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Hybrid Life-Cycle Assessment: Introduction and Implementations

Open Inventory Data Manipulation Autumn School (OIDMAS), Grosshöchstetten, October 2022

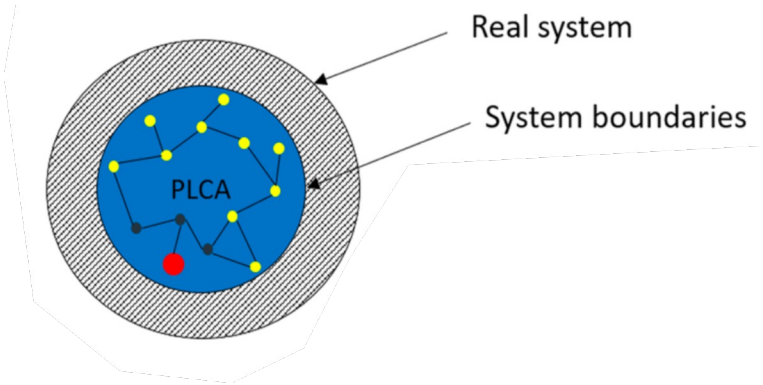
LCA and EEIOA

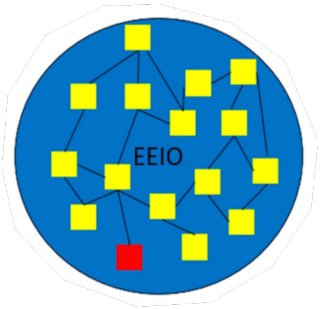
Process-Based Life-Cycle Assessment (PLCA)

Based on detailed description of value chains and exchanges with the environment. *"Precice, but lacks accuracy."*

Environmentally-Extended Input-Output Analysis (EEIOA)

Based on national inventories and trade tables. *"More likely to cover true value, but lacks precision."*





Figures adapted from: https://doi.org/10.1016/j.jclepro.2017.10.176
Compare also: workshop presentation by Suh: https://slideplayer.com/slide/5338710/

LCIA: Mathematical Formulation

Life-Cycle Inventory (LCI):

$$\vec{g} = \hat{B}\vec{s} = \hat{B}\hat{A}^{-1}\vec{f}$$

where

$\vec{g}$ … inventory vector
$\vec{s}$ … scaling vector
$\vec{f}$ … final demand vector
$\hat{B}$ … inventory matrix
$\hat{A}$… technology matrix

Life-Cycle Impact Assessment (LCIA):

$$\vec{h} = \hat{C}\vec{g} = \hat{C}\hat{B}\hat{A}^{-1}\vec{f}$$

where

$\vec{h}$ … impact vector
$\hat{C}$ … characterization matrix

Notation and nomenclature follows Suh and Tukker, compare (2.45), (2.47) and (8.27): https://doi.org/10.1007/978-94-015-9900-9

EEIOA: Mathematical Formulation

Input-Output Analysis (IOA):

$$\vec{x} = \hat{A}\vec{x} + \vec{f} = \left(\mathbb{I} - \hat{A}\right)\vec{f}$$
$$\vec{f} = \left(\mathbb{I} - \hat{A}\right)\vec{x}$$

Environmentally-Extended IOA (EEIOA):

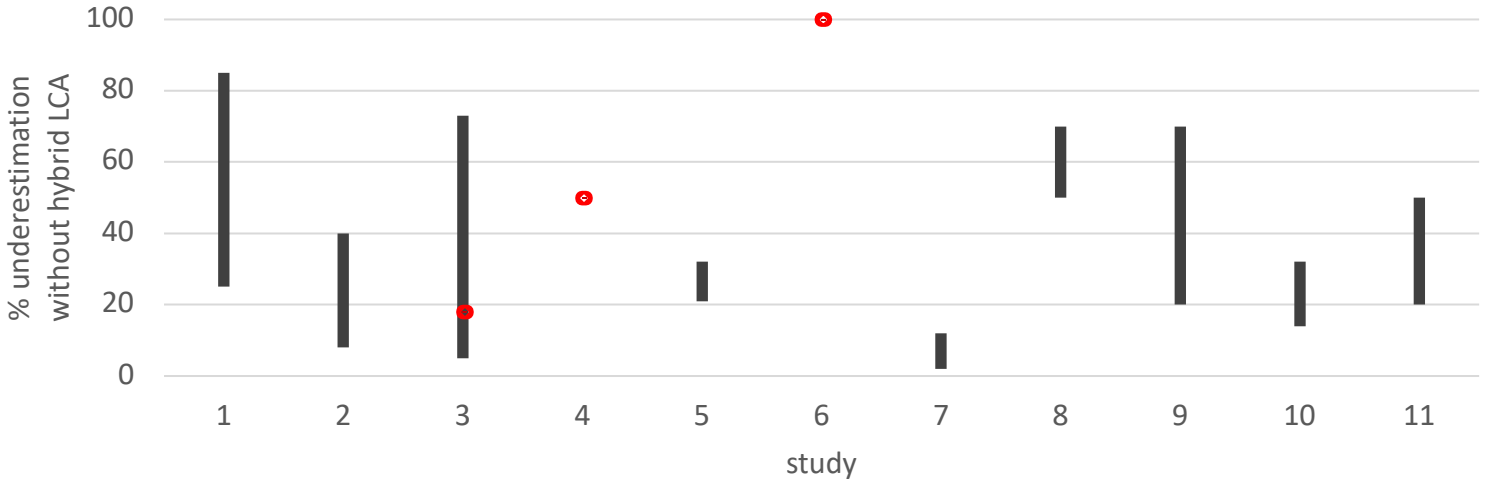
$$\vec{x}^{P^*} = \widehat{D}^P\left(\mathbb{I} - \hat{A}\right)^{-1}\vec{f}$$

where

$\vec{x}$ … total output of all sectors
$\vec{f}$ … total final demand (“exogenous demand”)
$\hat{A}$… technical coefficient matrix (“intersectoral direct requirements”)
$\vec{x}^{P^*}$ … pollution vector (“environmental burdens”)
$\widehat{D}^P$ … direct impact coefficient matrix

Notation and nomenclature follows Miller and Blair, compare (2.11), (2.10) and (10.2): https://doi.org/10.1017/CBO9780511626982

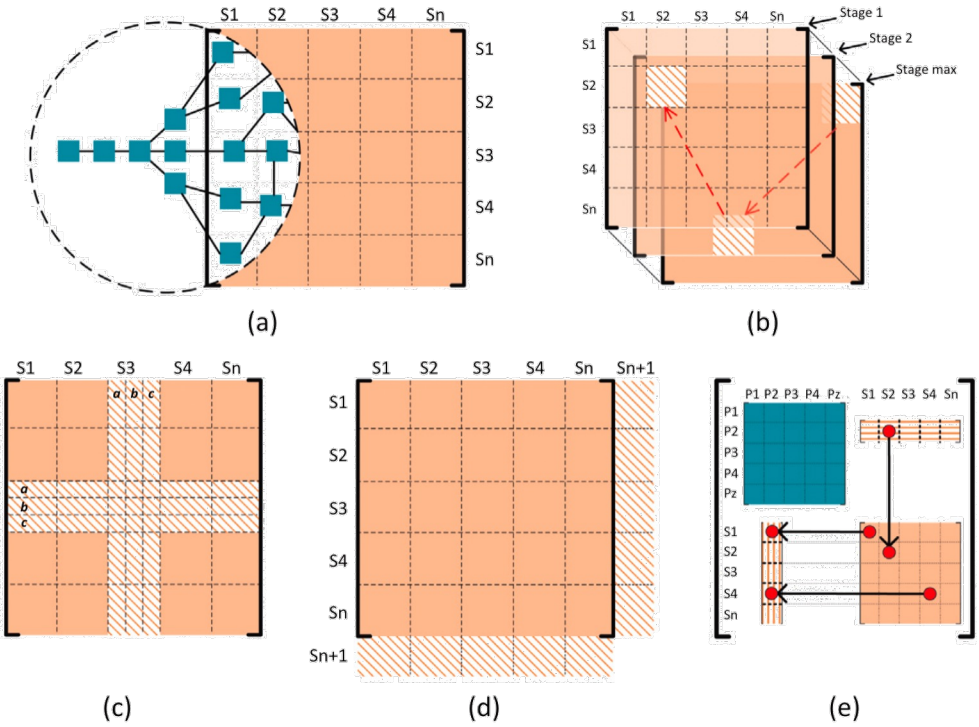
What's wrong with PLCA?



Studies using life-cycle assessment with a purely process-based inventory tend to show lower emissions than if they had used a hybrid approach.
The underestimation ranges up to 100%.

Source: own research, compare dataset at https://doi.org/10.5281/zenodo.7224559

Hybridization: Different Methods



(a) Tiered

(b) Path Exchange

(c) Matrix Augmentation (sector disagg.)

(d) Matrix Augmentation (new sector)

(e) Integrated

Input-output matrix

Process data

Process data system boundaries

Modified section of the input-output matrix

Link from process to input-output matrix

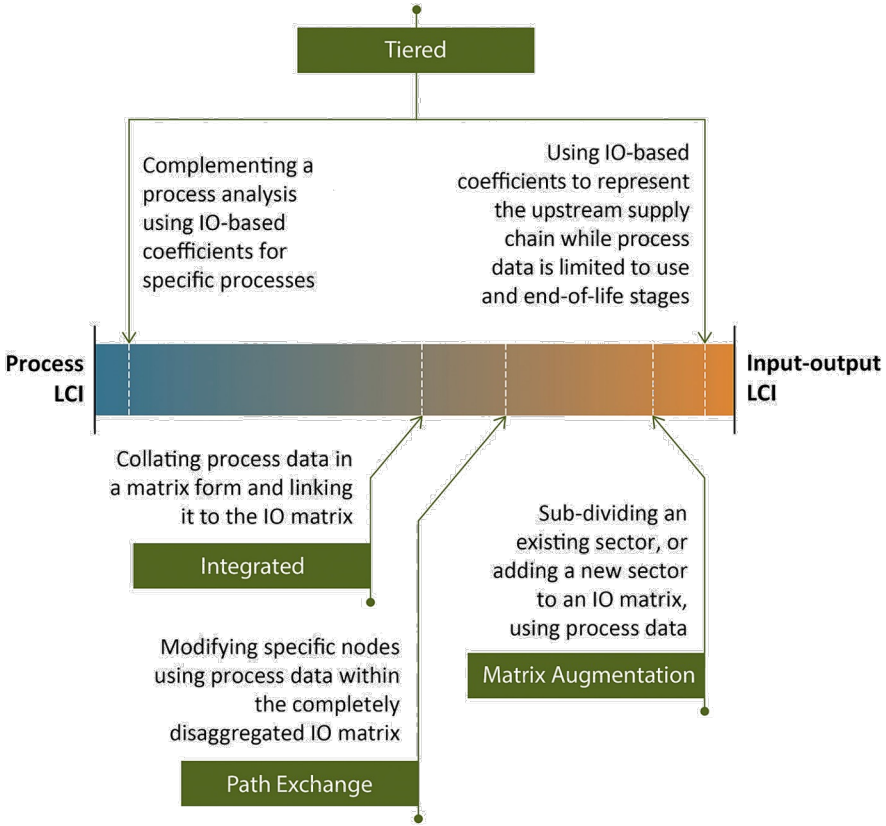
Sector to sector transaction

Downstream cut-off matrix

Upstream cut-off matrix

Figure adapted from: https://doi.org/10.1016/j.jclepro.2017.10.176

Hybridization: Different Methods

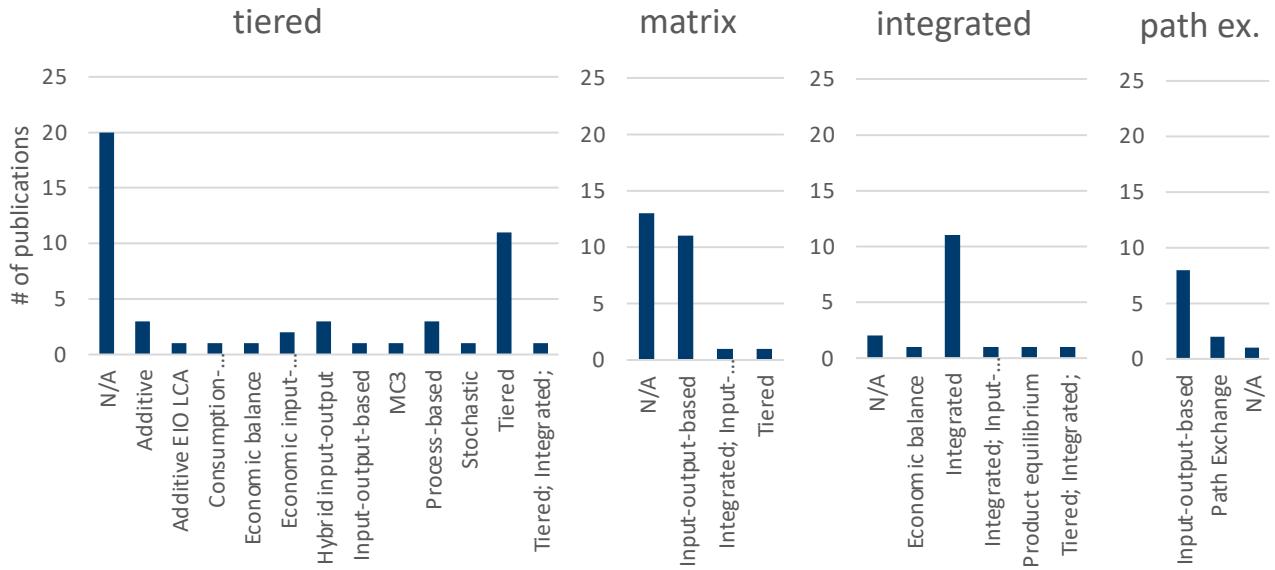


Different hybridization techniques:

1. 3 of 4 methods augment either the process data or the input/output data
2. 1 of 4 methods augments both data
3. attempt to solve different contraints of using either PLCA or EEIOA
4. vary in their success of solving the respective contraints
5. are implemented differently, depending on the practitioners

Figure adapted from: https://doi.org/10.1016/j.jclepro.2017.10.176

Methods: Terminology (or lack thereof)



There is still a lack of universally accepted nomenclature in defining different hybridization methodologies. Studies published up to 2015 show a wide range of definitions used by authors. Here, they are classified using Crawford et al. (2018).

Source: own research, compare dataset at https://doi.org/10.5281/zenodo.7224559

Method: “Matrix Augmentation Hybrid 1”

(also “input-output hybrid”)

Attempts to Solve:

Aggregation Error in EEIOA

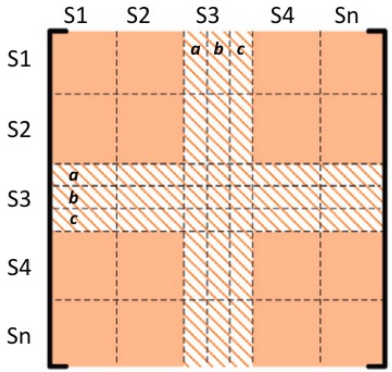
Basic Idea:

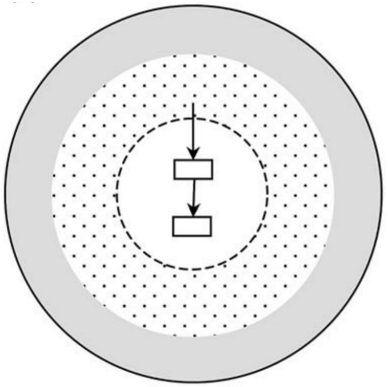
Split up a sector of the economy into sub-sectors corresponding to products (where process-information is available).

Required Assumption:

The technical coefficient matrix is unaffected by the introduction of the new sector.

Representation:





Figures adapted from: https://doi.org/10.1016/j.jclepro.2003.04.001 and https://doi.org/10.1016/j.jclepro.2017.10.176

Primary source for method: https://doi.org/10.1016/j.jclepro.2003.04.001 (“model III” in this publication)

Method: “Matrix Augmentation Hybrid 2”

(also “input-output hybrid”)

Attempts to Solve:

Aggregation Error in EEIOA

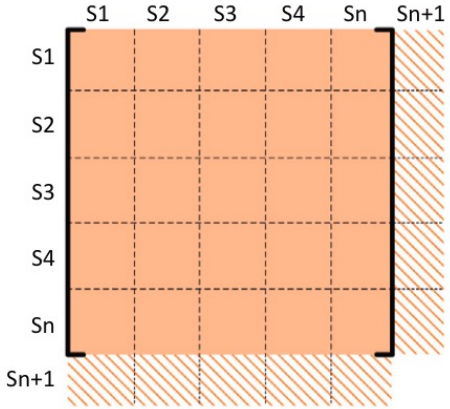
Basic Idea:

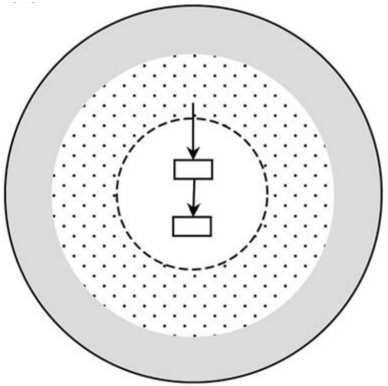
Represent a product (where process-information is available) as a new hypothetical sector of the economy.

Required Assumption:

The technical coefficient matrix is unaffected by the introduction of the new sector.

Representation:





Figures adapted from: https://doi.org/10.1016/j.jclepro.2003.04.001 and https://doi.org/10.1016/j.jclepro.2017.10.176

Primary source for method: https://doi.org/10.1016/j.jclepro.2003.04.001 (“model II” in this publication)

Method: “Path Exchange Hybrid”

Attempts to Solve:

Aggregation Error in EEIOA

Basic Idea:

Structural Path Analysis (SPA):

$$(\mathbb{I} - \hat{A})^{-1} = \mathbb{I} + \hat{A} + \hat{A}^2 + \hat{A}^3 + \cdots$$

Required Assumption:

Representation:

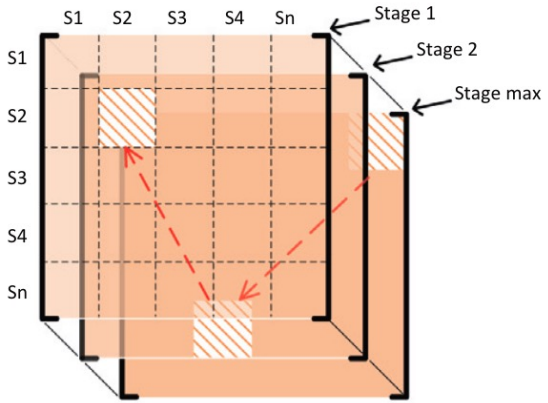


Figure adapted from: https://doi.org/10.1016/j.jclepro.2017.10.176

Primary source for method: https://doi.org/10.1021/es902090z

Method: “Tiered Hybrid”

Attempts to Solve:
Aggregation Error in PLCA

Basic Idea:
PLCA for use & disposal phase & several important upstream processes. The remaining input requirements from EEIOA.

Main Issues:

Double counting of commodity flows. No interaction between PLC and IO inventories.

Representation:

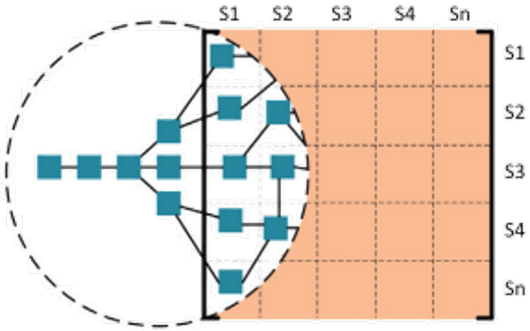


Figure adapted from: https://doi.org/10.1016/j.jclepro.2017.10.176
Primary source for method: https://doi.org/10.1016/j.jclepro.2017.10.176

Method: “Integrated Hybrid”

Attempts to Solve:

Aggregation Error in PLCA

Basic Idea:

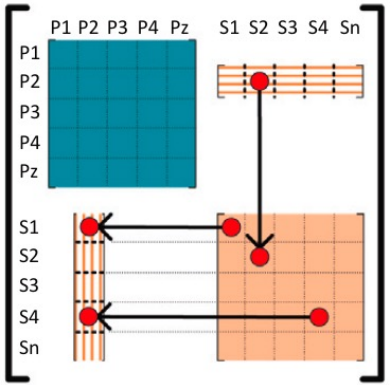
Connect the technology matrix to the input-output table via “up/downstream cutoffs”.

Main Issues:

Double counting of commodity flows.

Nomenclature differences of datasets.

Representation:

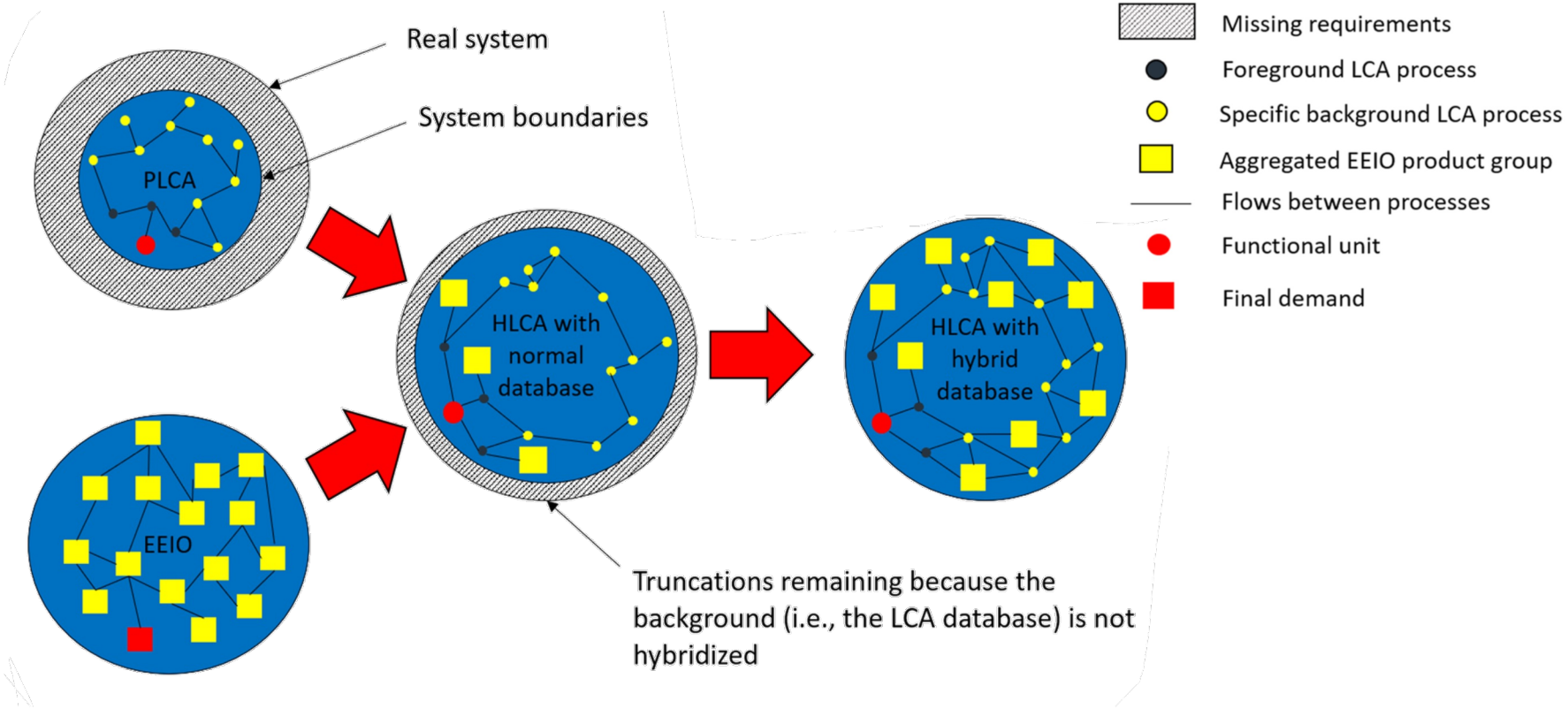


$$\hat{x}^{P^*} = \begin{bmatrix} \hat{D}^P & 0 \\ 0 & \hat{D}^P \end{bmatrix} \begin{bmatrix} \hat{A} & \hat{X} \\ \hat{Y} & \mathbb{I} - \hat{A} \end{bmatrix}^{-1} \begin{bmatrix} \vec{f} \\ 0 \end{bmatrix}$$

Figure adapted from: https://doi.org/10.1016/j.jclepro.2017.10.176

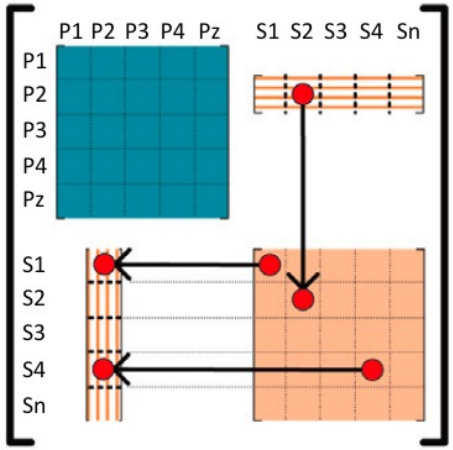
Primary source for method: https://doi.org/10.1016/j.jclepro.2003.04.001

Integrated Hybrid: Overview (1/2)



Figures adapted from: https://doi.org/10.1111/jiec.12979

Integrated Hybrid: Overview (2/2)



Input-output matrix

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Figures adapted from: https://doi.org/10.1016/j.jclepro.2017.10.176

Integrated Hybrid: Mathematical Formulation

Primary sources: https://doi.org/10.1016/j.jclepro.2017.10.176 and https://doi.org/10.1111/jiec.12945

Tools

`pylcaio`

"An object class to hybridize lifecycle assessment (LCA) and environmentally extended input-output (EEIO) databases"

Developed initially by Dr. Maxime Agez

https://ciraig.org/index.php/project/pylcaio
https://github.com/OASES-project/pylcaio

Originally developed at:

POLYTECHNIQUE MONTRÉAL
UNIVERSITÉ D'INGÉNIERIE

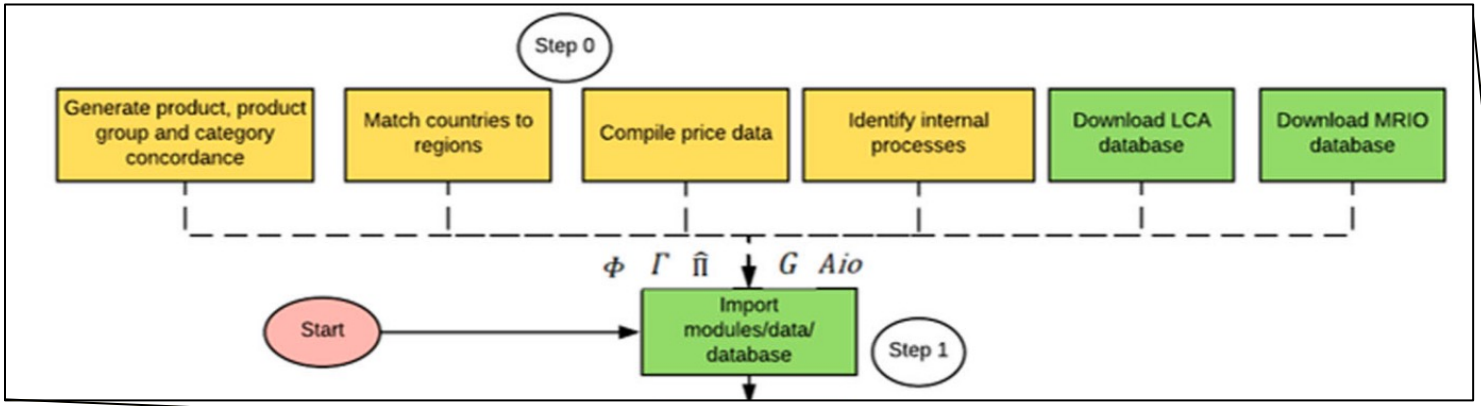
CIRAIG

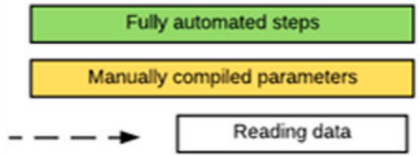
Improved through:

73 NRP
Sustainable Economy
National Research Programme

Oases

`pylcaio` diagram (1/2)





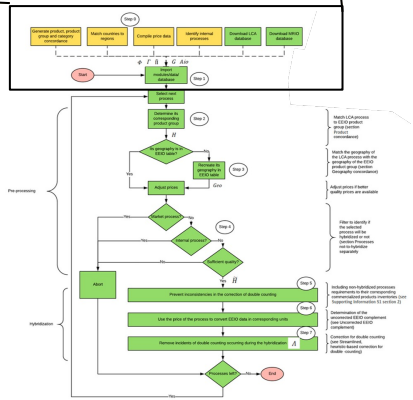


Figure adapted from: https://doi.org/10.1111/jiec.12979

`pylcaio` diagram (2/2)

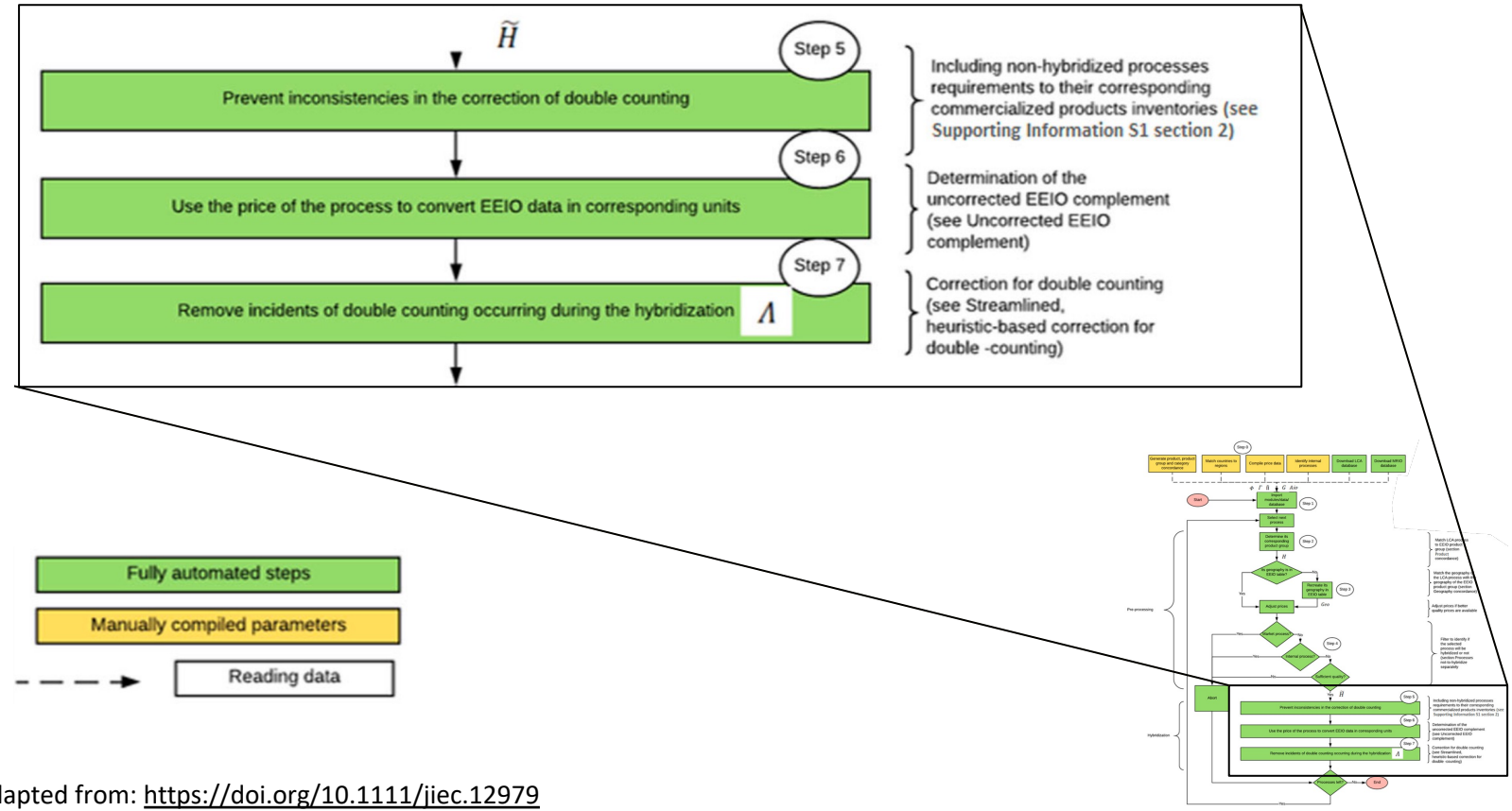


Figure adapted from: https://doi.org/10.1111/jiec.12979

Walkthrough Example

Go to: https://github.com/Depart-de-Sentier/Autumn-School-2022/tree/main/tutorials/hybridization

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Now it’s your turn!

Compare: https://github.com/Depart-de-Sentier/Autumn-School-2022/blob/main/tutorials/hybridization/readme.md

Literature

OVERVIEW

Crawford et al., 2018 “Hybrid life cycle inventory methods”
https://doi.org/10.1016/j.jclepro.2017.10.176
Suh et al., 2005 “Methods for Life Cycle Inventory of a product”
https://doi.org/10.1016/j.jclepro.2003.04.001

INTEGRATED HYBRID METHODOLOGY (`pylcaio`)

Agez et al., 2020 “Hybridization of complete PLCA and MRIO databases”
https://doi.org/10.1111/jiec.12979
Agez et al., 2018 “Lifting the veil on the correction of double counting”
https://doi.org/10.1016/j.jclepro.2017.10.176

Links

- Presentations and Tutorials
  - https://github.com/Depart-de-Sentier/Autumn-School-2022
- Development Environment for the Autumn School
  - http://autumn.brightway.dev/
- `pylcaio`
  - https://github.com/CIRAIG/pylcaio
  - https://github.com/OASES-project/pylcaio
- `Brightway`
  - https://github.com/brightway-lca
  - https://2.docs.brightway.dev/

Wir schaffen Wissen – heute für morgen

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