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Calculating the Material Input per Service Unit using the *Ecoinvent* Database

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Abstract: The availability of life cycle inventories is one of the biggest challenges for life cycle wide environmental assessment. There are several life cycle assessment (LCA) databases providing inventory data as well as resource and emission profiles of processes for impact assessment methods like ReCiPe or IMPACT 2002+. But the use of these LCA databases for input oriented environmental assessment is very limited as they cover only a part of all relevant input flows. The paper describes current challenges when calculating the input oriented Material Input per Service Unit (MIPS) indicators based on LCA inventory data from the Ecoinvent database. Propositions are made how to address these challenges. As a conclusion, further need of research to reach a full compatibility of LCA databases and the MIPS concept is pointed out.

Keywords: *Material Input per Service Unit, input oriented environmental assessment, resource efficiency, life cycle analysis, unused extraction, Ecoinvent*

1. Introduction

Environmental assessment has become widely accepted to gain knowledge about the ecological impacts of our production and consumption patterns. Up to today, environmental assessment is mainly output and emission oriented. This has multiple challenges: many emissions last decades or even centuries in the ecosphere, which makes the assessment of future impacts very difficult. In addition, it can be assumed that we have limited knowledge about all existing environmental toxins, their interactions and the resulting impact on humans and nature. Thus, an output-oriented assessment focuses specific emissions and their impacts. Changing the perspective to an input oriented approach can provide a less complex solution to estimate the overall environmental burden [1]. As all emissions and related impacts result from the extraction of natural resources, one can say that a reduction of the inputs can also lead to a decrease of all emissions and environmental impacts.

Today there are various input oriented approaches like the ecological footprint [2], the Emergy approach [3] or the concept *Material Input per Service Unit* (MIPS) [1]. While the ecological footprint has been integrated in life cycle assessment (LCA) databases, Emergy and MIPS have not been considered yet. Facing this, the paper makes first propositions for the integration of MIPS into the LCA database *Ecoinvent* [4].

The MIPS concept is a holistic approach including an assessment framework as well as indicators. MIPS can provide the baseline for the development of different sustainability strategies and pathways for Product-Service-Systems [5]. It is strictly input-oriented quantifying the life cycle wide amount of material resources (Material Input, MI), which are necessary to provide a specific service (S) as is described by (1).

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$$MIPS = \frac{MI}{S} = \frac{Material\ Input}{Service\ Unit} \quad (1)$$

The material resources are classified into five indicators (resource categories, see Table 1). They are measured in mass units.

Table 1: Overview of the MIPS Resource Categories (based on [6],[7],[8])

Resource category	Description
Abiotic Raw Materials	Mineral raw materials, fossil fuels, spoils (as overburden from mining activities or excavated materials for infrastructure)
Biotic Raw Materials	Plant biomass from cultivation, biomass from uncultivated areas, counted as fresh mass (meat is reduced to plant biomass inputs unless it is from wild animals)
Water	Surface, ground and deep ground water (separated according to process and cooling water)
Air	Oxygen molecules (bonded in combustion air, chemical and physical transformation)
Earth Movements	Mechanically moved soil (while ploughing) or alternatively soil erosion in agriculture and silviculture

The material resources include not only economically used raw materials, but also unused extraction by means of raw materials without economic value. Examples for unused extraction are overburden from mining activities, soil excavation when building infrastructure, harvest residues in agriculture and forestry, and loss of soil in the form of erosion [9]. The rational for the consideration of unused extraction is that environmental impacts of resource extraction do not always depend on the chemical properties of the material flows. The extent of impacts like translocation of fertile soil, the impact to groundwater level, and the resulting change of landscape induced by raw material extraction rather depends on the overall extraction volume [10]. A comprehensive study of the sustainability of mining in Australia ([11], p.120) stresses that waste rock / overburden is a fundamentally strategic and critical issue facing the mining sector in Australia, as well as worldwide, yet it remains under-recognised for the range of issues (environmental and economic) it presents.“

In the inventory analysis phase of the MIPS concept, there is no need to account for outputs in such detail as for LCA, as the focus lies on the inputs. On the other hand, unused extraction is not considered in LCA [1]. A further difference to LCA is that MIPS requires no impact assessment phase as such. Instead, the material resources are classified as described above (Table 1). This classification comes along with a loss of detail, as it gives no conclusions on specific emissions and toxic elements. Still a quantification of specific emissions can be done by deepening the inventory analysis.

To calculate the MIPS more easily, life cycle data for the material input of numerous process chains in the field of materials, fuels, transport services and food can be found in the material intensity (MIT) table of the Wuppertal Institute [12]. The MIT table has been continuously updated with new data sets since the 1990s and currently contains about 400 datasets. However, compared to the *Ecoinvent* database [3], MIT factors are only available for a relatively small amount of processes. *Ecoinvent* provides live cycle inventories for about 9,000 processes in its newest version 3. While *Ecoinvent* provides about 30 life cycle impact assessment methods to calculate results for diverse ecological impacts, there is no sufficiently standardized method to calculate the amount of resources taken from nature following the MIPS concept. This is also true for other LCA databases like the European Life Cycle Database (ELCD) [13]. Hence there is great need for an approach allowing to use LCA data for the calculation of the MIPS. This would not only increase data availability but will also provide an answer to the question of how far environmental burden estimated with the MIPS concept correlates with LCA methods like ReCiPe, Impact 2002+ or Eco-indicator.

There are several challenges to be faced to reach this goal. In the following a description is given to what extent data from *Ecoinvent* can be used to calculate the specific resource categories of the MIPS concept, which data is missing, and how missing data could be implemented into the *Ecoinvent* database.

2. Correlation of *Ecoinvent* Data and Resource Categories

Until now, the MIPS concept has not been considered within LCA databases. This is due to the fact that the concept was not developed in line with the LCA framework [14] but as a separate holistic approach. In reference [15], a midpoint characterisation method is described and applied for the first time to calculate the MIPS resource category "abiotic raw materials" from the *Ecoinvent* database. Abiotic MI characterisation factors for the use with *Ecoinvent 2.2* are beta released with that paper and are ready for use with any LCA software. Furthermore [15] points out the need to integrate missing input data into *Ecoinvent* to allow an integrative calculation without the additional use of characterization factors.

Based on [15], this paper describes to what extent *Ecoinvent* can be used currently to calculate the Material Input for all resource categories of the MIPS concept and which modifications are needed to reach a full compatibility with MIPS.

The current version of the *Ecoinvent* database is version 3. It brings significant differences compared to the previous version 2.2, *e.g.*, a strongly increased number of processes and a new data format. The flow nomenclature has been changed: processes that illustrate exchanges within technosphere are now divided in products and activities consistently. In addition there have been minor changes concerning the elementary flows, which reflect exchanges from and to nature [16]. As *Ecoinvent* version 3 was published shortly before finishing this paper, the research results in this paper are based on version 2.2. However, first experiences with version 3 show that there are only minor differences regarding the implementation of MIPS.

In *Ecoinvent* natural resources taken from nature are reflected by elementary flows in the compartment "from nature". They are further classified into the different subcompartments "in ground", "biotic", "in air", "in water" and "land" [4]. This classification does not exactly match with the MIPS resource categories. Apart from this, the elementary flows in *Ecoinvent* represent only a part of the inputs considered by MIPS, as the MIPS concept covers all inputs from nature. Hence, several flows are missing to allow a proper calculation of all resource categories. The following describes, which data are missing and how they could be implemented.

2.1. Abiotic Raw Materials

In the MIPS concept the category "abiotic raw materials" considers all kinds of minerals, fossil fuels as well as spoils (like overburden from mining activities or excavated materials for infrastructure). Apart from few exceptions (*e.g.,* volume occupied) all elementary flows in *Ecoinvent* categorized as "in ground" refer to abiotic material. Hence they just need to be classified into the MIPS resource category "abiotic resources". However, elementary flows only reflect used extraction, or in case of metals, only parts of used extraction. While for non-metallic minerals the share of unused extraction such as basalt or sand is often negligible, the mining of metals or coal goes in line with significant amounts of unused extraction, which can have a high share in the overall amount of resource use [17]. Hence, the amounts of excavated rocks and soil from mining activities have to be included for mining processes. In case of metal mining, also the remaining share of gross ore has to be added to the specific elementary flows, as the elementary flows of metals only represent the metal content (net ore). Expression (2) condenses the procedure described in [15]. It illustrates how to calculate a characterization factor (CF) to integrate the unused extraction (UE) per metal content (x_m).

$$CF = \left(\frac{UE}{x_m}\right) + \frac{1}{x_m} \qquad (2)$$

While information about the gross ore is given by the name of the specific elementary flow (*e.g.*, silver, 0.01% in crude ore, in ground), the overburden reported from mining companies can be derived from data gathered in [17]. An example is provided in Table 2.

Table 2: Characterization Factors considering Unused Extraction based on [17]

Elementary flow in *Ecoinvent V. 2.2*	UE per kg gross ore	x_m per kg gross ore	CF
Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	1.19 kg	0.116	18.9 kg
Iron, 46% in ore, 25% in crude ore, in ground	0.88 kg	0.25	7.5 kg
Silver, 0.01% in crude ore, in ground	0.70 kg	0.0001	17,000 kg

However the procedure of adding the unused extraction using a characterization method as described in [15] has some disadvantages: Due to the limited number of elementary flows in *Ecoinvent*, it is not possible to consider regional differences of unused extraction for substances such as hard coal and lignite. In fact it is possible to use world average values instead, but for a deeper analyses this might not be sufficient as the amount of unused extraction can vary significantly, depending not only on the raw material, but also on the region of extraction and its mining technique (*e.g.*, open pit or underground mining). An example for this is the overburden of hard coal mining, which varies by a factor seven depending on the mining region [17].

A workaround mentioned in [15] is to add the amount of unused extraction directly as an input to all extraction processes instead of adding unused extraction factors to the characterization method. Therefore the creation of a new "in ground"-elementary flow is necessary, which could *e.g.*, be called "overburden, from extraction side". In the case of metals, this elementary flow must also consider parts of the gross ore, since existing elementary flows only represent the net ore.

However, the problem remains that even *Ecoinvent version 3*, which compared to version 2.2 contains an increased number of region specific processes [16], provides mining processes only for a limited number of regions or countries. In the case of lignite, country specific mining processes are missing completely. Currently, only processes for global average and the European region are available. Hence, the number of extraction process has to be increased. In a first step, this could be done for the largest producing countries.

For resources with a limited availability (especially rare earth metals) it should be discussed, in how far the consideration of regional differences for unused extraction - even with strong deviations – is reasonable. For instance copper is mainly extracted from a few large mines worldwide. Companies purchase copper from regional storage and hence might not have the possibility to choose from a specific mine. In these cases a world average value could be the preferred alternative.

Apart from mining excavation MIPS also considers movements of earth or mud for construction or maintenance of infrastructure (*e.g.*, construction of buildings, roads, pipelines, waterways, railways) (see section 1). Therefore, yet another elementary flow has to be added to the processes, which could be *e.g.*, "soil, moved". This is especially significant for road infrastructure. For instance, according to [18] the construction of a typical Finnish motorway required 650 t of abiotic earth excavation and rock spoil per one meter of motorway. Out of this, only 43 t could be reused on the construction site. The remaining 607 t of unused excavation and spoil constitute 88 % of the abiotic Material Input of construction and maintenance of the motorway over its assumed lifetime of 60 years.

2.2. Biotic Raw Material

The resource category "biotic raw materials" contains all plant biomass from cultivated areas as well as plant and animal biomass from uncultivated areas [1]. Animals from cultivated areas (*e.g.*, cattle breeding) are accounted for by the plant biomass input for their production. Biomass is accounted for with its moisture content at the time of harvest, including unused extraction such as roots or leaves.

In *Ecoinvent*, the subcompartment "biotic" only includes elementary flows for wood and for peat. Peat is considered as abiotic material in MIPS, so it has to be classified into the resource category "abiotic material". The elementary flows for wood refer to the volume. They would have to be multiplied by their density, which could be added as a CF within the before mentioned characterization method. Also, the amount of unused extraction can be added as a factor. An example is provided in Table 3. Nevertheless, the density of wood depends strongly on the type of wood. As the elementary flows do not distinguish between different wood types, this approach allows only a rough estimation to calculate the resource input of wood.

Table 3: Characterization Factor to include wood in the MIPS Resource Category "Biotic Raw Material". Unused Extraction is based on [17].

Elementary Flow	Unit	Assumed Density	Unused Extraction Factor	Characterisation Factor
Wood, primary forest, standing	1 m^3	500 kg/m^3	1.15	575 kg

Other biomass is only considered by its gross calorific value and by the amount of CO_2 from atmosphere bound in the biomass. The elementary flow for CO_2 (flow "Carbon dioxide, in air") can be used to calculate the dry matter of biomass as described in [20]. This also allows only a very rough estimation as the relation of carbon content and fresh mass differs greatly depending on the type of biomass.

For an accurate analysis it is necessary to add new elementary flows for biomass in all relevant processes of the database. In *Ecoinvent* version 2.2 these processes are listed in the subcategory "production" of the category "biomass" and in the subcategory "plant production" of the category "agricultural production". The elementary flows have to reflect the amount of used and unused extraction. An example for this would be the production process referring to the production of 1 kg of potatoes at farm level. As input an elementary flow called *e.g.*, "potatoes, whole plant, at time of harvest" with the amount of 1.03 kg could be added, as the unused extraction for potatoes is 0.03 kg/kg [17].

Beside the technical implementation, the consideration of the moisture content is a challenge, because the moisture content can vary significantly depending on the cultivation conditions. *Ecoinvent* provides information about the moisture content only for the production at farm level, but not at the time of harvest. Regarding this, a standardization of the moisture content as it is recommended within the Economy wide Material Flow Analysis compilation guide seems reasonable [19].

As for abiotic unused extraction, [17] provides unused extraction for multiple plants. However, the values mainly refer to the global average. There is further need for research to establish a consistent database providing unused extraction and moisture content for biomass, which could then be integrated into the *Ecoinvent* database. As a first step however, estimated values could be used to fill data gaps.

2.3. Earth Movement

Within the resource category "Earth movement in forestry and agriculture" mechanically moved soil (mainly by ploughing), which is defined as having more than 2 % humus content [1] is considered. Instead of moved soil, the amount of soil erosion can be used, when data for soil movement are missing [8]. The amount of soil erosion differs greatly from the amount of mechanically moved earth as it is quite low [21].

Ecoinvent does not provide elementary flows for earth movement in agriculture and silviculture. This is true for soil erosion as well as mechanically moved soil. Assuming that elementary flows for biomass have been integrated into *Ecoinvent* as described in chapter 2.2, the amount of soil erosion and mechanically moved soil could be considered multiplying the amounts of the specific biomass with a factor in the characterization method (*e.g.*, 1.82 kg soil erosion/kg wheat [21]) - similar to the consideration of unused extraction for abiotic flows. However, this allows to differentiate earth movement according to specific crops, but not according to the cultivation method, which has a significant influence on the amount of soil movement [21].

Hence, for exact calculations, the use of characterization factors is not suitable. Instead, additional elementary flows have to be added to biomass production processes. For mechanically moved soil this could be *e.g.*, a flow named "soil, ploughed", which could be added to the input side of the process. Flows for soil erosion have to be added to the output side as they result from arable farming.

Data for some crops are available in the MIT-list [12] or can be found in [21] or [22]. Nevertheless there is no extended data collection, which matches with all *Ecoinvent* processes. As a first step, the authors of this paper recommend to implement data for soil erosion, as they are required to calculate the Material Footprint [8].

2.4. Water

The MIPS concept considers water taken from nature or retained for processing and cooling. Apart from turbine water, all ten elementary flows of *Ecoinvent* match with the resource category water. They can be considered by using the above described characterization method. The elementary flows refer to the volume so that they have to be converted in weight. In the case of saltwater however, the density depends on the salt content, which is not designated in *Ecoinvent*. For sea water the density is assumed to be 1025 kg/m^3, for sole we assume 1100 kg/m^3.

Instead of turbine water, MIPS only accumulates the discharge rate as the difference between the minimum and the maximum water level within one year for conventional storage hydroelectricity plants and run-of-the-river hydroelectricity with a water level regulating function.

Hence, a new elementary flow would have to be created, which could be *e.g.*, “water, retained, unspecified natural origin”. This elementary flow has to be added in processes of storage plants, which in *Ecoinvent 2.2* are reflected by the process “Reservoir hydropower plant (Switzerland)”, “Reservoir hydropower plant, non-alpine regions (Europe)“ and “Reservoir hydropower plant, alpine regions (Europe)”. Data about the discharge rate can be gathered from hydropower operators [6]. Current data used for electrical power mixes in the MIT list of the Wuppertal Institute [12] is rather old and originate from the study [23]. The study accounts for an overall water consumption for non-alpine reservoir hydropower plants in Germany of 1.900 m^3/MWh, whereof 80 % result from the discharge rate. It is indicated that this discharge rate can differ greatly as it depends on the drop height. An example is given for alpine reservoir hydropower plants in Switzerland, where due to a lower discharge rate the water consumption is about 200 m^3/MWh.

A new definition for the calculation of the resource category water could be to account for water used in turbines of reservoir plants as done in *Ecoinvent* instead of the water retained, as the usage of water in turbines also induces environmental impacts. However, this would drastically increase the amount of water.

2.5. Air

The resource category air considers air input for combustion and further chemical transformation and air for physical transformation. For combustion processes, the air requirement is calculated by the specific stoichiometric oxygen (O) demand, which is described in formula (3), where x_{iF} is the mass fraction of the component i in the fuel, v_i is the stoichiometric number, $\widetilde{M}_{O_2}$ is the molar mass of the oxygen, $\widetilde{M}_i$ the molar mass of the fuel component, and x_{O_2F} the possible share of oxygen in the fuel.

$$O = \sum x_{iF} * v_i * \frac{\widetilde{M}_{O_2}}{\widetilde{M}_i} - x_{O_2F} \qquad (3)$$

In contrast to the IPCC 2007 method [24] where CO_2 emissions resulting out of biomass combustion are excluded from the characterization of global warming potential (GWP), oxidation in biomass combustion is also considered in the resource category air.

Up to version 2.2, *Ecoinvent* does not consider air or oxygen as a process input. In *Ecoinvent version 3*, a new elementary flow “oxygen” (subcompartment “in air”) has been introduced, but it has only been implemented in few processes like “air separation, cryogenic”. To consider oxygen input for combustion and other chemical or physical processes (*e.g.*, cement production), the elementary flow “oxygen” has to be consistently added to the input side of such processes.

An approach to calculate the resource category air for combustion processes from *Ecoinvent* data is to use the characterisation method. With help of conversion factors air inputs can be estimated considering the elementary flows for flue gas. An example is provided in Table 4.

Table 4: Characterization Factors reflecting the Air Requirement for selected Flue Gases (average composition 23.2 mass-% O_2, 75.5 mass-% N, 1.3 mass-% Ar).

Elementary Flow in Compartment Air	Formula	Oxygen Share [mass-%]	Characterization Factor
"Carbon dioxide, fossil" "Carbon dioxide, non-fossil"	CO_2	72.7	0.727
"Carbon monoxide, fossil" "Carbon monoxide, non-fossil"	CO	57.1	0.571
Nitrogen oxides	NO_2	53.3	0.533
Sulphur dioxide	SO_2	49.9	0.499
Water	H_2O	88.8	0.888

Nevertheless, the characterisation approach has some uncertainties: The possible share of oxygen within the fuel has to be subtracted from the overall oxygen consumption. This cannot be realised with the characterisation method, as there is no information from which fuel the emissions occur. Hence, for fuels like coal, which have a significant oxygen share, assumptions made with the characterisation method may turn out too high. Also, emissions resulting from fermentation must not be considered within the resource category air, as no oxidation takes place, but elementary flows do not differ in emissions from combustion and emissions from fermentation. For example, such a differentiation would be necessary for nitrous oxide as it is emitted from different contributors [25]. As consequence, the proper solution would be to integrate also the oxygen demand for combustion directly as input in the specific processes.

3. Conclusions

As shown in this paper, *Ecoinvent* does not provide sufficient input flows for the calculation of the MIPS. Some of the resulting data gaps can be filled using a characterization method, but for deeper analyses the integration of additional elementary flows and country specific extraction processes is necessary. Table 5 provides an overview of required elementary flows to be integrated in *Ecoinvent*.

Table 5: Elementary Flows to be integrated into *Ecoinvent* for the Calculation of the MIPS

Resource category	**Process**	**Elementary Flows from Nature Considering**
Abiotic Resources	Metal mining	Unused extraction, Part of used extraction (difference from gross ore minus net ore)
	Fossil fuels and minerals extraction	Unused extraction
	Construction	Moved soil
Biotic Resources	Biomass production	Used extraction, Unused extraction
Earth Movement	Biomass production	Ploughed soil Soil erosion (output flow)
Water	Reservoir hydropower plants	Retained water
Air	Combustion processes	Oxygen
	Further processes with chemical or physical air transformation	Oxygen (or air)

To consider the unused extraction, the INDI-LINK project [17] provides an extended (non-public) database. The database is being updated for producing input-output environmental extensions in the CREEA project (http://www.creea.eu/).

Regarding earth movement induced by biomass production, consistent and country specific data are missing. There is great need to frequently collect and update resource data so that they can be integrated into LCA databases. This should be done in the context of further research projects. In the long run the establishment of a resource agency providing consistent and regularly updated resource extraction data for LCA databases and statistical offices, as proposed in [26], seems reasonable.

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