



HAL
open science

Are Existing LCIA Methods Related to Mineral and Metal Resources Relevant for an AESA Approach Applied to the Building Sector? Case Study on the Construction of New Buildings in France

Nada Bendahmane, Natacha Gondran, Jacques Chevalier

► To cite this version:

Nada Bendahmane, Natacha Gondran, Jacques Chevalier. Are Existing LCIA Methods Related to Mineral and Metal Resources Relevant for an AESA Approach Applied to the Building Sector? Case Study on the Construction of New Buildings in France. *Sustainability*, 2024, 16 (3), pp.1031-10.3390/su16031031 . hal-04417251

HAL Id: hal-04417251

<https://hal.science/hal-04417251v1>

Submitted on 28 Jun 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Article

Are Existing LCIA Methods Related to Mineral and Metal Resources Relevant for an AESA Approach Applied to the Building Sector? Case Study on the Construction of New Buildings in France

Nada Bendahmane ^{1,2} , Natacha Gondran ^{1,*} and Jacques Chevalier ²

¹ Mines Saint-Etienne, CNRS, Univ Jean Monnet, Univ Lumière Lyon 2, Univ Lyon 3 Jean Moulin, ENS Lyon, ENTPE, ENSA Lyon, UMR 5600 EVS, 42023 Saint-Etienne, France; nada.bendahmane@cstb.fr

² Université Paris-Est, Centre Scientifique et Technique du Bâtiment, 24 rue Joseph Fourier, 38400 Saint-Martin-d'Hères, France

* Correspondence: gondran@emse.fr

Abstract: Considering the challenges that mineral and metallic resources represent for the building sector, there is a need to propose decision-support tools to building stakeholders. One of the possibilities could be to integrate an indicator of pressure on mineral resources in an absolute environmental sustainability assessment (AESA) approach, using life cycle impact assessment (LCIA) methods. This paper will analyze the existing LCIA indicators that can be used to represent the impact on mineral resources of new constructions, with a case study on new buildings in France in 2015. This analysis aims to find out whether the existing LCIA methods dealing with mineral and metallic resources issues are adapted to the specific stakes of the building sector in an AESA approach. The AESA approach considered is the one proposed by Bjørn and Hauschild. Several steps are detailed in this paper. Firstly, bibliographic research was carried out to identify existing LCIA methods related to the mineral resources. Secondly, selection criteria were defined in order to select those LCIA methods relevant for the building sector. Thirdly, the scope of the case study was defined and its inventory analysis was conducted using the Ecoinvent 3.5 database, selecting only the mineral and metallic input flows. Finally, the comparison between the inventory of mineral and metallic flows issued from the inventory analysis and the substances considered in the selected LCIA methods was effected. The results show that none of the existing LCIA methods are compatible with the aim of developing an LCIA indicator for mineral and metallic resources that is compatible with an AESA approach, in particular for the building sector.

Keywords: sustainable building; mineral and metallic resources; life cycle impact assessment (LCIA) indicators; absolute environmental sustainability assessment (AESA)



Citation: Bendahmane, N.; Gondran, N.; Chevalier, J. Are Existing LCIA Methods Related to Mineral and Metal Resources Relevant for an AESA Approach Applied to the Building Sector? Case Study on the Construction of New Buildings in France. *Sustainability* **2024**, *16*, 1031. <https://doi.org/10.3390/su16031031>

Academic Editors: Farzad Jalaei, Jieying Jane Zhang and Ahmad Jade

Received: 7 November 2023

Revised: 11 January 2024

Accepted: 17 January 2024

Published: 25 January 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The building consumes significant resources [1]. In France, on average, constructing a single house consumes 1.2 tons per square meter of living space, while the construction of a residential collective building consumes 1.6 tons per square meter of living space [2]. Mineral and metal resources represent 96% of the mass of these resources [2]. Then, the anthropogenic stock of mineral and metal resources is growing. In France, in 2016, the construction sector produced 70% of the mass of the total national waste and 93% of these wastes are non-dangerous mineral and metal wastes [3].

The building sector stakeholders, as part of sustainable construction modelling, using BIM for example, need tools to better identify mineral and metal resources issues to foster their optimal use. A crucial issue for the mineral and metal resources indicators is to highlight the interest of circular economy projects that preserve natural resources.

One track of response to this challenge, to which this research aims to contribute, is to integrate an indicator for the pressure on mineral and metal resources within an absolute environmental sustainability assessment (AESA) approach.

The AESA approach aims to evaluate if a given system is environmentally sustainable [4] by proposing absolute environmental sustainability indicators (AESIs), in contrast to the relative environmental sustainability indicators (RESIs) commonly used for decision making, in methods such as LCA.

The RESIs allow a system to be compared to another according to their environmental score, but do not allow the sustainability of systems to be assessed in an absolute way, i.e., by considering the stability of ecosystems. The LCA-based AESA approach aims to compare the environmental pressures of the system to the portion of the “carrying capacity” that can be allocated to that same system [4].

Carrying capacity was defined as “the maximum environmental interference that a natural system can withstand without experiencing negative changes in its structure or functioning that are difficult or impossible to reverse” [4] where an environmental interference refers to anthropogenic changes such as emissions or resource use [5].

In the AESA approach, two types of methods can be distinguished: LCA-based AESA methods and planetary boundary-based LCA (PB-LCA). LCA-based AESA methods are based on environmental metrics that are commonly used within the LCA community, and in particular those which are compliant with the environmental footprint (see for example [6]). Planetary boundaries are used to define global normalization references for the selected impact category metrics. These normalization references are then compared with the environmental impacts generated by the system under study to evaluate its sustainability.

On the contrary, PB-LCA methods propose specific LCIA methods, directly expressed in planetary boundary metrics, i.e., calculating characterization factors based on planetary boundary parameters and values [7].

Unlike conventional LCA, expressing elementary flows on an annual basis becomes necessary to articulate impacts in planetary boundary metrics. Thus, it is necessary to define the functional unit as the yearly delivery of a function and the life cycle inventory should be modelled to represent the annual average elementary flows linked to the consistent ongoing fulfilment of that functional unit [8].

The AESA methods are based on an absolute sustainability approach. Consequently, they utilize LCIA methods related to damage to ecosystems, omitting indicators related to non-renewable resources. Indeed, the depletion of non-renewable resources such as minerals and metals constitutes more of a socio-economic concern than an environmental issue [4,5,7].

The strong sustainability objective—to maintain the natural capital in the context of mineral and metal resources—could be translated into an acceptable consumption rate of resources equal to zero (no consumption). However, not integrating the question of mineral and metal resources into an AESA approach (that pretend to be relatively exhaustive in view of assessing the sustainability) does not seem acceptable in the context of the building sector as it may lead to ignoring this important issue when carrying out AESA studies.

Although most AESA methods do not consider the mineral and metal resources, a few studies outlined in the literature [9–11] have addressed this issue. However, all studies propose a single value of planetary boundary or carrying capacity for all the resources that are aggregated together. This approach inherently clashes with the concept of absolute sustainability since if a resource holds unique functional importance, its complete depletion cannot be substituted by the preservation of other resources.

Most of the identified methods aligned with the approach proposed by [6], which describes the general framework of LCA-based AESA. This framework comprises four steps: estimating the environmental impact using LCIA methods; quantifying the carrying capacity or planetary limit or safe operating space; assigning these to the system under study; assessing sustainability by comparing the estimated impact and the assigned carrying capacity.

The research objectives guiding this paper are as follows: How are pressures on mineral and metal resources currently assessed in LCA? Among the LCA characterization methods identified for mineral and metal resources, which is the most suitable for an absolute assessment approach?

2. Materials and Methods

This section aims to identify the best LCIA candidate method, among LCIA existing metrics relative to mineral and metal resources use, for an LCA-based AESA approach in the building sector. Firstly, AESA methods that consider an indicator for mineral and metal resources are reviewed. Secondly, the LCIA methods identified in the literature are selected based on three criteria (availability of the method in LCA software commonly used among the building sector and the resource stakes considered by the LCIA method). Finally, an analysis methodology is applied to the selected LCIA methods. The analysis methodology is achieved by releasing an LCA on new construction in France in 2015. Figure 1 presents the methodological steps followed in this study.

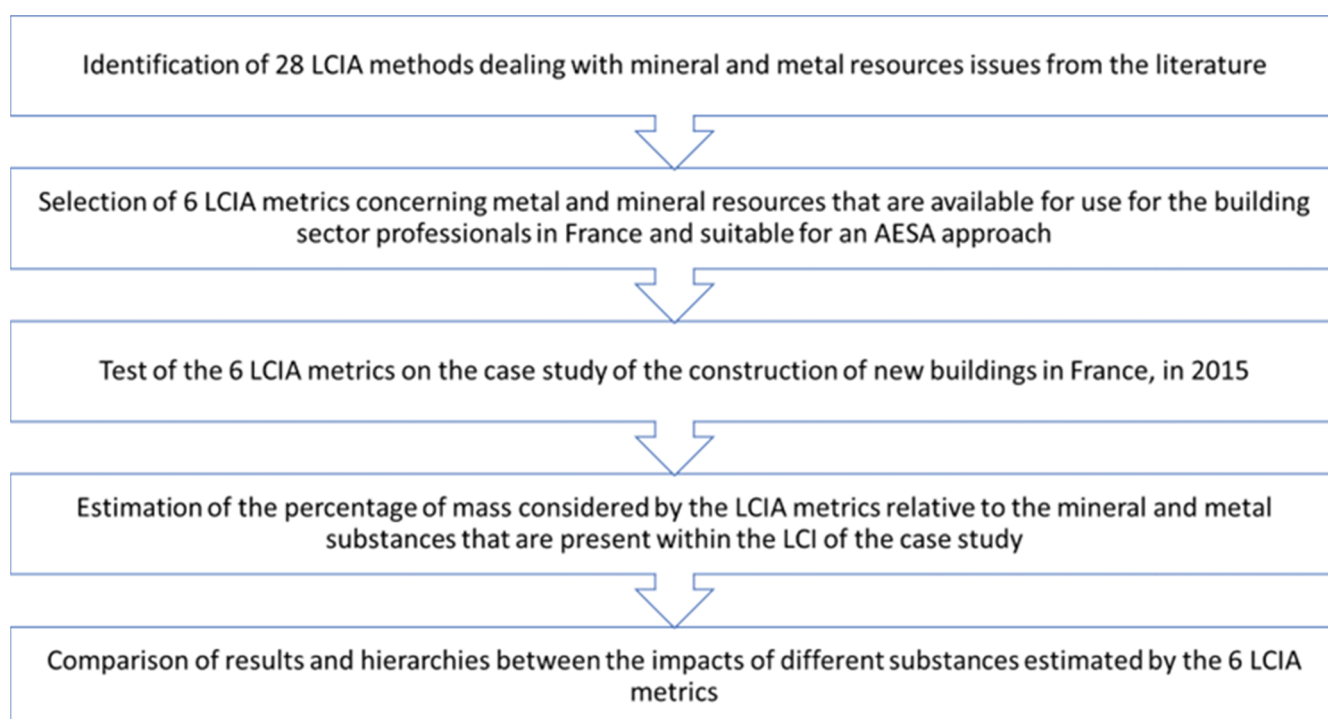


Figure 1. The methodological steps proposed in this study to identify the best candidate LCIA method for an LCA-based AESA approach.

2.1. Identification of Mineral and Metal Resource Metrics and Normalization References Identified in the AESA Literature

The AESA methods are based on the planetary boundaries framework (PB) [12] that are positioned in a perspective of strong sustainability [6]. Therefore, the existing AESA methods rely on LCIA indicators that relate to ecosystem diversity damage and currently exclude indicators about the scarcity of non-renewable resources. This means that an AESA study will a priori not estimate an activity's potential impacts on non-renewable resources as mineral and metal materials [7].

However, in the few publications identified in the literature, some have proposed approaches to integrate resource-related LCIA methods into an AESA method:

- Yossapol et al. [9] defines a carrying capacity as the total amount of existing accessible geologic reserves divided by a time horizon that is equal to the time required for all users to adapt to resource depletion. This time horizon has been arbitrarily set at

200 years for all the resources and users. This approach, which follows the LCA-based AESA method, has limitations. Firstly, adaptability depends on several factors that are differentiated for different users and resources [13], so considering the same time horizon for all resources is a large approximation. Secondly, this approach does not consider flows from the circular economy.

- The approach proposed by Sala et al. [14], which is integrated in the PB-LCA approach, consists in adapting the characterization factors of ADPelements ultimate reserves [15] by applying the factor 2 concept. Indeed, according to S. Bringezu et al., 2015–2019 and C. Buczko et al., 2016 [16–18], it is necessary to halve material consumption at a global level to achieve global sustainability. The proposal of Sala et al., 2020, has some limitations: (a) the planetary boundary is the same for all resources, (b) the geographical specificities of each resource are not considered since the limit is set at the global scale, and (c) the flows from the circular economy are not included.
- Vargas-Gonzalez et al. [11] proposes an approach that fits into the LCA-based AESA category of methods and determines limits for each resource type using user adaptability as defined by de Bruille [13]. Following this approach, Vargas-Gonzalez et al. defines optimal extraction rates by dividing the available stock by the number of years needed for users to adapt. It then defines reduction factors by dividing the current extraction rate by the optimal extraction rate. These reduction factors were evaluated for 25 resources that the author estimated as key resources. Once the reduction factors were estimated for the 25 resources, an average reduction factor was calculated. The average reduction factor obtained, with a value of 4.08, was used as a weighting factor for the LCIA results obtained with the ADPelements indicator. However, as argued by the author himself, establishing a single value for resources-carrying capacity contradicts the concept of absolute sustainability: if a resource holds a unique functionality, its complete depletion cannot be assessed as sustainable. On the other hand, this approach does not integrate flows from the circular economy and is on a global scale, which neglects the geographical specificities of each resource.
- Baabou et al. [19] proposes an approach that falls into the LCA-based AESA category of methods and addresses some of the limitations identified in the approaches presented above. Indeed, this method is also inspired by the work of de Bruille, 2014 and consists of defining a carrying capacity as the maximum annual dissipation rate needed to maintain the functions of a material until the moment when all users have adapted to its depletion. That is, to conserve the reserve of a given resource in such a way that the adaptation time of the users is equal to the depletion time. Thus, Baabou et al., by using the rate of dissipation rather than the rate of extraction, takes into account, in a way, the recycling of resources. In addition, carrying capacities are calculated and results are given for each resource, making this method a first major contribution to the integration of mineral and metal resources within an AESA approach. However, it has some limitations. Indeed, the approach proposed by De Bruille [13] and on which the work of Baabou et al. is based, does not consider the impact of user adaptability. That is, when a user, who initially consumes a resource A, consumes a resource B to adapt to the depletion of resource A, the method does not allow the quantification of the impact on the additional consumption of the resource B as a result of the adaptation of this user.

The majority of these methods are based on the LCA-based AESA approach. Bjorn et al. establishes a general framework of the LCA-based AESA which consists of four steps, as defined below: estimating the environmental impact using LCIA methods; quantifying the carrying capacity or the planetary limit or the safe operating space; assigning them to the system under study; evaluating the sustainability by comparing the estimated impact and the assigned carrying capacity [4].

Thus, as a first working hypothesis, this research work will be based on the LCA-based AESA methods but will seek to overcome the limitations identified above. To do so, a first

step is to identify the best LCIA candidate method for an LCA-based AESA approach in the building sector.

2.2. Relevance and Limits of Existing LCIA Methods for the Building Sector

In the life cycle assessment community, the mineral and metal resources issue has been widely discussed and many LCIA methods were developed to represent this issue. Liu et al. [20] showed that the material production phase of a road tunnel construction constitutes a significant proportion—79% to 87%—of carbon emissions of the construction. Notably, concrete exhibits the highest carbon emissions contribution, succeeded by steel [20]. Sonderegger et al. [21] and Berger et al. [22] established a complete review of the existing LCIA methods and provided recommendations to select the method depending on the application. At the French level and for the building sector, the CSTB (French Scientific and Technical Centre of Buildings) conducted various projects on the circular economy in the building sector using LCA (life cycle assessment) in order to make decision makers of construction projects aware of the issues of mineral and metal resources. Throughout these studies, the CSTB experts identified various limits of the LCIA methods related to mineral and metal resources in view of contributing to decision-support for the building decision-makers:

- The current LCIA methods inadequately account for the very heavy materials such as aggregates that are used in large quantities in the building sector and widely available globally. However, these resources face local limitations. Indeed, resources used in smaller quantities within the building sector, such as gold, emerge as the biggest contributors to the overall impact on mineral and metal resource, contradicting the priorities of decision-makers [23,24].
- The scale of evaluation of LCIA methods is global which is not suitable for most local resources such as aggregates where the life cycle is mainly regional and for which the level of pressure on the same type of resources varies according to the different territories [24].
- The reuse/recovery actions are not considered nor valorized by the existing LCIA resources impact category's indicators, whereas they allow for a reduction in the extraction of mineral resources [24].

2.3. The Selection of LCIA Methods

Once the LCIA methods in the literature were identified, they have been selected based on two criteria in order to conduct an analysis methodology to see whether they are adapted for an AESA approach in the building sector.

2.3.1. The LCIA Methods Identified in the Literature

Since no consensus was found in the LCA community regarding which impact assessment of mineral and metal resources to favor, several characterization methods have been developed [1], each using a different impact mechanism. The methods identified by Sonderegger et al. [21] and Berger et al. [22] will be the starting point of our study and the Impact World+ method, identified from the literature, will be added to the selection. Sonderegger et al. [21] classified the identified methods in four categories (depletion, future efforts, thermodynamic accounting and supply risk methods) based on the impact mechanisms used by these methods. This categorization is similar to the one proposed by the ILCD [13] adding the "supply risk" methods.

2.3.2. Criteria of Selection of Mineral Resources LCIA Indicators for the Building Sector

The identified LCIA methods were selected based on different selection criteria. The first selection criterion is the availability of the methods on SIMAPRO[®] (v9.1.0) [25], which is one of the LCA software programs most commonly used within the building sector by French professionals. The methods that are available on SIMAPRO[®] but are superseded, are not considered as they are not recommended and their characterization factors are

incompatible with the used inventory database, Ecoinvent 3.5 [26]. The second selection criterion is related to the category of the methods. The LCIA methods under the thermodynamic accounting category (thermodynamic rarity, CExD, SED and CEENE) were excluded as the ILCD judged this category of methods as insufficient regarding the environmental relevance and the stakeholder's acceptance [13]. These methods evaluate an inherent property of the resources, e.g., the exergy, which does not consider the scarcity and the societal value of these resources [22,27]. Therefore, they were considered as not relevant to express the impact on mineral and metal resources in a context of decision support for building actors. The LCIA methods from the supply risk category (GeoPolRisk, ESP, ESSENZ) quantify the potential issues of availability of mineral and metal resources for a product or system under study considering the geopolitical and socio-economic aspects. Therefore, they do not express the environmental availability of the resources and do not evaluate the pressures of the studied system on the depletion of mineral and metal resources. As the aim of this research is to identify methods that represent the pressure of a given building project on mineral and metal resources, as well as the potential vulnerability of this building model to a decrease of these resources, these methods were also excluded. The third selection criterion concerns the geographical context of the methods: the LIME2 and Swiss Ecological Scarcity LCIA methods are developed respectively in Japan and Switzerland and are representative of the Japanese and Swiss contexts, but our study will be conducted on a French case study, thus they are not suitable for our case and will be excluded. Concerning the CML-IA method, which uses the ADPelements, the characterization factors are given for economic reserves, reserve base, and ultimate reserves. In this study only the ADPelements (ultimate reserves) was considered since it is the best proxy to evaluate the natural stocks in a future perspective [22]. Table 1 resumes the LCIA methods that were identified in the literature.

Table 1. Identified LCIA methods dealing with mineral and metal resources. The selected methods are highlighted in bold.

Category	Methods	Indicators	Units	References	LCIA Methods in Ecoinvent v3.5
Depletion methods	CML-IA baseline	ADPelements (ultimate reserves)	éq. Kg Sb	[15,28]	Yes
	CML-IA non-baseline	ADPelements (reserve base)	éq. Kg Sb	[15,28]	Yes
	CML-IA non-baseline	ADPelements (economic reserves)	éq. Kg Sb	[15,28]	Yes
	Swiss Ecological Scarcity	Mineral resources	UBP	[29]	Yes
	-	AADP	éq. Kg Sb	[30]	No
	-	AADP (update)	éq. Kg Sb	[31]	No
	EDIP 97	Resources (all)	PR	[32]	Superseded
	EDIP 2003	Resources (all)	PR2004	[33]	Yes
LIME2 (midpoint)	Mineral resources (metals)	%	[34]	No	
Future Efforts methods	LIME2 (endpoint)	User Cost	\$	[34]	No
	-	Ore Grade Decrease	Kg	[35]	No
	-	ORI (Ore Requirement Indicator)	Kg ore/Kg metal × year	[36]	No
	-	SOP (Surplus Ore Potential)	Kg	[37]	No
	Eco-indicator 99	Minerals	MJ surplus	[38]	Superseded
	IMPACT 2002+	Mineral extraction	MJ surplus	[39]	Yes

Table 1. Cont.

Category	Methods	Indicators	Units	References	LCIA Methods in Ecoinvent v3.5
Future Efforts methods	Stepwise 2006	Mineral extraction	EUR	[40]	No
	ReCiPe	Mineral resource scarcity	Kg Cu eq	[41]	Yes
	-	Surplus Cost Potential	\$/kg	[42,43]	No
	Future Welfare Loss	Externality cost of exhaustion	\$	[44]	No
	EPS 2000/2015	Depletion of reserves	ELU	[45]	Superseded
	IMPACT World +	MACSI	Kg deprived/Kg dissipated	[13,46]	Yes
Thermodynamic Accounting methods	-	Thermodynamic Rarity	MJ	[47]	No
	CExD	Non-renewable, metals, minerals	MJ	[47]	Yes
	-	SED	MJ	[47]	No
	CEENE	Metal ores, Minerals	MJ	[48]	Yes
Supply Risk methods	-	GeoPolRisk		[49]	No
	-	ESP		[50]	No
	-	ESSENZ		[51,52]	No

2.3.3. The Selected LCIA Methods

Based on the criteria mentioned above, five methods were then selected as the ones that may be commonly used by building sector decision-makers, recommended by environmental footprint (or ILCD) and candidates for an AESA approach. The CML-IA (ultimate reserves) method uses the ADPelements (ultimate reserves) indicator that is expressed in kg antimony equivalent. This later evaluates the depletion of a resource by calculating the ratio of the extraction rate and the square of the estimated ultimate reserve [15,28]. The characterization factors of the EDIP method describe the fraction of the available resource reserve per person considering the economic reserves assessed in 2004, and are expressed in Person Reserve [32,33]. The IMPACT 2002+ method uses the characterization factors of the EcoIndicator99 method [38] reported to a reference substance, iron, and is expressed in MJ Surplus [39]. The ReCiPe method expresses the average additional quantity of ore produced in the future due to the extraction of 1 kg of a given resource, considering all its future production reported to the copper as a reference substance, with the characterization factors expressed in Kg Cu eq [41]. The IMPACT WORLD+ method uses the MACSI (Material Competition Scarcity Indexes). This factor evaluates the fraction of resources meeting the needs of future users who may not be able to adapt to a complete dissipation of the stocks easily available. It is expressed in terms of kg of resource of which the user is deprived per kg of dissipated resource [13,46]. In Table 1, the selected LCIA methods are highlighted in bold.

2.4. Analysis Methodology

A method in two steps was developed in order to assess the applicability of the selected LCIA methods for the building sector. Figure 2 represents the steps of this analytical method.

Firstly, an inventory analysis was conducted on a case study related to the building sector. Secondly, the mineral and metal inventory flows of the case study were compared to the mineral and metal flows for which the LCIA methods proposes characterization factors (CFs), using two indexes: Pn_i and Pm_i . The calculation of the Pn_i and Pm_i indexes is conducted in the interpretation step of the LCA framework.

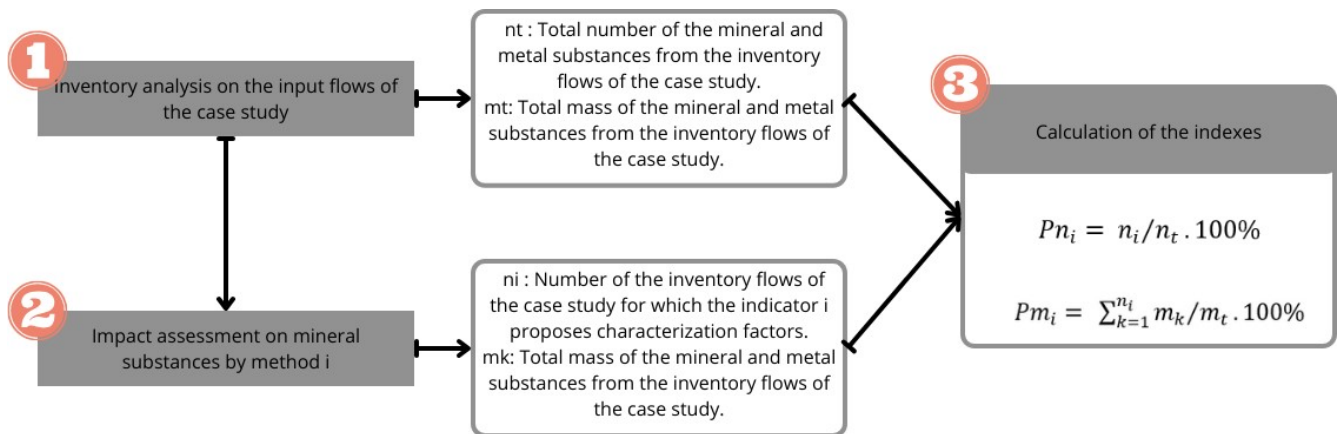


Figure 2. The main steps of the analytical methodology of the LCIA methods.

The index Pn_i estimates the percentage of mineral and metal substances from the inventory flows that are considered by each indicator i according to Equation (1).

$$Pn_i = n_i/n_t \times 100\% \quad (1)$$

With:

Pn_i : Percentage of mineral and metal substances from the inventory flows of the case study for which the indicator i proposes a CF.

n_i : Number of the inventory flows of the case study for which the indicator i proposes characterization factors.

n_t : Total number of the mineral and metal substances from the inventory flows of the case study.

Theorem 1. Estimation of the percentage of substances considered by LCIA indicator i .

The index Pm_i estimates the percentage of the mass of the mineral and metal substances considered by the indicators out of the total mass of mineral and metal resources involved in the inventory flows as described in Equation (2).

$$Pm_i = \sum_{k=1}^{n_i} m_k/m_t \times 100\% \quad (2)$$

With:

Pm_i : Percentage of the mass of mineral and metal substances from the inventory flows of the case study for which the indicator i proposes a CF.

m_k : Mass of the inventory flow k for which the indicator i suggests a characterization factor.

m_t : Total mass of the mineral and metal substances from the inventory flows of the case study.

Theorem 2. Estimation of the percentage of mass considered by LCIA indicator i .

3. Case Study and Results

In order to test the functionality of the six selected LCIA metrics relative to mineral and metal resources and to compare their results and the impacts and hierarchy of impacts between the various mineral and metal substances used by the building sector, these six LCIA metrics were tested on the case study of the construction of new buildings in France.

3.1. Application of the Proposed Approach on the Construction of New Housing Units in France in 2015

The goal of this study is to compare the results of several LCIA methods and metrics about mineral and metal resources issues when applied to the building sector. The scope of the selected case study is the construction of new housing units in France in 2015 as described by Leonardon et al. [2]. The functional unit of the LCA may be defined as “the construction of new housing units in France, in one year”.

The first step was to establish the LCI of the mineral and metal substances mobilized by the building sector. To achieve this, it was necessary to estimate the number of buildings constructed thanks to the Sit@del2 database [53]. This database provides the public statistical system relative to new construction of housing and non-domestic premises. The scenario AME (Avec Mesures Existantes—With Existing Measures) of the SNBC (Stratégie Nationale Bas Carbone—French National Low Carbon Strategy) was also used. The scenario AME describes the effect of current French public policies on energy consumption and greenhouse gas emissions. Four types of housing units were considered: isolated individual housing, grouped individual housing, collective housing and retirement homes. The total mineral and metal materials consumption for new housing in 2015 in France is about 41.523 ktons, distributed as described in Table 2.

Table 2. Mineral and metal resource consumption for the construction of new housing in 2015 in France [2].

Material	Mass (10 ³ tons)
TOTAL	4.15×10^4
Aggregates	1.80×10^4
Sand	1.39×10^4
Cement	4.40×10^3
Terracotta	2.83×10^3
Plaster	1.34×10^3
Steel	6.79×10^2
Glass	9.50×10^1
Mineral wool	9.70×10^1
Slate	6.80×10^1
Aluminium	1.80×10^1
Copper	2.10×10^1
Zinc	1.00×10^1

The results of the application of the identified LCIA metrics on this LCI are presented and analyzed below.

3.2. The Life Cycle Inventory Analysis

The inventory analysis was conducted on the defined case study using the Ecoinvent 3.5 database [26]. As a result of the inventory analysis, 501 flows were obtained including 133 mineral and metal flows of 4.57×10^7 t. The five heaviest mineral or metal substances are: “gravel” (3.39×10^7 t); “calcite” (5.15×10^6 t); “clay, unspecified” (4.68×10^6 t); “Gypsum” (1.47×10^6 t); “Shale” (1.37×10^5 t).

3.3. Life Cycle Impact Assessment: The Lack of Characterization Factors

The results are shown in Table 3 using a colour code: green when the percentage of the resources considered by each characterization method is higher than 70%, yellow when the percentage is between 30% and 70% and red when it is less than 30%.

Table 3. Results of the P_n and P_m indexes for each LCIA method.

Methods	Indicators	Unit	References	P _n	P _m
				Percentage of Substances That Are Considered	Percentage of Mass That Are Considered
CML-IA baseline	ADPelements (ultimate reserves)	éq. Kg Sb	[15,28]	57.03%	0.17%
Impact 2002 +	Mineral Extraction	MJ Surplus	[39]	27.13%	0.16%
EDIP 2003	Resource consumption	PR2004	[33]	55.04%	0.16%
ReCiPe	Mineral resource scarcity	Kg Cu eq	[41]	73.64%	13.69%
Impact World +	Material Competition Scarcity Index	kg deprived/kg dissipated	[13,46]	15.50%	10.44%

The results presented above show that the P_n and P_m indexes are very low for the majority of the LCIA indicators. As an example, for the ADPelements indicators, which is one of the indicators recommended by the ILCD [27] and the one used in the French national addition to the European standard NF EN 15804 + A1 [54] concerning environmental declarations for construction products (NF EN 15804 + A1, 2014), the P_n indicator is only 57%. This means that the impact on resource depletion of 43% of the substances of the mineral and metal inventory flows are not estimated and are then completely neglected within the estimation of the impact on mineral and metal resources. Besides, considering the P_m index, nearly 99% of the mass of the materials involved in this case study (representing the construction of new housing units in France in 2015) would not be considered by the ADPelements indicator and would not then appear in the results of impacts on mineral and metal resources. This represents an important limit of the concerned methods, yet they are widely used in the building sector.

3.4. Different Results and Priorities Highlighted for Different LCIA Methods

Figure 3 shows the distribution of the impacts estimated for the different substances for each LCIA method that was studied. Each time, the 10 substances with the highest impact were shown. It can be noticed that the results and priorities highlighted differ significantly according to the different LCIA methods. This can be explained as each method represents a different issue concerning the general subject of impact on mineral and metal resources. However, as there is still no consensus for the LCIA method [13], it is difficult, if not impossible, for a building decision maker to make up his mind on the hierarchy of impacts related to the various mineral and metal resources that are used for a given building project.

Two methods highlight the impact of the substance “clay, unspecified” (ReCiPe (Kg Cu eq) and IMPACT WORLD+ (Kg deprived/Kg dissipated)). The “Cadmium” appears as the most worrying concerning the impact on mineral and metal resources for two indicators (CML-IA baseline (Kg Sb eq) and EDIP (PR2004)). Finally, for one method, copper appears as the most impactful on mineral and metal resources (IMPACT 2002+ (MJ Surplus)).

However, since the methods do not estimate the impact for all the mineral and metal substances that are present in the life cycle inventory, as mentioned above, the results obtained cannot be fully trusted.

In order to complete this analysis, the aim was to compare the impact assessment results for a few mineral or metal substances in order to identify the variation of results, and hierarchy of estimated impacts between several given substances. Unfortunately, no substance was found to be covered simultaneously by the six selected LCIA methods. From the 133 mineral and metal substances of the inventory flows, no substance is considered by each of the six LCIA methods considered in this study.

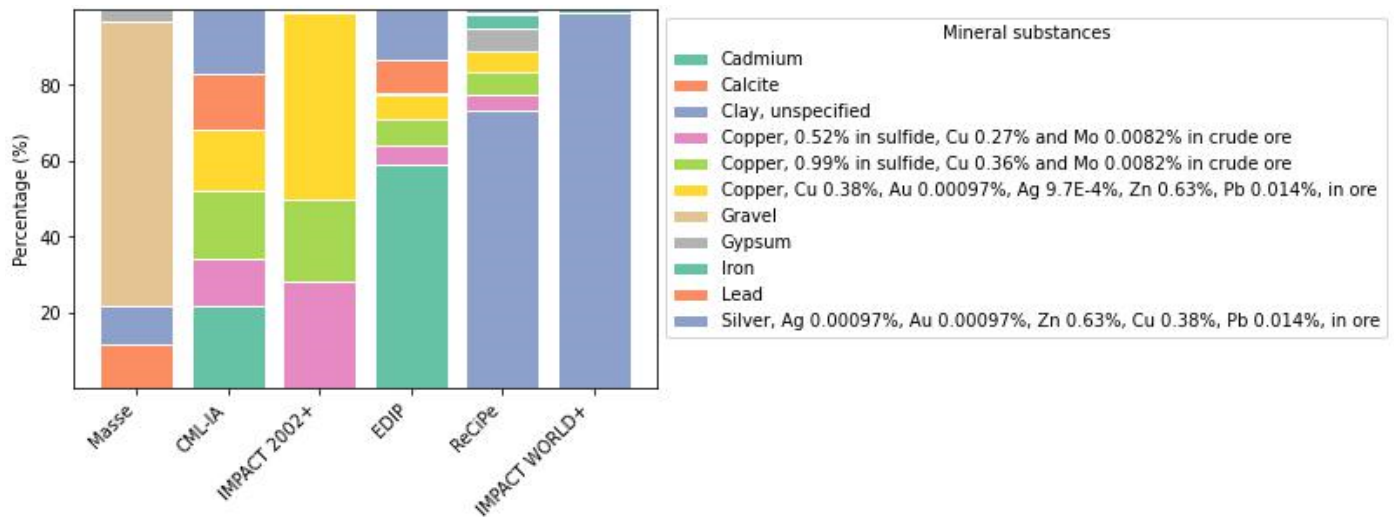


Figure 3. The repartition of the impacts of the mineral and metallic substances with the highest impact estimated using each LCIA method and the highest mass.

3.5. The Impact of Very Heavy Materials Is Invisible

Figure 3 shows that the substances that are represented with the highest impact by the studied characterization methods have a very low mass, while the substances with the highest mass have a low impact. All the considered LCIA methods estimate an impact equal to zero for the substance “gravel”, whereas it is the substance used with the highest mass.

Considering the increasing number of new buildings—360,000 each year on average in France [1]—the quantity of materials needed every year for the building sector is huge. Natural aggregates are the most-used resources in the building sector. In our case study, it represents 74% of the total mass of the building. However, the environmental impacts and pressure on natural resources of natural aggregates extraction cannot be neglected. Indeed, aggregates are now facing shortages all over the world (from Europe to China, for example) and their extraction generates negative environmental and social impacts [55]. Thus, a decision support tool that considers this resource is necessary.

4. Discussion

4.1. Regionalization

Some mineral and metal resources, such as natural aggregates, are considered very abundant at the global level. However, their supply is regional or departmental [24] and because of their overexploitation in the construction sector, some densely urbanized regions (Ile de France, in France, for example) face a supply constraint [56]. It is therefore necessary to consider the impact of natural aggregates on a local scale. Especially since some circular economy initiatives are implemented to reduce their use and recycle them [24], it is necessary to give some hints to the decision-makers about the potentially positive impacts of these projects that use recycled materials. The most-used LCIA methods do not allow an evaluation of pressures on local resources and the impact of very heavy materials such as aggregates and sand are hidden in LCA results since metals such as cadmium have the most influence on the total impact.

It then appears necessary to integrate, within the LCIA assessment of mineral and metal resource, the various spatial scales of their different markets to better support decision-making in the building sector. Then, within the framework of an AESA approach applied to mineral resources, this would mean defining a critical rate of use depending on the scale of the market of each substance. Indeed, if the market for most of the metal resources has a world scale [57], the most ponderous mineral resources that are particularly used in the building sector have national, or regional markets [58]. This has two consequences for developing an AESA method to mineral and metal resource:

- Each substance will have to be studied separately, from the inventory phase up to environmental assessment to define the relevant scale for its market, and then its environmental assessment (regional, national or global)
- The “acceptable environmental burden” will have to be defined in the form of an “acceptable use rate” for each substance and each relevant geographical scale.

4.2. Assimilation, a Solution to Improve the Completeness of the CF?

This study reveals a lack of characterization factors of the analyzed LCIA methods when applied to the construction of new housing units in France in 2015. This represents a considerable limit of these LCIA methods for the building sector. This lack of data means that when an LCIA method is used to estimate the impact of a building project, an important percentage of the mass of the project is not characterized, which represents an important limit to existing LCIA methods on resource dissipation issues. This issue is particularly problematic when LCA is used as a decision-support tool within the building sector because of the high dependency and impact of this sector on mineral and metal resources [59]. If regulations or ecodesign are based on LCA in the building sector [47,48], this may raise several critical questions. Indeed, a building decision-maker could not identify, through an LCA study, the strengths and weaknesses of a project concerning mineral and metal resources, or may be misled by an under-representation of the impacts on the most critical resources.

This lack of characterization factors is due to two aspects: the first one is that the level of detail of the inventory flows of the background database (such as Ecoinvent) evolves over time and the LCIA methods do not offer an updated set of characterization factors for every evolution of the Ecoinvent database. The second one is that the level of flow details requires a large amount of data to characterize all the different flows. Table 4 shows the list of the flows of copper and gold issued from the inventory analysis and their corresponding impact using the CML-IA and Impact World+ methods. This table shows that: (i) Not all the flows are described with the same level of detail, which explains the evolution of the inventory flows in Ecoinvent. (ii) Some flows do not have a corresponding CF, which means that those flows were integrated into the Ecoinvent base after the latest update of the LCIA method. (iii) All the flows, corresponding to the same resource (e.g., copper), have the same characterization factors, which means that the LCIA method developers assimilate the flows between them to improve the completeness of the set of CF.

Assimilation is a post-treatment process that aims to improve the completeness of the set of characterization factors of a given method to estimate an indicator. The idea of this process is to assimilate flow A to flow B and to consider that the characterization factor of flow A and B are the same, as is the case for the flows of copper and gold as shown in Table 4. Some methods use assimilation for substances of different minerals or metals. For example, the French national addition to the European standard NF EN 15804 + A1 concerning environmental declarations for construction products proposes to use as an indicator of mineral and metal resources depletion, the ADPelements indicator within the LCA that are realized in the context of a building project. To overcome the lack of characterization factors of the ADPelements indicator, this French document proposes some assimilation rules between different mineral and metal substances. Table 5 shows an example of the assimilated substances with the proposed assimilation (EN15804/CN, 2016).

It appears in Table 5 that, due to lack of available data, numerous substances are assimilated to silicon whereas their characteristics in terms of use, availability and chemical composition may be very different. This assimilation reduces the lack of characterization of the different substances by making approximations that are acceptable to provide orders of magnitude. However, when it comes to decision-support tools, those approximations may not be acceptable. For example, “clay” is assimilated to “silicon”, which may be justified by a relatively similar state of natural resources, but clay and silicon do not have the same functions within a building project and cannot be substituted one to the other. The same may apply for the assimilation made by the method’s developers concerning the flows of

copper, for example, because the different flows of copper do not have the same properties and thus the same functions. It does not, therefore, seem a rigorous choice to assimilate one to the other in the view of a building decision-maker.

This problem of assimilation brings us back to our initial objective to adapt a mineral and metal resource indicator to an AESA approach. Indeed, to integrate the mineral and metal resources in an AESA approach, it is necessary to define a *critical* or *sustainable* threshold for the rate of use of mineral and metal resources. This rate of use should be defined at the scale of each substance, for all the different reserves available for each type of resource. This implies the need to be able to characterize the specific impact of each mineral and metal substance. Thus, the assimilation methods cannot be mobilized for this purpose.

Table 4. Flows of copper and gold and their estimated impact using the CML-IA and Impact World+ method.

Mineral and Metal Substances	CML-IA (Kg Sb eq/Kg)	Impact World+ (Kg Deprived/Kg)
Copper	1.37×10^{-3}	1.20×10^{-1}
Copper ore	0.00×10	1.20×10^{-1}
Copper, 0.52% in sulfide, Cu 0.27% and Mo $8.2 \times 10^{-3}\%$ in crude ore	1.37×10^{-3}	1.93×10^{-3}
Copper, 0.59% in sulfide, Cu 0.22% and Mo $8.2 \times 10^{-3}\%$ in crude ore	1.37×10^{-3}	1.20×10^{-1}
Copper, 0.97% in sulfide, Cu 0.36% and Mo $4.1 \times 10^{-2}\%$ in crude ore	1.37×10^{-3}	1.20×10^{-1}
Copper, 0.99% in sulfide, Cu 0.36% and Mo $8.2 \times 10^{-3}\%$ in crude ore	1.37×10^{-3}	1.20×10^{-1}
Copper, 1.13% in sulfide, Cu 0.76% and Ni 0.76% in crude ore	1.37×10^{-3}	1.20×10^{-1}
Copper, 1.18% in sulfide, Cu 0.39% and Mo $8.2 \times 10^{-3}\%$ in crude ore	1.37×10^{-3}	1.20×10^{-1}
Copper, 1.42% in sulfide, Cu 0.81% and Mo $8.2 \times 10^{-3}\%$ in crude ore	1.37×10^{-3}	1.20×10^{-1}
Copper, 2.19% in sulfide, Cu 1.83% and Mo $8.2 \times 10^{-3}\%$ in crude ore	1.37×10^{-3}	1.20×10^{-1}
Copper, Cu 0.2%, in mixed ore	1.37×10^{-3}	1.20×10^{-1}
Copper, Cu 0.38%, Au $9.7 \times 10^{-4}\%$, Ag $9.7 \times 10^{-4}\%$, Zn 0.63%, Pb 0.014%, in ore	1.37×10^{-3}	1.20×10^{-1}
Copper, Cu $3.2 \times 10^0\%$, Pt $2.5 \times 10^{-4}\%$, Pd $7.3 \times 10^{-4}\%$, Rh $2.0 \times 10^{-5}\%$, Ni $2.3 \times 10^0\%$ in ore	1.37×10^{-3}	1.20×10^{-1}
Copper, Cu $5.2 \times 10^{-2}\%$, Pt $4.8 \times 10^{-4}\%$, Pd $2.0 \times 10^{-4}\%$, Rh $2.4 \times 10^{-5}\%$, Ni $3.7 \times 10^{-2}\%$ in ore	1.37×10^{-3}	1.20×10^{-1}
Gold	5.20×10^1	8.60×10^{-1}
Gold, Au $1.1 \times 10^{-4}\%$, Ag $4.2 \times 10^{-3}\%$, in ore	5.20×10^1	8.60×10^{-1}
Gold, Au $1.3 \times 10^{-4}\%$, Ag $4.6 \times 10^{-5}\%$, in ore	5.20×10^1	8.60×10^{-1}
Gold, Au $1.8 \times 10^{-4}\%$, in mixed ore	5.20×10^1	0.00×10
Gold, Au $2.1 \times 10^{-4}\%$, Ag $2.1 \times 10^{-4}\%$, in ore	5.20×10^1	8.60×10^{-1}
Gold, Au $4.3 \times 10^{-4}\%$, in ore	5.20×10^1	8.60×10^{-1}
Gold, Au $4.9 \times 10^{-5}\%$, in ore	5.20×10^1	8.60×10^{-1}
Gold, Au $5.4 \times 10^{-4}\%$, Ag $1.5 \times 10^{-5}\%$, in ore	5.20×10^1	0.00×10
Gold, Au $6.7 \times 10^{-4}\%$, in ore	5.20×10^1	8.60×10^{-1}
Gold, Au $6.8 \times 10^{-4}\%$, Ag $1.5 \times 10^{-4}\%$, in ore	5.20×10^1	0.00×10
Gold, Au $7.1 \times 10^{-4}\%$, in ore	5.20×10^1	8.60×10^{-1}
Gold, Au $9.7 \times 10^{-4}\%$, Ag $9.7 \times 10^{-4}\%$, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	5.20×10^1	8.60×10^{-1}
Gold, Au $9.7 \times 10^{-5}\%$, Ag $7.6 \times 10^{-5}\%$, in ore	5.20×10^1	0.00×10

Table 5. The proposed assimilation for some substances not considered in the ADPelements indicator.

Substances Not Considered in ADPelements	Proposed Assimilation (EN 15804 + A1/CN)
Basalt	Silicon
Clay	Silicon
Clay and soil, extracted for use	Silicon
Clay, bentonite	Silicon
Clay, unspecified	Silicon
Granite	Silicon
Gravel	Silicon

Table 5. Cont.

Substances Not Considered in ADPElements	Proposed Assimilation (EN 15804 + A1/CN)
Metamorphous rock, graphite containing	Silicon
Natural aggregate	Silicon
Olivine	Silicon
Perlite	Silicon
Pumice	Silicon
Sand	Silicon
Sand and clay	Silicon
Sand and gravel	Silicon
Sand, gravel and stone, extracted for use	Silicon
Sand, quartz	Silicon
Sand, quartz, in ground	Silicon
Sand, river, in ground	Silicon
Shale	Silicon
Slate	Silicon

4.3. The Flows from the Circular Economy Are Not Considered

In an AESA approach, it is necessary to define an “acceptable use rate” for each mineral and metal substance. Considering the non-renewable aspect of mineral and metal resources, their extraction and use is therefore by definition unsustainable. Given that a resource is only exhausted when it is dissipated and can no longer be reused [30,31,46,60], a possible substitution for natural mineral and metal resources would be the secondary resources present in the anthroposphere. Thus, we propose to define this acceptable use rate of mineral and metal resources as a use that is limited to secondary materials from the circular economy. However, built as they are and considering their impact mechanism, the selected LCIA methods related to mineral and metal resources do not integrate the flows from the circular economy [10]. From this observation, the use of the studied LCIA methods is not compatible with the aim of developing an LCIA indicator for mineral and metal resources that is compatible with an AESA approach in a context of decision support of the building stakeholders.

5. Conclusions and Perspectives

This study highlighted different limits for the use of existing LCIA methods related to mineral and metal resources in an LCA-based AESA approach: (i) there is a big lack in the set of characterization factors for mineral and metal resources of the LCIA methods, (ii) the heavy materials, as aggregates, are evaluated at a global scale, thus, they have a very low CF, which makes their estimated impact invisible within the total impact of the case study despite their huge mass and recognized regional availability issues, (iii) the material flows issued from the circular economy are not integrated into the existing LCIA methods. It can be concluded that the existing LCIA methods are not suitable to represent the pressures on mineral and metal resources in the building sector for an AESA approach. Based on this, some principles can be defined to orientate methodological development. Firstly, the proposed indicators will have to be applied as characterization factors at the level of the life cycle inventory such as the PB-LCA method developed by Ryberg et al. [7]. It is not, therefore, as a normalization reference at the level of the impact estimated by an existing LCIA mineral resource indicator such as the carrying capacity approach [8]. Secondly, it will have to consider the most suitable spatial scale for each substance flow in coherence with the main economic scale of the markets for each substance. Thirdly, it will have to consider flows from the circular economy, by translating the hypothesis of strong sustainability for the depletion of mineral and metal resources problem as the exclusive use of the flows issued from reuse and recycling.

Author Contributions: Conceptualization, N.B., N.G. and J.C.; methodology, N.B.; software, N.B.; validation N.G. and J.C.; formal analysis, N.B., N.G. and J.C.; investigation, N.B., N.G. and J.C.;

resources, N.B., N.G. and J.C.; data curation, N.B., N.G. and J.C.; writing—original draft preparation, N.B.; writing—review and editing, N.B., N.G. and J.C.; visualization, N.B., N.G. and J.C.; supervision, N.G. and J.C.; project administration, N.G. and J.C.; funding acquisition, N.G. and J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was conducted within the CIFRE 2020/0534 convention, which was funded by the ANRT (Agence Nationale de la Recherche Technologique) and the CSTB.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data used in this study can be found following the link: <https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-5/>, accessed on 14 April 2022.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Sameer, H.; Bringezu, S. Life Cycle Input Indicators of Material Resource Use for Enhancing Sustainability Assessment Schemes of Buildings. *J. Build. Eng.* **2019**, *21*, 230–242. [CrossRef]
2. Leonardon, P.; Laurenceau, S.; Louerat, M.; Core, E. Prospective De Consommation De Matière Pour Les Batiments Neufs Aux Horizons 2035 Et 2050. ADEME CSTB 2018, 116. Available online: <https://www.actu-environnement.com/media/pdf/news-34726-etude-ademe-besoin-materiaux-construction-decembre2019.pdf> (accessed on 6 November 2023).
3. Ghewy, X. *Bilan 2012 de La Production de Déchets en France*; (CGDD) Commissariat Général Au Développement Durable: Paris, France, 2019; p. 4.
4. Bjørn, A.; Richardson, K.; Hauschild, M.Z. A Framework for Development and Communication of Absolute Environmental Sustainability Assessment Methods. *J. Ind. Ecol.* **2019**, *23*, 838–854. [CrossRef]
5. Bjørn, A.; Hauschild, M.Z. Absolute versus Relative Environmental Sustainability: What Can the Cradle-to-Cradle and Eco-Efficiency Concepts Learn from Each Other? Bjørn and Hauschild Cradle to Cradle versus Eco-Efficiency. *J. Ind. Ecol.* **2013**, *17*, 321–332. [CrossRef]
6. Bjørn, A.; Chandrakumar, C.; Boulay, A.M.; Doka, G.; Fang, K.; Gondran, N.; Hauschild, M.Z.; Kerkhof, A.; King, H.; Margni, M.; et al. Review of Life-Cycle Based Methods for Absolute Environmental Sustainability Assessment and Their Applications. *Environ. Res. Lett.* **2020**, *15*, 083001. [CrossRef]
7. Ryberg, M.W.; Owsianiak, M.; Richardson, K.; Hauschild, M.Z. Development of a Life-Cycle Impact Assessment Methodology Linked to the Planetary Boundaries Framework. *Ecol. Indic.* **2018**, *88*, 250–262. [CrossRef]
8. Andersen, C.E.; Ohms, P.; Rasmussen, F.N.; Birgisdóttir, H.; Birkved, M.; Hauschild, M.; Ryberg, M. Assessment of Absolute Environmental Sustainability in the Built Environment. *Build. Environ.* **2020**, *171*, 106633. [CrossRef]
9. Yossapol, C.; Axe, L.; Watts, D.; Caudill, R.; Dickinson, D.; Mosovsky, J. Carrying Capacity Estimates for Assessing Environmental Performance and Sustainability. In Proceedings of the Conference Record 2002 IEEE International Symposium on Electronics and the Environment, San Francisco, CA, USA, 6–9 May 2002.
10. Klinglmair, M.; Sala, S.; Brandão, M. Assessing Resource Depletion in LCA: A Review of Methods and Methodological Issues. *Int. J. Life Cycle Assess.* **2014**, *19*, 580–592. [CrossRef]
11. Vargas-Gonzalez, M.; Witte, F.; Martz, P.; Gilbert, L.; Humbert, S.; Jolliet, O.; van Zelm, R.; L’Haridon, J. Operational Life Cycle Impact Assessment Weighting Factors Based on Planetary Boundaries: Applied to Cosmetic Products. *Ecol. Indic.* **2019**, *107*, 105498. [CrossRef]
12. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S.; Lambin, E.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecol. Soc.* **2009**, *14*, 32. [CrossRef]
13. De Bruille, V. Impact de l’utilisation Des Ressources Minérales et Métalliques Dans Un Contexte de Cycle de Vie: Une Approche Fonctionnelle. Doctoral Dissertation, École Polytechnique de Montréal, Montréal, QC, Canada, 2014.
14. Sala, S.; Crenna, E.; Secchi, M.; Sanyé-Mengual, E. Environmental Sustainability of European Production and Consumption Assessed against Planetary Boundaries. *J. Environ. Manag.* **2020**, *269*, 110686. [CrossRef]
15. van Oers, L.; de Koning, A.; Guinée, J.B.; Huppes, G. *Abiotic Resource Depletion in LCA: Improving Characterisation Factors for Abiotic Resource Depletion as Recommended in the New Dutch LCA Handbook*; Road and Hydraulic Engineering Institute: Delft, The Netherlands, 2002; pp. 1–75.
16. Bringezu, S. Possible Target Corridor for Sustainable Use of Global Material Resources. *Resources* **2015**, *4*, 25–54. [CrossRef]
17. Bringezu, S. Toward Science-Based and Knowledge-Based Targets for Global Sustainable Resource Use. *Resources* **2019**, *8*, 140. [CrossRef]
18. Buczko, C.; Hinterberger, F.; Stricks, V. *Towards SDG Implementation: The Role of Global Resource Policy and Resource Targets*; Brief for GSDR–2016 Update; United Nations Department of Economic and Social Affairs: New York, NY, USA, 2016; p. 4.

19. Baabou, W.; Bjørn, A.; Bulle, C. Absolute Environmental Sustainability of Materials Dissipation: Application for Construction Sector. *Resources* **2022**, *11*, 76. [[CrossRef](#)]
20. Liu, T.; Zhu, H.; Shen, Y.; Li, T.; Liu, A. Embodied Carbon Assessment on Road Tunnels Using Integrated Digital Model: Methodology and Case-Study Insights. *Tunn. Undergr. Space Technol.* **2024**, *143*, 105485. [[CrossRef](#)]
21. Sonderegger, T.; Berger, M.; Alvarenga, R.; Bach, V.; Cimprich, A.; Dewulf, J.; Frischknecht, R.; Guinée, J.; Helbig, C.; Huppertz, T.; et al. Mineral Resources in Life Cycle Impact Assessment—Part I: A Critical Review of Existing Methods. *Int. J. Life Cycle Assess.* **2020**, *25*, 784–797. [[CrossRef](#)]
22. Berger, M.; Sonderegger, T.; Alvarenga, R.; Bach, V.; Cimprich, A.; Dewulf, J.; Frischknecht, R.; Guinée, J.; Helbig, C.; Huppertz, T.; et al. Mineral Resources in Life Cycle Impact Assessment: Part II—Recommendations on Application-Dependent Use of Existing Methods and on Future Method Development Needs. *Int. J. Life Cycle Assess.* **2020**, *25*, 798–813. [[CrossRef](#)]
23. CSTB; FCRBE. FuturREuse: Les Impacts Environnementaux du Réemploi Dans le Secteur de la Construction. FCRBE_Brochures 2021, 1–23. Available online: https://opalis.eu/sites/default/files/2022-02/FCRBE-booklet-01-environmental_impact-FR.pdf (accessed on 6 November 2023).
24. Rodriguez, J.; Monfort, D.; Bazzana, M.; Schiopu, N.; Bonnet, R.; Sement, N.; Chevalier, J. Développements Méthodologiques OVALEC—Économie Circulaire Pour Les Flux Matériaux/Déchets de Bâtiment. 2016. Available online: <https://www.cstb.fr/assets/communiqués/ovalec-281116.pdf> (accessed on 6 November 2023).
25. Brachet, A. Méthodologie d'évaluation Hybride Des Interactions Entre La Biodiversité et Les Systèmes Urbains: Vers Une Synergie Entre l'Analyse de Cycle de Vie, l'expertise Écologique et La Data Science. Doctoral Dissertation, Muséum National D'histoire Naturelle, Paris, France, 2020.
26. Moreno Ruiz, E.; Valsasina, L.; Brunner, F.; Symeonidis, A.; FitzGerald, D.; Treyer, K.; Bourgault, G.; Wernet, G. *Documentation of Changes Implemented in Ecoinvent Database v3.5*; Ecoinvent: Zürich, Switzerland, 2018; Volume 5, pp. 1–97.
27. ILCD. *ILCD Handbook*; Publications Office of the European Union: Luxembourg, 2011; Volume 53, ISBN 9788578110796.
28. Guinée, J.B.; Heijungs, R. A Proposal for the Definition of Resource Equivalency Factors for Use in Product Life-cycle Assessment. *Environ. Toxicol. Chem.* **1995**, *14*, 917–925. [[CrossRef](#)]
29. Frischknecht, R.; Büsser Knöpfel, S. *Swiss Eco-Factors 2013 According to the Ecological Scarcity Method*; Federal Office for the Environment FOEN: Bern, Switzerland, 2013; Volume 256.
30. Schneider, L.; Berger, M.; Finkbeiner, M. The Anthropogenic Stock Extended Abiotic Depletion Potential (AADP) as a New Parameterisation to Model the Depletion of Abiotic Resources. *Int. J. Life Cycle Assess.* **2011**, *16*, 929–936. [[CrossRef](#)]
31. Schneider, L.; Berger, M.; Finkbeiner, M. Abiotic Resource Depletion in LCA—Background and Update of the Anthropogenic Stock Extended Abiotic Depletion Potential (AADP) Model. *Int. J. Life Cycle Assess.* **2015**, *20*, 709–721. [[CrossRef](#)]
32. Wenzel, H.; Hauschild, M.Z.; Alting, L.; Overcash, M. Environmental Assessment of Products. *Int. J. Life Cycle Assess.* **1997**, *4*, 6. [[CrossRef](#)]
33. Hauschild, M.Z.; Potting, J. Spatial Differentiation in Life Cycle Impact Assessment—The EDIP 2003 Background for Spatial Differentiation in LCA Impact Assessment. *Environ. News* **2005**, *80*, 1–195.
34. Itsubo, N.; Inaba, A. *LIME2 Life-Cycle Impact Assessment Method Based on Endpoint Modeling Chapter 2: Characterization and Damage Evaluation Methods*; The Life Cycle Assessment Society of Japan: Tsukuba, Japan, 2014.
35. Vieira, M.D.M.; Goedkoop, M.J.; Storm, P.; Huijbregts, M.A.J. Ore Grade Decrease as Life Cycle Impact Indicator for Metal Scarcity: The Case of Copper. *Environ. Sci. Technol.* **2012**, *46*, 12772–12778. [[CrossRef](#)] [[PubMed](#)]
36. Swart, P.; Dewulf, J. Quantifying the Impacts of Primary Metal Resource Use in Life Cycle Assessment Based on Recent Mining Data. *Resour. Conserv. Recycl.* **2013**, *73*, 180–187. [[CrossRef](#)]
37. Vieira, M.D.M.; Ponsioen, T.C.; Goedkoop, M.J.; Huijbregts, M.A.J. Surplus Ore Potential as a Scarcity Indicator for Resource Extraction. *J. Ind. Ecol.* **2017**, *21*, 381–390. [[CrossRef](#)]
38. Goedkoop, M.; Spriensma, R. The Eco-Indicator 99—A Damage Oriented Method for Life Cycle Impact Assessment. Methodology Report. Available online: https://www.researchgate.net/publication/247848113_The_Eco-Indicator_99_A_Damage_Oriented_Method_for_Life_Cycle_Impact_Assessment#fullTextFileContent (accessed on 6 November 2023).
39. Jolliet, O.; Margni, M.; Charles, R.; Humbert, S.; Payet, J.; Rebitzer, G.; Rosenbaum, R. IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. *Int. J. Life Cycle Assess.* **2003**, *8*, 324–330. [[CrossRef](#)]
40. Weidema, B.P.; Wesnae, M.; Hermansen, J.; Kristensen, I.; Halberg, N. *Environmental Improvement Potentials of Meat and Dairy Products*; Publications Office of the European Union: Luxembourg, 2008; Volume 23491, ISBN 9789279097164.
41. Goedkoop, M.; Huijbregts, M. *ReCiPe 2008—A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and Endpoint Level. First Edition (Revised). Report 1: Characterization*; Ruimte en Milieu, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer: Den Haag, The Netherlands, 2012; pp. 1–137.
42. Vieira, M.D.M.; Ponsioen, T.C.; Goedkoop, M.J.; Huijbregts, M.A.J. Surplus Cost Potential as a Life Cycle Impact Indicator for Metal Extraction. *Resources* **2016**, *5*, 2. [[CrossRef](#)]
43. Vieira, M.D.M.; Huijbregts, M.A.J. Comparing Mineral and Fossil Surplus Costs of Renewable and Non-Renewable Electricity Production. *Int. J. Life Cycle Assess.* **2018**, *23*, 840–850. [[CrossRef](#)]
44. Huppertz, T.; Weidema, B.P.; Standaert, S.; de Caemel, B.; van Overbeke, E. The Social Cost of Sub-Soil Resource Use. *Resources* **2019**, *8*, 19. [[CrossRef](#)]

45. Steen, B. *A Systematic Approach to Environmental Priority Strategies in Product Development (EPS)*; Centre for Environmental Assessment of Products and Material Systems: Gothenburg, Sweden, 2014.
46. Bulle, C.; Margni, M.; Patouillard, L.; Boulay, A.M.; Bourgault, G.; De Bruille, V.; Cao, V.; Hauschild, M.; Henderson, A.; Humbert, S.; et al. IMPACT World+: A Globally Regionalized Life Cycle Impact Assessment Method. *Int. J. Life Cycle Assess.* **2019**, *24*, 1653–1674. [[CrossRef](#)]
47. Valero, A.; Valero, A. Thermodynamic Rarity and the Loss of Mineralwealth. *Energies* **2015**, *8*, 821–836. [[CrossRef](#)]
48. Dewulf, J.; Bösch, M.E.; De Meester, B.; Van Der Vorst, G.; Van Langenhove, H.; Hellweg, S.; Huijbregts, M.A.J. Cumulative Exergy Extraction from the Natural Environment (CEENE): A Comprehensive Life Cycle Impact Assessment Method for Resource Accounting. *Environ. Sci. Technol.* **2007**, *41*, 8477–8483. [[CrossRef](#)] [[PubMed](#)]
49. Cimprich, A.; Karim, K.S.; Young, S.B. Extending the Geopolitical Supply Risk Method: Material “Substitutability” Indicators Applied to Electric Vehicles and Dental X-ray Equipment. *Int. J. Life Cycle Assess.* **2018**, *23*, 2024–2042. [[CrossRef](#)]
50. Schneider, L.; Berger, M.; Schüler-Hainsch, E.; Knöfel, S.; Ruhland, K.; Mosig, J.; Bach, V.; Finkbeiner, M. The Economic Resource Scarcity Potential (ESP) for Evaluating Resource Use Based on Life Cycle Assessment. *Int. J. Life Cycle Assess.* **2014**, *19*, 601–610. [[CrossRef](#)]
51. Bach, V.; Berger, M.; Henßler, M.; Kirchner, M.; Leiser, S.; Mohr, L.; Rother, E.; Ruhland, K.; Schneider, L.; Tikana, L.; et al. Integrated Method to Assess Resource Efficiency—ESSENZ. *J. Clean. Prod.* **2016**, *137*, 118–130. [[CrossRef](#)]
52. Bach, V.; Berger, M.; Finogenova, N.; Finkbeiner, M. Analyzing Changes in Supply Risks for Abiotic Resources over Time with the ESSENZ Method—A Data Update and Critical Reflection. *Resources* **2019**, *8*, 83. [[CrossRef](#)]
53. CGDD De Sitadel à Sit @ Del2. Service de L’observation et des Statistiques. 2011, 2. Available online: <https://artificialisation.developpement-durable.gouv.fr/bases-donnees/sitadel-2> (accessed on 6 November 2023).
54. EN 15804; Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products. European Standard: Brussels, Belgium, 2014.
55. Ren, Z.; Jiang, M.; Chen, D.; Yu, Y.; Li, F.; Xu, M.; Bringezu, S.; Zhu, B. Stocks and Flows of Sand, Gravel, and Crushed Stone in China (1978–2018): Evidence of the Peaking and Structural Transformation of Supply and Demand. *Resour. Conserv. Recycl.* **2022**, *180*, 106173. [[CrossRef](#)]
56. Ioannidou, D.; Meylan, G.; Sonnemann, G.; Habert, G. Is Gravel Becoming Scarce? Evaluating the Local Criticality of Construction Aggregates. *Resour. Conserv. Recycl.* **2017**, *126*, 25–33. [[CrossRef](#)]
57. Calvo, G.; Valero, A. Strategic Mineral Resources: Availability and Future Estimations for the Renewable Energy Sector. *Environ. Dev.* **2021**, *41*, 100640. [[CrossRef](#)]
58. Veraart, F. Land or Lakes: Gravel Excavation in Dutch Spatial and Resources Policies through the Lens of Sustainability Developments, 1950–2015. *Land Use Policy* **2019**, *82*, 367–374. [[CrossRef](#)]
59. Kedir, F.; Hall, D.M. Resource Efficiency in Industrialized Housing Construction—A Systematic Review of Current Performance and Future Opportunities. *J. Clean. Prod.* **2021**, *286*, 125443. [[CrossRef](#)]
60. Stewart, M.; Weidema, B. A Consistent Framework for Assessing the Impacts from Resource Use—A Focus on Resource Functionality (8 pp). *Int. J. Life Cycle Assess.* **2005**, *10*, 240–247. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.