Photo by Julia Cilleruelo Palomero | Cuba

Quantifying Circular Economy with Life Cycle Assessment

Circularity Package add-on to ecoinvent

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Circularity package

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1 Introduction

Both Life Cycle Assessment (LCA) as a tool and Circular Economy as a concept work towards sustainable development, only that both approaches are currently done individually: one assessment doesn't include the other.

Several circularity indicators have been proposed to quantify Circular Economy. After an initial assessment, two indicators were chosen for their completeness and ability to be integrated into LCA. The Material Circularity Indicator (MCI) proposed by the Ellen MacArthur Foundation and ANSYS Granta takes into account material flows [1], whist the Circularity Index (CI) proposed by J. M. Cullen also takes into account the energy required for primary vs. secondary material production [2].

Circularity indicators can benefit hugely from a life cycle perspective, where circularity is considered not only in the last production stages but from the very beginning of raw material extraction. However, there is no current well-rounded solution for the integration of both, even though there have been initiatives from common LCA software.

SimaPro, for instance, proposes a calculation of the MCI within the software with the use of parameters for the variables required for the MCI calculation [3], but stays in the superficial model and doesn't look into the supply chain (background database). In 2018, GaBi had proposed a circularity tool, with an approach similar to that proposed in this report, that no longer is available in the market [4]. OneClick LCA promotes the calculation of a "building circularity score", which applies circularity for the buildings sector [5].

On the other hand there are some initiatives outside of LCA tools, like the MI: Product intelligence package [6], developed by ANSYS GRANTA exclusively for the CE100 group in theory based on Bill of Materials. Some solutions are even free to download. The Ellen MacArthur Foundation themselves offer a simple excel tool for free that carries out a simple calculation with user input values [7]. James Goddin has also made public an excel tool for the calculation of the MCI which is also used by Thinkstep-anz [8].

"Circularity Package" database improves assessments for the Circular Economy by allowing circularity to also be tracked down the supply chain, incorporating a broader visualisation of circularity and consequently more accurate evaluations than those available so far.

2 Goal and Scope of the Circularity Package database, use advice

The Circularity Package database is developed to support decision making in the field of Circular Economy. It builds on the ecoinvent 3.8 cut-off database and its process inventories, and adds support for circularity indicators required for the Material Circularity Indicator (MCI), [1], and the Circularity Index (CI), [2].

The core environmental indicators are not modified, nor are the process datasets, as they are already supported by the ecoinvent cut-off database. Also, the environmental impact indicators available in the LCIA Methods are not modified, for the same reason.

The new database adds extra information to process datasets and adds an LCIA method for circularity to support indicators such as virgin material extracted, waste produced, material recovered, and energy usage. The rules and variable definitions for the circularity indicators were adapted to work with an LCA database. This is explained in Section 3.

When using the circularity database in a specific case study, it is responsibility of the user to create a foreground system that works with the circularity LCIA method. That is, if a new primary material, waste, recycling or transforming process is added, care must be taken to adapt the model to fit the LCIA method for circularity.

3 Methodology: how was circularity implemented?

3.1 Required variables for circularity

The variables required for circularity calculations are described in Table 1. These variables are tracked throughout the ecoinvent database with shadow elementary flows, see Figure 1 for an example.

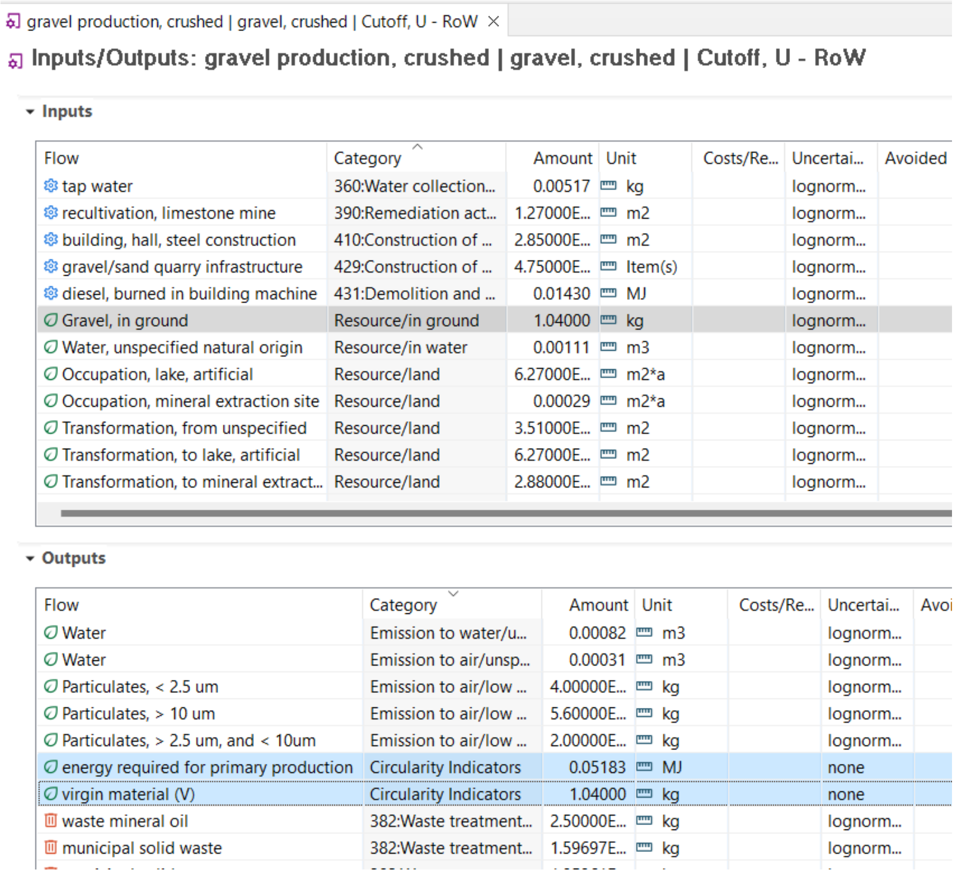
To avoid double counting, virgin material is obtained from the strict beginning of the supply chain, shadowing flows that contain "..., in ground" in their name. On the other hand, waste is obtained from final waste treatment processes which are at the end of a supply chain, i.e. incineration or landfill processes. Recycled material is tracked from dummy "Recycled Content cut-off processes". The rest of the variables are tracked within the processes along the supply chain, with a certain criterion described in Table 1. Figure 3 helps understand this visually.

A gravel producing process, an example with a screenshot in Figure 1, has a certain amount of virgin material coming from the elementary flow "gravel in ground" which is tracked in the output with an elementary flow for virgin material. Next to it, the elementary flow called “energy required for primary production” shadows the total energy required for that specific process.

Another example is the incineration of waste plastic, Figure 2. As a final waste treatment process, a shadow elementary flow for final waste produced is included, as well as a shadow elementary flow for secondary material produced or “recovered EoL material”, which tracks the input flow for sludge with a negative amount, a sign of recovered material in the ecoinvent database.

Table 1: Variables required for circularity indicator calculations, and their respective location in the ecoinvent database

Circularity Variable		MCI	CI	Circularity Package	Location in ecoinvent database
Virgin material	V	x		x	Elementary flows with names "*Material name*, in ground"
Recycled material	R	x		x	Processes that contain "Recycled Content cut-off" in their name.
Recovered recycled materials	R_r	x		x	Input flows with negative amounts. These are recovered materials in ecoinvent.
Input recycled materials	R_i	x		(x)	Calculated variable: $R_i = R + R_r$
Mass	M	x		(x)	Calculated variable: $M = V + R_i$
Total waste for final disposal	W	x		x	Mainly processes under the category "3821: Treatment and disposal of non-hazardous waste" and "3822: Treatment and disposal of hazardous waste"
Waste from recycling processes	W_C	x		x	Mainly processes under the category "3811: Collection of non-hazardous waste"
Waste from the production of secondary material feedstock for second life material	W_F	x		x	Processes that produce recycled material, at the category "C: Manufacturing"
Energy required for primary material production	E_p		x	x	Energy required in processes that involve the production of primary materials or products
Energy required for secondary material production	E_s		x	x	Energy required in processes that involve the production of secondary materials
Life time of product	L	x		(x)	Input by user
Utility of product (number of uses)	U	x		(x)	Input by user



gravel production, crushed | gravel, crushed | Cutoff, U - RoW

Inputs/Outputs: gravel production, crushed | gravel, crushed | Cutoff, U - RoW

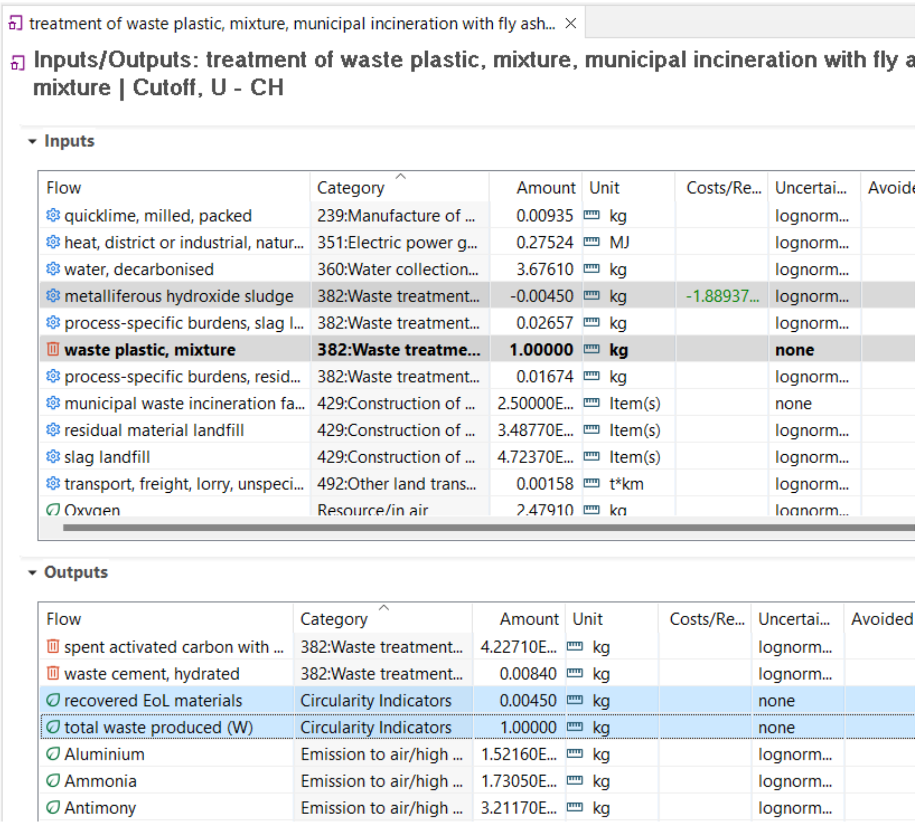
Inputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertai...	Avoided
tap water	360:Water collection...	0.00517	kg		lognorm...	
recultivation, limestone mine	390:Remediation act...	1.27000E...	m2		lognorm...	
building, hall, steel construction	410:Construction of ...	2.85000E...	m2		lognorm...	
gravel/sand quarry infrastructure	429:Construction of ...	4.75000E...	Item(s)		lognorm...	
diesel, burned in building machine	431:Demolition and ...	0.01430	MJ		lognorm...	
Gravel, in ground	Resource/in ground	1.04000	kg		lognorm...	
Water, unspecified natural origin	Resource/in water	0.00111	m3		lognorm...	
Occupation, lake, artificial	Resource/land	6.27000E...	m2*a		lognorm...	
Occupation, mineral extraction site	Resource/land	0.00029	m2*a		lognorm...	
Transformation, from unspecified	Resource/land	3.51000E...	m2		lognorm...	
Transformation, to lake, artificial	Resource/land	6.27000E...	m2		lognorm...	
Transformation, to mineral extract...	Resource/land	2.88000E...	m2		lognorm...	

Outputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertai...	Avoi
Water	Emission to water/u...	0.00082	m3		lognorm...	
Water	Emission to air/unsp...	0.00031	m3		lognorm...	
Particulates, < 2.5 um	Emission to air/low ...	4.00000E...	kg		lognorm...	
Particulates, > 10 um	Emission to air/low ...	5.60000E...	kg		lognorm...	
Particulates, > 2.5 um, and < 10um	Emission to air/low ...	2.00000E...	kg		lognorm...	
energy required for primary production	Circularity Indicators	0.05183	MJ		none	
virgin material (V)	Circularity Indicators	1.04000	kg		none	
waste mineral oil	382:Waste treatment...	2.50000E...	kg		lognorm...	
municipal solid waste	382:Waste treatment...	1.59697E...	kg		lognorm...	

Figure 1: Screenshot of a production process with some virgin material being extracted from earth



treatment of waste plastic, mixture, municipal incineration with fly ash...

Inputs/Outputs: treatment of waste plastic, mixture, municipal incineration with fly a mixture | Cutoff, U - CH

Inputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertai...	Avoide
quicklime, milled, packed	239:Manufacture of ...	0.00935	kg		lognorm...	
heat, district or industrial, natur...	351:Electric power g...	0.27524	MJ		lognorm...	
water, decarbonised	360:Water collection...	3.67610	kg		lognorm...	
metalliferous hydroxide sludge	382:Waste treatment...	-0.00450	kg	-1.88937...	lognorm...	
process-specific burdens, slag l...	382:Waste treatment...	0.02657	kg		lognorm...	
waste plastic, mixture	**382:Waste treatme...**	**1.00000**	**kg**		**none**	
process-specific burdens, resid...	382:Waste treatment...	0.01674	kg		lognorm...	
municipal waste incineration fa...	429:Construction of ...	2.50000E...	Item(s)		none	
residual material landfill	429:Construction of ...	3.48770E...	Item(s)		lognorm...	
slag landfill	429:Construction of ...	4.72370E...	Item(s)		lognorm...	
transport, freight, lorry, unspeci...	492:Other land trans...	0.00158	t*km		lognorm...	
Oxygen	Resource/in air	2.47910	kg		lognorm...	

Outputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertai...	Avoided
spent activated carbon with ...	382:Waste treatment...	4.22710E...	kg		lognorm...	
waste cement, hydrated	382:Waste treatment...	0.00840	kg		lognorm...	
recovered EoL materials	Circularity Indicators	0.00450	kg		none	
total waste produced (W)	Circularity Indicators	1.00000	kg		none	
Aluminium	Emission to air/high ...	1.52160E...	kg		lognorm...	
Ammonia	Emission to air/high ...	1.73050E...	kg		lognorm...	
Antimony	Emission to air/high ...	3.21170E...	kg		lognorm...	

Figure 2: Screenshot of a waste treatment process for final disposal and some material recovery.

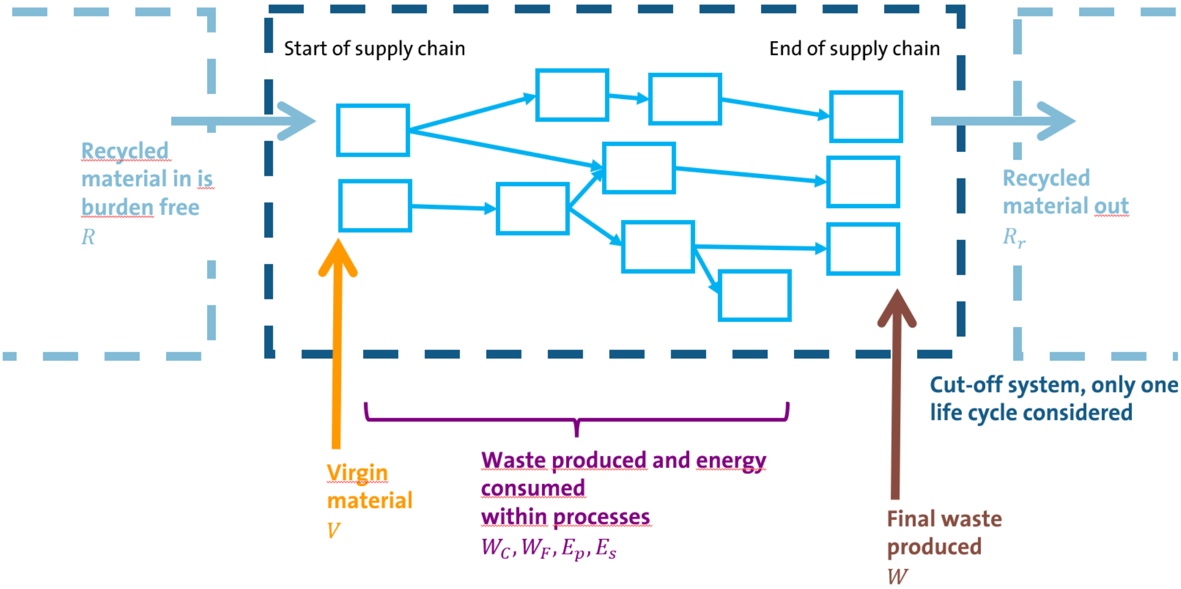


Figure 3: A generic life cycle model to explain the location of the shadowing elementary flows with respect to the supply chain

3.2 Adapted Circularity indicator calculations to fit LCA

The circularity indicators were revised to fit the information that is given from an LCA database. The following two sections show the adaptation and the algorithms that are used.

3.2.1 Material Circularity Indicator (MCI)

According to [1], the MCI is calculated following:

$$MCI_P = 1 - LFI \cdot F(X) \tag{1}$$

$$MCI_P = max\ (0, MCI_P) \tag{2}$$

Where the Linear Flow Index, LFI, takes into account the linear flow of materials, and the utility factor, $F(X)$, looks at life time of products, L, compared to average and utility of the product, U, compared to average. Both equations are shown below.

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \tag{3}$$

$$X = \frac{L}{L_{av}} \cdot \frac{U}{U_{av}}$$

(4)

$$F(X) = \frac{0.9}{X}$$

(5)

The circularity methodology developed for LCA considers that

$$M = V + R_i$$

(6)

Furthermore, it is common in LCA databases that waste, W, is not given per material but rather aggregated, e.g. “municipal solid waste”. Consequently, the total waste produced of a product system will be seen as larger than the virgin material used in the first place. To get a more realistic idea of the total waste coming from virgin material, Equation (7) was instead.

$$W = V - R_r$$

(7)

Consequently, the LFI doesn’t use total waste produced any longer, but rather

$$LFI = \frac{2V - R_r}{2M + \frac{W_F - W_C}{2}}$$

(8)

3.2.2 Circularity Index (CI)

Following [2], the CI is a product of two factors:

$$CI = \alpha\beta$$

(9)

$$CI_{max} = 1$$

(10)

Where alpha, α, looks at recovered recycled material, R_r, over total material demand:

$$\alpha = R_r/(V + R_i)$$

(11)

And beta, β, looks at energy required to recover material, with respect to energy required for primary production, E_p. The energy required to recover material is considered to be the same as energy required or secondary production, E_s.

$$\beta = 1 - \frac{E_s}{E_p} \tag{12}$$

3.3 Quantifying Circularity

The algorithms described above are integrated to a script in openLCA to calculate the circularity indicators, described in section 3.3.2. But before, circularity variables can already be quantified by running the model with the LCIA Method for Circularity developed with the database, Figure 4. This is further explained in the following section.

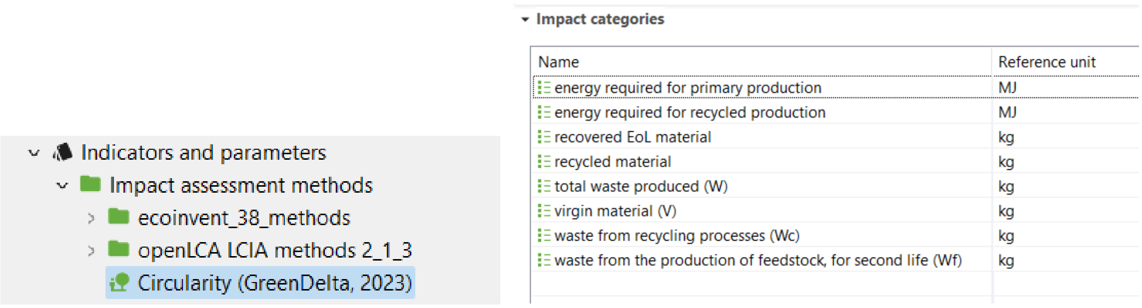


Figure 4: The Circularity LCIA Method allows to quantify circularity variables of the model

3.3.1 Understanding supply chain in terms of Circularity

The model can be calculated with the LCIA Method developed for Circularity, see Figure 5, which tracks the shadowing elementary flows (explained in section 3.1) and displays information of circularity variables across the supply chain. These can be visualised in the results tab in several ways, as usual in openLCA, from a contribution tree to a Sankey diagram. Figure 6 shows a screenshot of the results and some supply chain information.

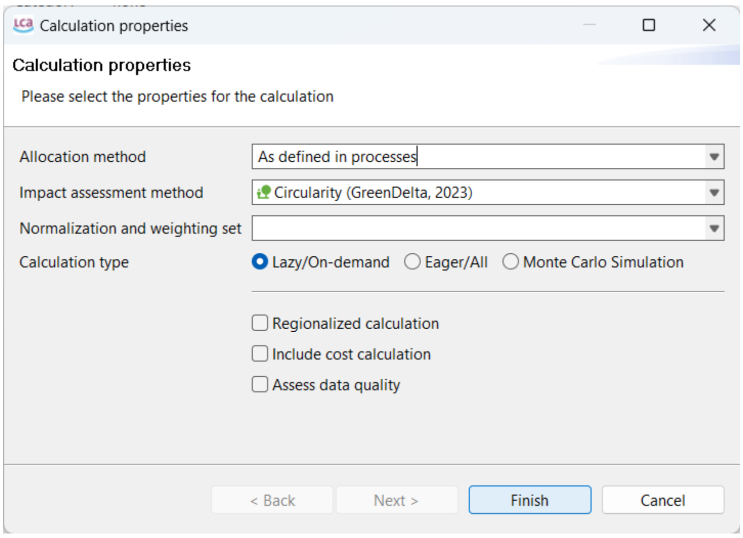


Figure 5: To visualise circularity across the supply chain, calculate the model with the LCIA Method for Circularity within the database

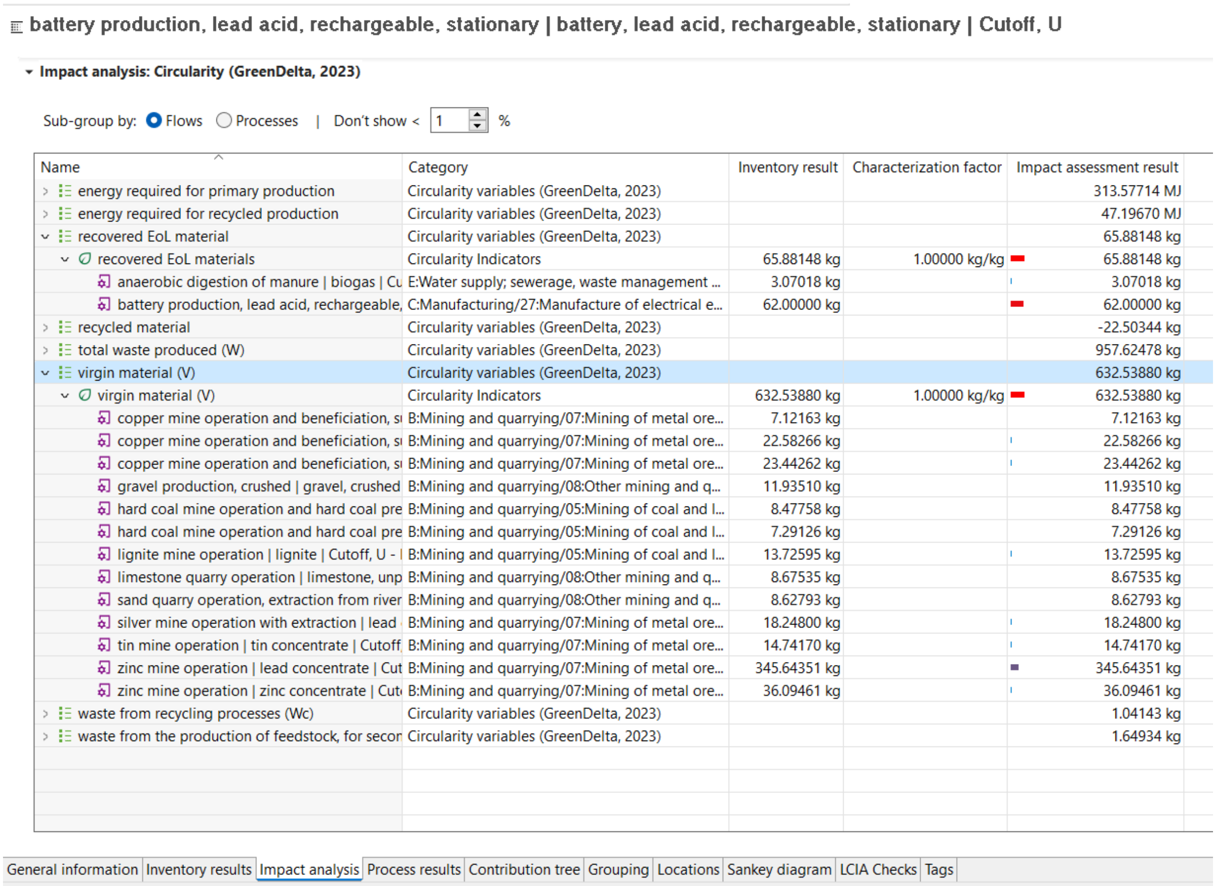


Figure 6: Screenshot for one of the multiple ways to visualise results for circularity across the supply chain with openLCA

3.3.2 Quantifying Circularity with Circularity Indicators

The database comes with an attached jython script which can be opened and run directly in openLCA, Figure 7. It allows to input the last variables required for the calculation of the MCI: life time and utility of the product compared to average.

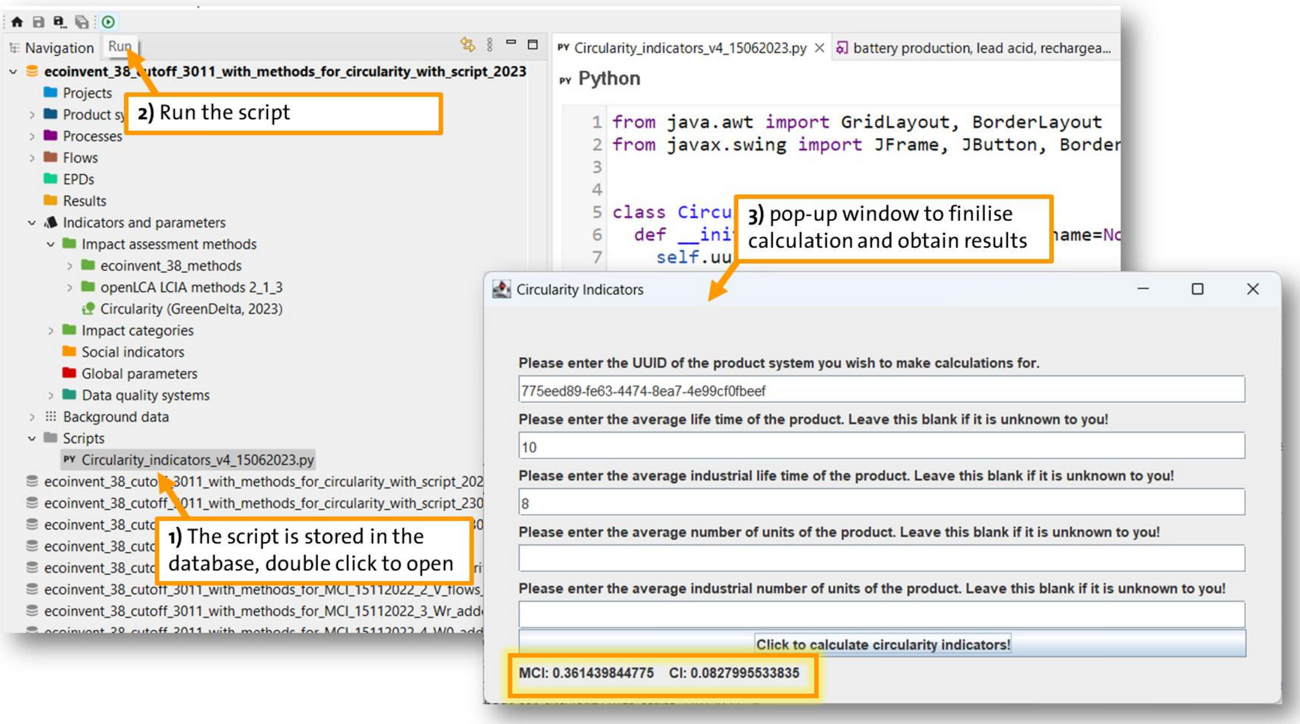


Figure 7: Circularity indicators script for openLCA allows to make calculations for the MCI and the CI within openLCA

4 Summary

Increasing attention is given to the idea of a Circular Economy as a way forwards for sustainable development, especially as governmental initiatives also consider it in their agenda for sustainable growth, such as the Circular Economy Action Plan from the European Green Deal, [9].

A lack of perspective of the overall picture of a product's supply chain, or a lack of a good way to quantify circularity can very easily lead to misleading ideas over a good circular decision, or very bluntly: greenwashing.

To avoid this, this report proposed a methodology where circularity is integrated to Life Cycle Assessment, where the same model used for an LCA can quantify circularity across the supply chain. The methodology is implemented in the ecoinvent 3.8 cut-off database, where shadowing elementary flows tracking circularity variables such as virgin material used, waste produced or energy used is quantified thanks to a circularity LCIA method developed, as well as an add-on jython script to finally calculate circularity indicators (Material Circularity Indicator and Circularity Index).

Circularity Package database can help assess a circular solution, with a full life cycle perspective.

5 How to obtain the database & Support

You can acquire the database licence in our marketplace for data: openLCA Nexus https://nexus.openlca.org/databases

Licence holders will also have access to maintenance updates.

Do you have any questions? You can contact us following this link: https://www.openlca.org/contact/

Need support? Book direct support with us through Nexus: https://nexus.openlca.org/service/openLCA%20Support%20(help%20desk)

6 References

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