports from both institutions contain data on the production of some construction raw materials in Germany. It was decided not to use these data, as they differ considerably for the raw materials for which information was available in both reports. Alternatively, local association data was used for the calculation of demand growth because it seems to be more accurate. In some cases, there is no data for the demand available. When the product is mainly traded locally, the production is almost the same as the demand, so the numbers are used instead. In the case of slag sand there are no numbers of the demand available. Because the import accounts for around 40 % of the local production the numbers were not used in the analysis.

6.7 Primary Material Use

Recycled aggregate is mainly obtained by processing the waste fraction soil and stones, a smaller part comes from the processing of construction site waste. In total, approx. 12.5 % of the demand for aggregates in Germany is covered by secondary raw materials. Klicken oder tippen Sie hier, um Text einzugeben. Various secondary products are used for cement clinker production. They include, in particular, sewage sludge from drinking water treatment, foundry sands from metal processing, and fly ash from hard coal and lignite-fired power plants. Blast furnace slag, which is a by-product of pig iron production, is also added to the cement clinker in the grinding process. Together, these secondary products account for 15.6 % of the raw materials used in the German cement industry. It is expected that this figure will decrease in the future as coal-fired power plants are shut down and traditional fuels are replaced in the iron industry. While high recycling rates of up to 95 % are achieved in container glass production, no secondary raw materials can be used in flat glass production. The high demands on optical quality require a very high degree of purity that cannot be achieved with recycled cullet. Therefore, only cullet that is produced during the production process is remelted [25]. The PMU values are displayed in (6.3)–(3.5).

$$PMU_{gravel,sand\ and\ natural\ stone} = 100 - 12{,}5 = 87{,}5 \tag{6.3}$$

$$PMU_{Cement} = 100 - 15{,}6 = 84{,}4 \tag{6.4}$$

$$PMU_{Flatglass} = 100 - 0 = 100 \tag{6.5}$$

By normalising the values with production data, the valuation is linked to the employed quantity of the commodity. This emphasises raw materials with low production figures. If, for example, the distance to target value is the same for all raw materials considered (as in the case of feasibility of exploration projects in the local consideration), this is divided by the production quantity of the commodity. This results in higher values for raw materials that are produced less.

7 Applied Datasets

The following datasets were used for the modelling of the case study:

- DE: Sand (grain size 0/2) (EN15804 A1-A3) (dried) Sphera
- DE: Gravel (Grain size 2/32) (EN15804 A1-A3) Sphera
- DE: Crushed stone grain 2-15 mm (EN15804 A1-A3) Sphera
- DE: Cement (CEM II 32.5) (economically allocated binders) Sphera
- DE: Cement (CEM I 32.5) (burden free binders) (EN15804 A1-A3) Sphera

- DE: Cement (CEM III/B) blast furnace cement (economically allocated binders) Sphera
- DE: Silica sand (Excavation and processing) Sphera
- DE: Soda (Na2CO3) Sphera
- DE: Limestone, gravel (grain size 16/32) (EN15804 A1-A3) Sphera
- RER: dolomite production ecoinvent 3.5
- EU-28: Alumina production 2015 IAI
- DE: Steel cold rolled coil 2,5 mm Sphera
- GLO: Copper (99.99%; cathode) ICA
- EU-28: Aluminium oxide mix (alumina, Al2O3) Sphera

8 References

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