AESA approach applied to mineral and metal resources use sustainability in the building sector: The MiMOSA method

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Abstract. Considering the increase of natural resource use, humanity is facing the problem of resource depletion. The building sector is a major consumer of resources. The most consumed resources are mineral and metal resources. Thereby, the identification, and then optimisation, of mineral and metal resource use in the building sector appears as a necessity. One tool to quantify the use of those resources is LCA. Currently, several authors develop absolute environmental sustainability assessment (AESA) methods, combined with LCA, to compare the pressures of the studied project with the global carrying capacity of the planet. However, most of the AESA approaches do not actually include normalization factors about the use of resources, and in particular mineral and metal resources. Besides, the mainly used LCIA characterization methods of mineral and metal resources present several limits when applied to Circular Economy projects within the building sector. Thereby, the goal of this research project is to answer the following question: Can the consumption of mineral and metal resources for a given building project be considered sustainable? To answer this question, a methodology was developed. This methodology is inspired by the AESA approach by proposing a sustainable resource budget for each mineral or metal substance and will combine the MFA methods to the LCA method to calculate sustainability indicators for each mineral and metal resource. The Mineral and Metal absOlute Sustainability Assessment (MiMOSA) method integrates the circular economy actions and considers an appropriate spatial scale for each resource and will be presented in this paper.

1. Introduction

Considering the importance of mineral and metal resources for the construction sector and considering the resource shortages that humanity may face [1], it becomes essential to make aware and accompany building stakeholders and policymakers by estimating the pressure on mineral and metal resources of the building projects while promoting circular economy (CE) projects. Thus, indicators should be developed to answer the following question: Is the consumption of mineral and metal resources of the studied project sustainable or excessive? In other words, maximum resource budgets should be defined for each building project. This leads to the following research question: How to define a sustainable resource budget for mineral and metal resources that are non-renewable resources?

Throughout their existence on Earth, humans have accumulated a quantity of materials in the form of buildings, infrastructures and other consumer goods with a wide range of lifetimes. These materials constitute the anthropogenic stock [2] and represent a significant reservoir of secondary materials and
products for re-use. This phase aims to define the anthropogenic stock actually available, taking into account the life cycle of the products and goods in which the materials are stored and the yield of the different recovery channels. The European Directive 2008/98/E.C. has defined waste management guidelines and a hierarchy of CE actions to be undertaken [3], among them, recycling and reuse. Thus, a sustainable resource budget should take into account the flows issued from recycling and reuse.

The objective of this paper is to present a methodology for assessing the sustainability of mineral and metal resources in the building sector that couples the life cycle assessment (LCA) method with the material flow analysis (MFA) method in an absolute environmental sustainability assessment (AESA) approach. The Mineral and Metal absolute Sustainability Assessment (MiMOSA) method aims at, on the one hand, assessing the mineral and metal material requirements of a given construction project throughout its life cycle, on the other hand, estimating the CE material budgets that can be assigned to that project and finally making a comparison between the two values to assess the sustainability of the project regarding the use of mineral and metal resources.

LCA is a widely used method for assessing the inputs, outputs and potential environmental impacts of products and services and there is a high level of consensus on its use in both the scientific and regulatory communities [4–6]. In the framework of the method described in this article, the mineral and metal resource requirements of the building will be estimated based on the principles of the EN 15978 standard which governs the calculation method for the assessment of the environmental performance of buildings based on LCA [5].

The AESA approach aims to evaluate the environmental sustainability of a given product or service by comparing its environmental pressures to its allocated absolute environmental sustainability reference [7–9]. Within AESA methods, a system is considered to be sustainable if its estimated impacts are lower than its allocated absolute environmental sustainability reference [9]. In the existing literature, two approaches were identified for defining the absolute environmental sustainability references. Bjørn and Hauschild [10] proposes normalization factors for existing LCIA methods and indicators based on the carrying capacity, defined as “the maximum sustained environmental intervention a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert” [10]. Ryberg et al. [11] proposes an LCIA method (PB-LCIA) that directly assesses the impacts based on the control variable of the planetary boundaries (PB) as defined by Steffen et al. [12]. Since mineral and metal resource depletion is more of a socio-economic than an environmental problem, only a few studies link the concept of AESA to the issue of mineral and metal resources [13,14]. The developed methods aim to evaluate the pressure on mineral and metal resources based on an AESA approach.

Various limits in the existing LCIA methods have been identified when used to assess the pressure on mineral and metal resources in the building sector:

- The existing LCIA methods do not correctly address the very heavy materials such as aggregates that are used in a very large quantity in the building sector and are abundant at the global level, but whose resources may be subject to local constraints. Indeed, resources that are used in much smaller quantities in the building sector, such as gold, appear as the biggest contributors to the total mineral and metal resource impact in the building, which does not correspond to the concerns of decision-makers [15,16].
- The scale of evaluation of LCIA methods is global which is not suitable for most local resources such as aggregates of which life cycle is mainly regional and for which the level of pressure on the same type of resources varies a lot according to the various territories [17].
- The flows from reuse and recycling are not considered [16].

Considering these limits, the MiMOSA method aims to propose characterization factors based on a sustainable material budget which is the absolute environmental sustainability reference in this case. If the material needs of the studied building are lower than the assigned material budgets to the building,
then the building can be considered sustainable in absolute terms regarding its mineral and metal resource consumption. In this sense, the MiMOSA method is close to the PB-LCIA approach.

MFA methods aim to quantify and analyse the material flows and stocks of a particular socioeconomic system in a given territory. In the literature, a large variety of studies use the MFA method for CE projects as it provides a good understanding of the flows issued from the anthropogenic stock and their recovery potential as well as their mapping, both from a spatial and a processing point of view [18–20]. Within the described method, the MFA approach will be used in order to estimate the quantity of material flows issued from the anthropogenic stock that can be used as input to the construction project under study in order to calculate the material budgets for each flow.

This paper is a theoretical proposition for the MiMOSA method that is presented here as a matrix problem. The aim of this paper is to detail the different stages of calculation and define the different matrices and parameters used. A case study will be carried out in the next phases of the research project to validate the feasibility of the MiMOSA method, but, fictitious examples are given to facilitate understanding and to illustrate some of the steps of the methodology.

2. Materials and methods

2.1. The requirements of the MiMOSA method

Unlike the existing LCA methods, the MiMOSA method does not seek to evaluate the pressures of the technosphere activities on the ecosphere, but rather to assess the sustainability of the use of mineral and metal resources by estimating the flows that are already in the technosphere and that can be used.

Before developing the methodology, a list of requirements was defined. The MiMOSA method should:

- Assess sustainability in an absolute rather than a relative way.
- Integrate the secondary materials issued from reuse and recycling.
- Consider the most suitable spatial scale for each material.
- Take into account the quality of the secondary materials to evaluate the effective availability for the different functional uses.

2.2. How to define a sustainable resource budget for mineral and metal resources?

Given that mineral and metal resources are non-renewable resources, their extraction and use are, in the long term, limited to the capacity to reuse or recycle them in circular loops. So-called ‘secondary’ materials, that are present in the technosphere, are therefore gradually replacing ‘virgin’ resources that are present in the ecosphere, out of necessity [21–24]. Thus, the stock of secondary materials of each mineral and metal resource and its associated maximum flows may be considered as its sustainable budget.

This strong sustainability approach of the circular economy is certainly not achievable today due to technical, economic, insurance or other limits, but it allows to measure the efforts needed to reach a total circular economy, to identify the obstacles of the deployment of the circular economy in the building sector and to evaluate the feasibility of a complete circular economy with regard to the available secondary materials in the technosphere. Furthermore, the methodology as developed is currently positioned in this strong sustainability scenario but can be adapted to other scenarios where a percentage of virgin resources is considered.

In order to develop the MiMOSA methodology, we assume that:

- A sustainable consumption of mineral and metal resources is considered to be limited to the assigned secondary materials coming from the circular economy.
- The reuse actions are prioritized over recycling which is prioritized over other forms of recovery.
- Only the technical obstacles are taken into account, the economic or insurance obstacles were identified but are neglected within the methodology development.
2.3. Definition of the nomenclatures

In order to properly consider the different actions of CE in the building sector, it is necessary to express the quantities of the technosphere stocks and the associated flows at the level of the resources (e.g. steel, aluminum, aggregate) but also at the level of the building components (e.g. window, radiator, door). The MiMOSA method focuses on the material flows in the technosphere and does not consider the material flows coming from the ecosphere. Thus, the nomenclatures used are different from those generally used in LCA to describe the inventory flows as in the Ecoinvent database [25], for example, in the MiMOSA method, the glass is considered as a resource and not the sand since at the end of the recycling process, we obtain glass and not sand. In this sense, two nomenclatures, one at each level, resources and building components, are considered. The rows of the matrices represent the resources and components that may be used in the building. To guarantee homogeneity between the various databases and tools that will be used, these nomenclatures are inspired by already existing ones.

The components nomenclature considered in the MiMOSA method is based on TyPy, a database and management tool for building typologies and components developed by the Centre Scientifique et Technique du Bâtiment (CSTB) [20] and on the Inies nomenclature. Inies is the national French database which contains Environmental and health products declaration for construction products and equipment [26]. The units of these components may vary according to the type of component: for example, the quantity of an insulation product will be expressed in m² while radiators will be counted in units.

The resources nomenclature used in the MiMOSA method is the nomenclature used in TyPy [20] to describe the material composition of the components. However, this nomenclature will be slightly modified within the method in order to take into account the quality of the resources. The values of the matrices using this nomenclature represent the quantities of mineral and metallic resources and are expressed in mass (Kg).

2.4. The time scale

The time scale considered for the anthropogenic flows is the year. This scale has been considered as the most adapted to the temporal scale at which buildings are currently constructed and to the granularity of the available statistical data. Between 1990 and 2010, the average construction period for dwellings in metropolitan France varied between 11 and 13 months for single-family houses, and between 16 and 23 months for collective housing [27]. As the building's material requirements occur throughout its life cycle, for replacement of building products and equipment for example, it is necessary to calculate these matrices for each year of the building's life. Since the construction phase is the phase where the resource consumption is the most important [28], this paper, as a first approach, details the methodological development only for the construction phase of the building that occurs at the year t0.

2.5. Description of the needs of the construction project

The mineral and metal resource requirements of the construction project under study will be calculated for the construction phase and, as a first step, only the foreground system expressing the direct resource consumption of the building is considered, see figure 2. The direct resource consumption of the building are expressed as construction products and building equipment (e.g. window or electric heater) but also as resources (e.g. roofing aggregates) and in order to consider the recycling and reuse actions, the definition of material needs must be done at two levels, one at the level of construction products and building equipment and another at the level of mineral and metal resources. In this sense, two matrices are defined, the first one contains the construction products and equipment used in the building. The second contains the mineral and metal resource requirements. We define these needs matrices as follow:

- \( P_{\text{components}}(m, 1) \): matrix vector containing the construction products and building equipment used in the building project
- \( P_{\text{resources}}(n, 1) \): matrix vector containing the mineral and metal resources needs of the building in the foreground system.
With:
- \( m \): the number of lines of the components nomenclature
- \( n \): the number of lines of the resources nomenclature

The two matrices defined above are complementary, the total material needs of the building is equal to the sum of the matrix \( P_{\text{components}}(m, 1) \) and the matrix \( P_{\text{resources}}(n, 1) \).

**Figure 1.** Background and foreground system of a building regarding the resource consumption

2.6. *Description of the anthropogenic flows in the technosphere*

The aim of this section is to describe the material flows present in the technosphere, as described in figure 3, in order to determine the sustainable material budget assigned to the building project under study. As our concern is the building sector, we differentiate the flows issued from the building sector and the ones from the other activity sectors.

**Figure 2.** Material flows in the technosphere (the arrows)

2.6.1. *Anthropogenic flows from the building sector.* The building products and equipment stored in the building stock are estimated using the BPT-flux model which describes the building stock and estimates demolition waste using a bottom-up macro-component approach [20]. The BTP-flux model, in addition to the stock estimate, assess the waste flows coming from the building sector after demolition or renovation operations in a given territory for a specific year. The estimation of these flows considers different parameters, for example, the demolition rates by type of building and by year.
of construction. The output results are described in waste categories as defined by the French decree No. 2011-610 based on the European directive 2008/98/E.C. The waste categories used contain lines that correspond to resources and lines that correspond to building components. Thus, a first step is to separate these two categories and express the BTP-flux results using the components nomenclature and the resources nomenclature defined in this methodology.

- \( \text{MF}_{i,u,d}^{t0} \): waste category i calculated for year t, building use u, and construction period d as defined by Tirado et al. [20]
- \( \text{MF}_{k1}^{t0} \): matrix vector containing \( \text{MF}_{i,u,d}^{t0} \) for all the building uses and construction periods.
- \( A_{\text{components}}^{t0}(m,1) \): matrix vector containing the construction products and building equipment in the building stock reaching end of life in year t0, that are thus available for use at t0
- \( A_{\text{resources}}^{t0}(n,1) \): matrix vector containing the secondary mineral and metal resources contained in the building stock reaching end of life in year t0, that are thus available for use at t0
- \( W_{\text{components}}(m,k) \): matrix containing the conversion factors that allows to express the BTP-flux results related to components using the components nomenclature of the MiMOSA method
- \( W_{\text{resources}}(n,k) \): matrix containing the conversion factors that allows to express the BTP-flux results related to mineral and metal resources using the resources nomenclature of the MiMOSA method

With:
- \( k \): the number of lines of the waste category nomenclature

\[
A_{\text{components}}^{t0} = \text{MF}_{\text{components}}^{t0} W_{\text{components}} \tag{1}
\]

\[
A_{\text{resources}}^{t0} = \text{MF}_{\text{resources}}^{t0} W_{\text{resources}} \tag{2}
\]

2.6.2. Anthropogenic flows from other sectors. To our knowledge, there is no tool that estimates the stocks of materials contained in other sectors (automobiles, public works, household appliances, etc.) that can be used as input to the building sector. Therefore, a documentation and data collection work will be carried out in order to obtain the following matrices by defining for each material in which sector it can be stored:

- \( A_{\text{other sectors,components}}^{t0}(m,1) \): matrix vector containing the construction products and building equipment contained in other sectors
- \( A_{\text{other sectors,resources}}^{t0}(n,1) \): matrix vector containing the secondary mineral and metal resources contained in other sectors

Then the matrices containing the materials reaching their end-of-life at year t0 are estimated using the life span of goods and products and the year of their production.

- \( A_{\text{other sectors,components}}^{t0}(m,1) \): matrix vector containing the construction products and building equipment contained in other sectors reaching end of life in year t0
- \( A_{\text{other sectors,resources}}^{t0}(n,1) \): matrix vector containing the secondary mineral and metal resources contained in other sectors reaching end of life in year t0

2.6.3. The flows issued from reuse and recycling. In order to estimate the quantities of secondary mineral and metal resources issued from recycling and the building components issued from reuse, matrices containing the yields of the recovery channels for each material have been defined:

- \( Y_{\text{reuse}}(m,1) \): matrix vector containing the yields of reuse
- \( Y_{\text{recycling}}(n,1) \): matrix vector containing the yields of recycling

These matrices take into account losses at demolition or end of life, losses due to the collection, the transport, and the efficiency of the preparation process for reuse or the recycling process.
With the yield matrices defined, we calculate the matrices containing the quantities of secondary mineral and metal resources and the construction products and building equipment issued from recycling and reuse as follow:

- \( A_{components}(m, 1) \) : matrix vector containing the construction products and building equipment issued from reuse
- \( A_{resources}(n, 1) \) : matrix vector containing the secondary mineral and metal resources issued from recycling

\[
\begin{align*}
A_{components} &= \gamma_{reuse} \cdot (A_{building, to}^{components} + A_{other sectors, to}^{components}) \\
A_{resources} &= \gamma_{recycling} \cdot (A_{building, to}^{resources} + A_{other sectors, to}^{resources})
\end{align*}
\] (3)

With:
- \( \gamma \) the diagonal matrix calculated from any matrix vector \( V \), \( \gamma_{ij} = V_{ij} \delta_{ij} \) with \( \delta_{ij} \) the Kronecker Delta.

2.7. **The assigned material budgets to the project under study**

In order to estimate the resources and components budgets that can be assigned to the project that will be assessed, two matrices containing the assignation factors have to be defined, one for the building components issued from reuse and another for the secondary mineral and metal resources issued from recycling. The definition of the assignation factors is done using the sharing principles found in the literature. The sharing principles have not been selected yet but, the methodology is adapted to all of them. This choice of sharing principles is more a matter of ethic and political choices and has already been discussed in the literature [29]. A sensitivity study will be carried out at the end of the final stage of this research project in order to estimate the variations in the results due to the choice of the sharing principle. The matrices containing the assignation factors can be defined as follow:

- \( F_{components}(m, 1) \) : matrix vector containing the assignation factors for the construction products and building equipment issued from reuse
- \( F_{resources}(n, 1) \) : matrix vector containing the assignation factors for secondary mineral and metal resources issued from recycling

The assigned budgets are calculated as follow:

- \( B_{components}(m, 1) \) : matrix vector containing the assigned budget of construction products and building equipment issued from reuse
- \( B_{resources}(n, 1) \) : matrix vector containing the assigned budget of secondary mineral and metal resources issued from recycling

\[
\begin{align*}
B_{components} &= F_{components} \cdot A_{components} \\
B_{resources} &= F_{resources} \cdot A_{resources}
\end{align*}
\] (5)

These steps of calculations allow to estimate the share of consumption of components and mineral or metallic resources that may be used by the assessed project in an absolute environmental sustainability perspective.

2.8. **Calculation of sustainability indicators**

In order to prioritize the actions of reuse before the actions of recycling, the sustainability indicators are calculated within two steps. Figure 4 describes the global scheme of the calculation of the sustainability indicators. In grey, a fictive example to illustrate the methodology, in pink the result of the reuse indicator, in green the sustainability indicator for aluminum, the needs of aluminum are lower than the assigned aluminum budget, concerning the flat glass, the consumption is excessive and the result of the sustainability indicator is highlighted in red:
2.8.1. **Comparison at the level of building components.** The first step is to compare the $P_{\text{components}}(m, 1)$ matrix with the $B_{\text{components}}(m, 1)$ matrix. As a result of this comparison, the needs for construction products and building equipment not met by reuse are defined and contained in the $L_{\text{components}}(m, 1)$ matrix as follow:

- $L_{\text{components}}(m, 1)$ : matrix vector containing the needs for construction products and building equipment not met by the reuse

$$L_{\text{components}} = P_{\text{components}} - B_{\text{components}}$$  \hspace{1cm} (7)

We can calculate an indicator that expresses the percentage of components issued from the reuse used in the project

- $I_{\text{re-employment}}(m, 1)$ : matrix vector containing the percentage of components issued from the reuse

$$I_{\text{re-employment},i} = \frac{B_{\text{components},i}}{P_{\text{components},i}} \% ; \forall i \in [0; m]$$  \hspace{1cm} (8)

2.8.2. **Comparison at the level of mineral and metal resources.** The second step is divided in two sub-steps. The first one aims to traduce the needs for construction products and building equipment not met by the reuse into resources using a matrix containing the estimated material composition of the products and building equipment as defined in TyPy. Since there may be a case where the assigned budget is greater than the component requirement, only rows positive or equal to zero in the matrix are selected.

- $M(n, m)$ : matrix containing the estimated material composition of the construction products and building equipment as defined in TyPy

- $P_{\text{components},r}(n, 1)$ : matrix vector containing the mineral and metal resources needs included within the construction products and building equipment of the building that cannot be met by re-use

$$P_{\text{components},r,i} = M_{i} \cdot L_{\text{components},i} ; \forall L_{\text{components},i} \geq 0, \forall i \in [0; n]$$  \hspace{1cm} (9)

Then the mineral and metal resource requirements are compared with the recycling resource budget assigned to the project and the indicators of sustainability calculated.
\[ I_{s,i}(n, 1) = \frac{P_{\text{components}_i} + P_{\text{resources}_i}}{R_{\text{resources}_i}} ; \forall i \in [0; n] \]  

A building project can be considered as absolutely sustainable if:

\[ I_{s,i}(n, 1) = \frac{P_{\text{components}_i} + P_{\text{resources}_i}}{R_{\text{resources}_i}} \leq 1 ; \forall i \in [0; n] \]

3. Discussion

3.1. Quantification of the material flows in the technosphere

The MiMOSA method requires identifying and quantifying the flows from recycling and reuse each year and for different territories. However, there is a great lack of data regarding these flows and there are currently no tools to quantify their quantity and quality at the level of detail required by the MiMOSA method. In order to overcome this lack, and based on different documentary resources and by carrying out surveys with actors of building waste recovery and other sectors, these material flows are estimated. The estimation of these flows is done in a prospective way and does not reflect the reality but the potential of the flows resulting from the recycling and reuse by taking into account only the technical obstacles. This prospective quantification is in line with the assumptions of the method which considers that a sustainable consumption of mineral and metal resources is limited to the assigned secondary materials coming from the circular economy.

In order to quantify these flows, several assumptions are taken to be in agreement with the assumptions taken in the MiMOSA method, among them we list:

- The circular economy is already well deployed, i.e. the recovery channels are well developed.
- The sorting is done on the demolition site and there is no storage problem.
- Reuse is prioritized over recycling, which in turn is prioritized over other recovery channels.
- The secondary materials are used in priority in a use with the greatest functional quality.

Despite of this estimation, it will be necessary to provide more accurate input data to the MiMOSA method. In the meantime, we rely on this first rough estimated dataset and a sensitivity study will be done to estimate the influence of some assumed parameters on the results of the sustainability indicators.

3.2. The non-standardisation of the components: a reuse obstacle

In this method, the construction products and equipment resulting from the reuse are taken into account to calculate the material budgets, however, one of the technical obstacles of the reuse is to be considered and to be taken into account, the non-standardization of the products. Let's take an example, in the Inies database [26], the environmental and sanitary declaration of the windows are expressed in m² for the windows. However, if the needs and the material budgets are compared in m², the dimensional specifications of the windows are not taken into account and thus the obtained result is overestimated.

4. Conclusion

This paper proposes a new and innovative absolute sustainability assessment method that aims to represent the pressures on mineral and metal resources in the building sector by integrating the circular economy approach: the MiMOSA method. The objective of this work is to present a proof of concept and is not directly operational because of the lack of data and other limits identified in section 3.

The MiMOSA method still have to be tested on case studies to be validated and to evolve to better address operational issue of the use of mineral and metal resources in the building sector.
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