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Mapping the network of industrial processes from a Life Cycle Inventory database

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Life-Cycle Inventory (LCI): a few notations

- Flows: litre of fuel, kWh of electricity, ...
- Industrial processes have in/out flows: $\mathbf{p} = (p_\alpha \dots p_\mu)^T$.
- Process matrix: $\mathbf{P} = (\mathbf{p}_1, \dots, \mathbf{p}_n)$ can be partitioned $\mathbf{P} = \begin{pmatrix} \mathbf{A} \\ \mathbf{B} \end{pmatrix}$
- \mathbf{A} : technosphere flows; \mathbf{B} : to/from biosphere flows.
- Demand vector $\mathbf{f} = (f_1, \dots, f_\mu)^T$
- The scale vector \mathbf{s} determines total output $\mathbf{A}\mathbf{s} = \mathbf{f}$.

What can be done with Life-Cycle Inventory (LCI) ?

- Solve the **inventory problem**: if demand \mathbf{f} is fixed, what is \mathbf{s} ?
If \mathbf{A} square, non-singular $\mathbf{s} = \mathbf{A}^{-1}\mathbf{f}$.
- Intervention to/from environment: $\mathbf{B}\mathbf{s}$.
- CA: contribution analysis. Which processes contribute most to specific environmental input/output ?
- And much more...

LCI vs related fields

- Carbon Footprint.
- Material Flow Analysis MFA (stocks and flows, specific territory).
- IO analysis (industrial sector in/out, monetary, aggregate).
- Trade networks.

Networks and LCI ?

- Many measures in LCI/LCA, but topology not involved.
- Wood/Lenzen [3], "connectivity" measure is a proxy for average path length in IO economic analysis. It is studied across time for the Australian economy and shows **increasing complexity**.
- Heijungs et al. [2] builds monopartite projections (process/process, flow/flow), using Ecoinvent database. Main findings:
 - Sparse, small diameter. "small world".

Dataset

- Agribalyse 3 (food production, publicly available), [1].

Sample Product system: bipartite network representation

Direct neighbors of the process node "avocado production" are shown in fig. below (parent and child nodes not shown).

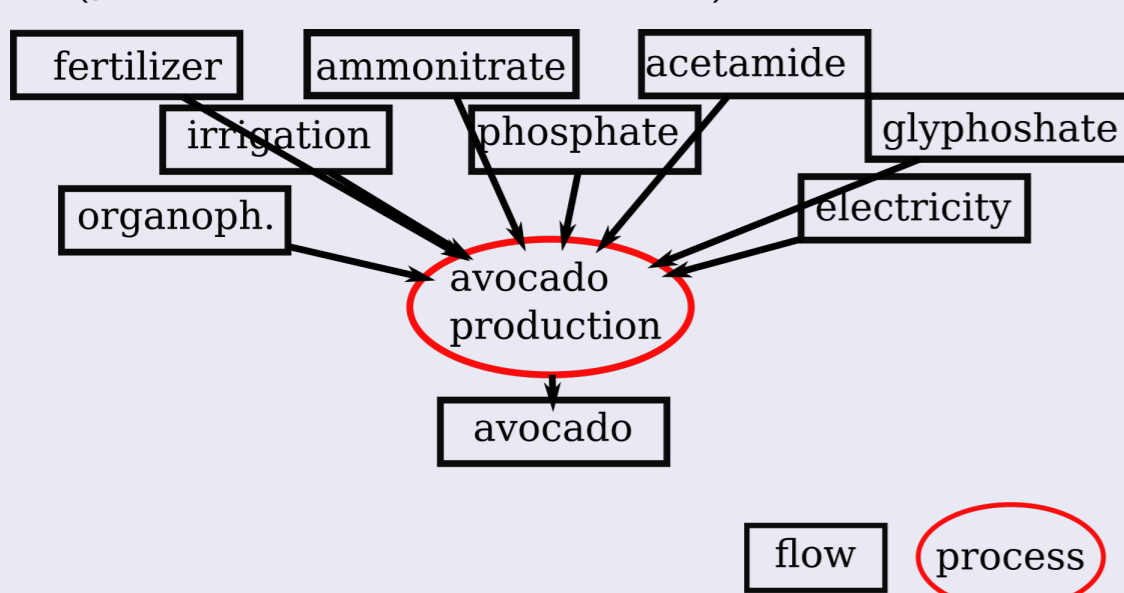


Figure: Network representation of avocado production, from Agribalyse 3

Mesoscale structure of the production network

LCA models represented as bipartite networks have a bow-tie structure.

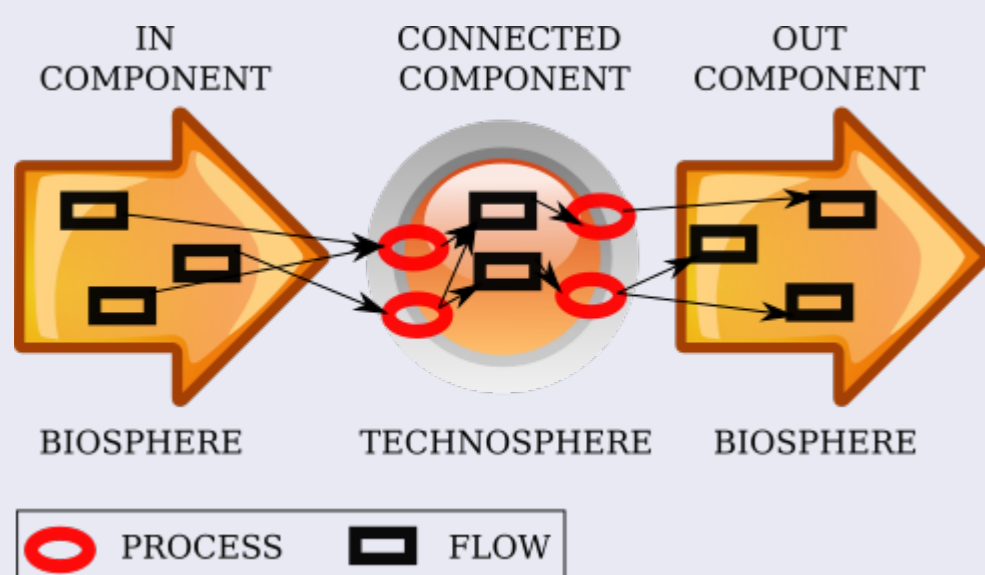


Figure: Mesoscale structure of LCI network.

Caveats

- Which representation: bipartite, or monopartite projection ?
 - Monopartite projection is used in [2].
 - Projection of bipartite networks is tricky, requires statistical validation. Weighted projection, statistical validation [4].
- Network measures on bipartite networks are specific.
- LCI databases reflect partially actual processes running in industries:
 - Modeling error, uncertainty in parameters' values, missing flows/processes.
 - One product vs all economy: final demand usually equal to 1 unit of product under study.
- Weighted analysis is hard: units [2]

Descriptive statistics

indicator	Agri.3	proc.	flows	Ecoinvent 2 [2]
Bi/mono-partite	bi			mono (proc./proc.)
nb. vertices	34837	15655	19182	4087
nb. edges	3547873			45020
edge density	0.03			0.00270
$\langle k_i \rangle$	7.7	8.2	7.3	11.0
median(k_i)	3	7	2.	
std(k_i)	88	8.1	121	
global clustering	0			0.00629
degree assortativity	-0.007			
largest comp. frac.	0.99			
edge reciprocity	5.10^{-5}			0.00391
diameter	13			16

- Sparse graph** with small diameter.
- 1 large connected component.
- Average degree low but flow have high dispersion.
- Specific bipartite quantities are needed, and Ecoinvent graph.

In-out matrix by category (techno+biosphere)

The number of edges between nodes belonging to categories are counted and represented below. The color of point (i, j) represents the number of edges going from category i to category j . It can be noticed that the matrix is not symmetric, dominant rows and columns are salient.

- Rows: others, elementary flows (raw input).
- Main outputs** (columns) elementary flows (waste), agricultural products.
- Conjecture**: importance of elementary flows might be specific to Agribalyse. Compare to other (e.g. industrial sectors).

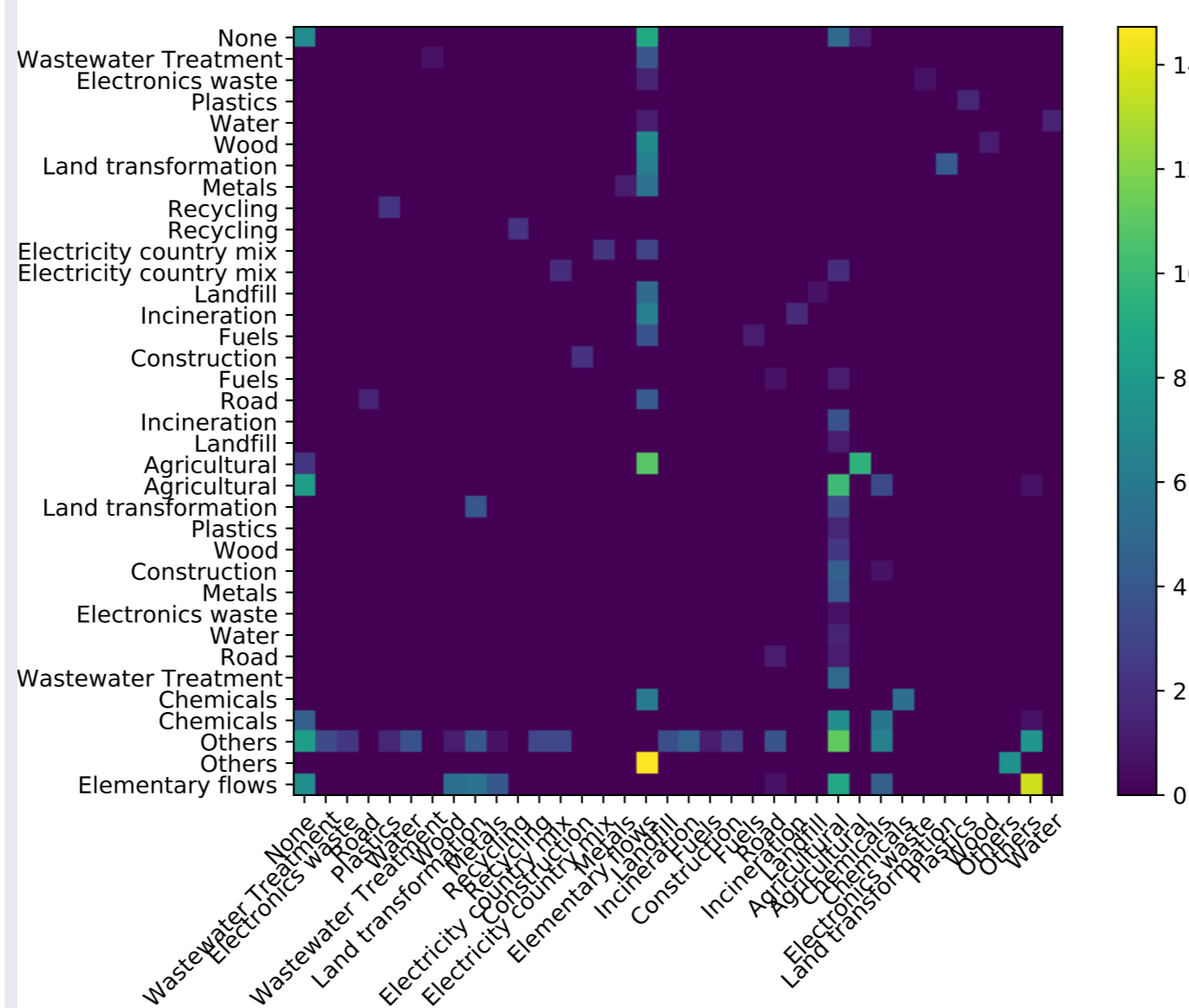


Figure: Edge-count matrix, by vertex category (color scale is logarithmic)

Processes degree (technosphere)

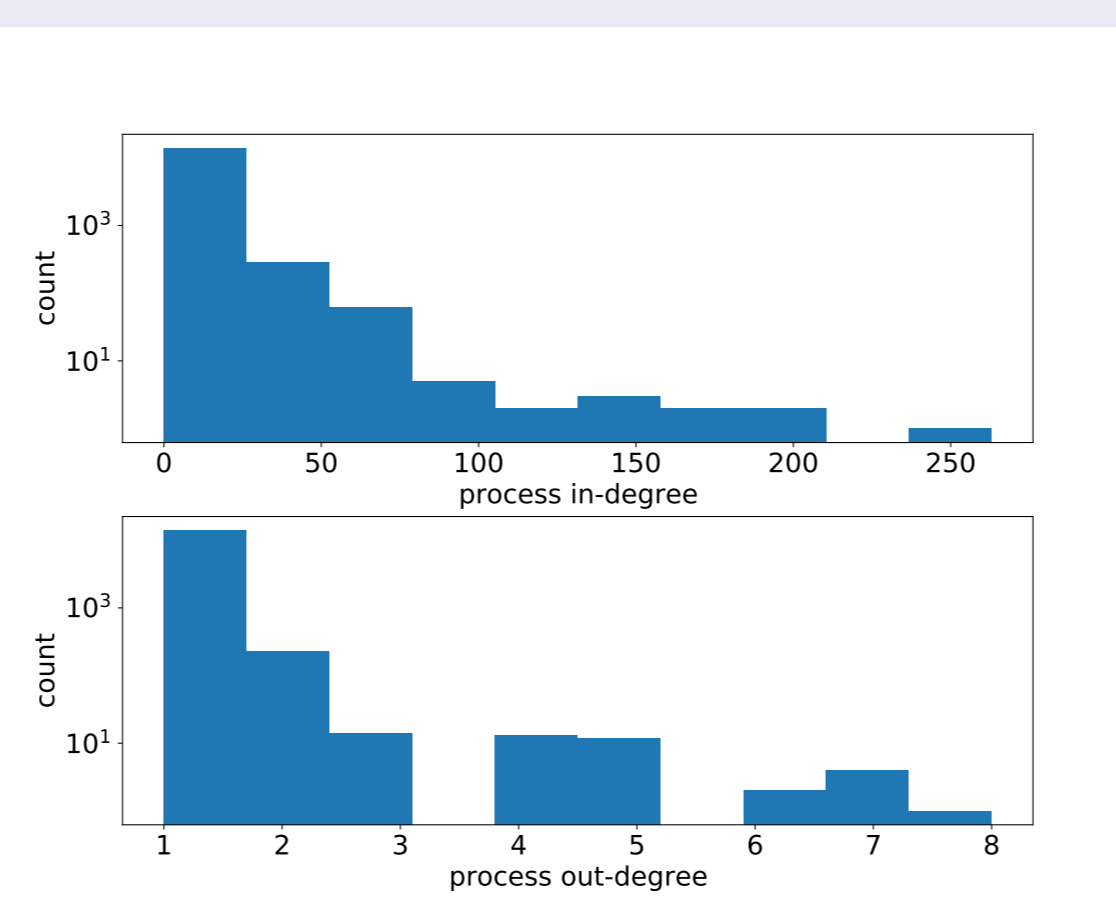


Figure: In and out-degree of processes (y-axis in logscale)

- Network characteristics **change** when including biosphere.
- Processes can take dozens of inputs and output a few products only.
- No fat tail.
- When biosphere is included, max degree is much larger.

Flows degree (technosphere)

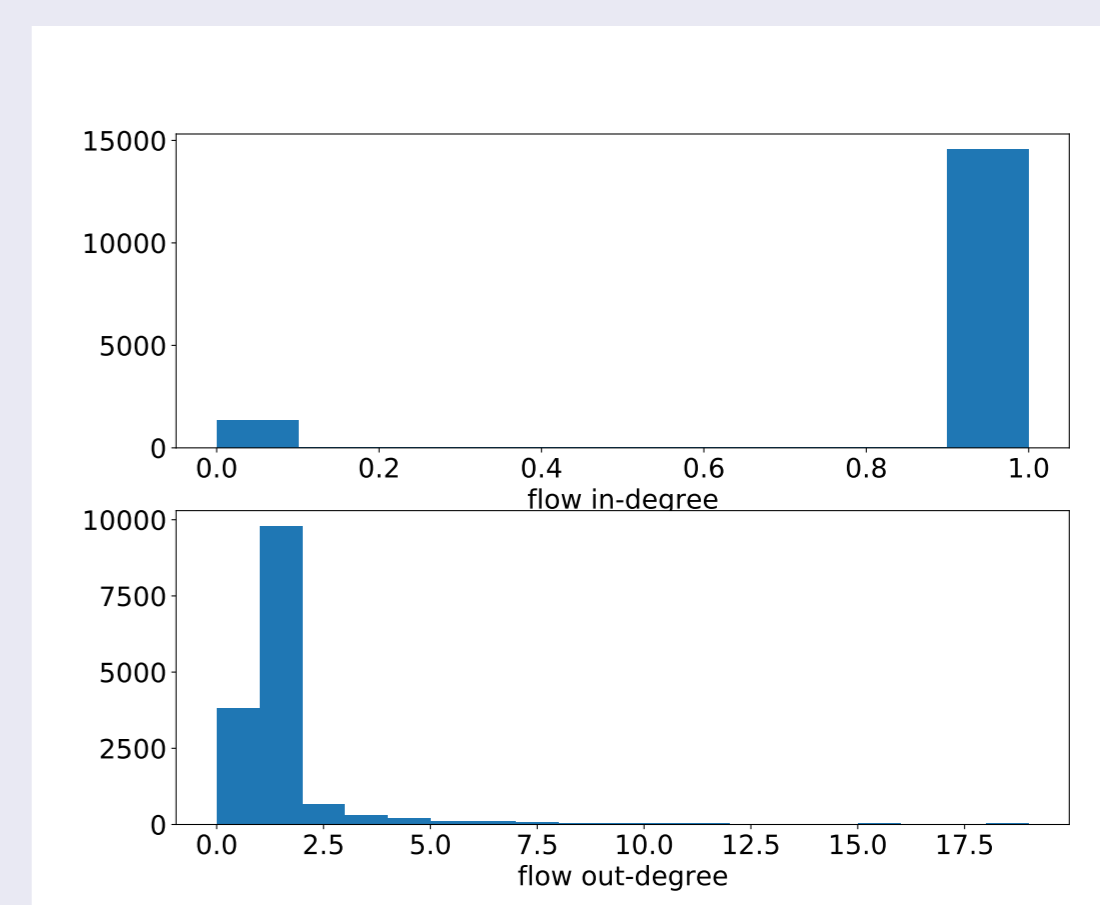


Figure: degree in out flow

- Most flows in technosphere are outputs of 1 process only.
- Hypothesis**: by-products are neglected in database ?
- Important minority of leaves (not used by any process, zero out-degree).
- Most flows are intermediate products.
- When biosphere is included, max degree is much larger.

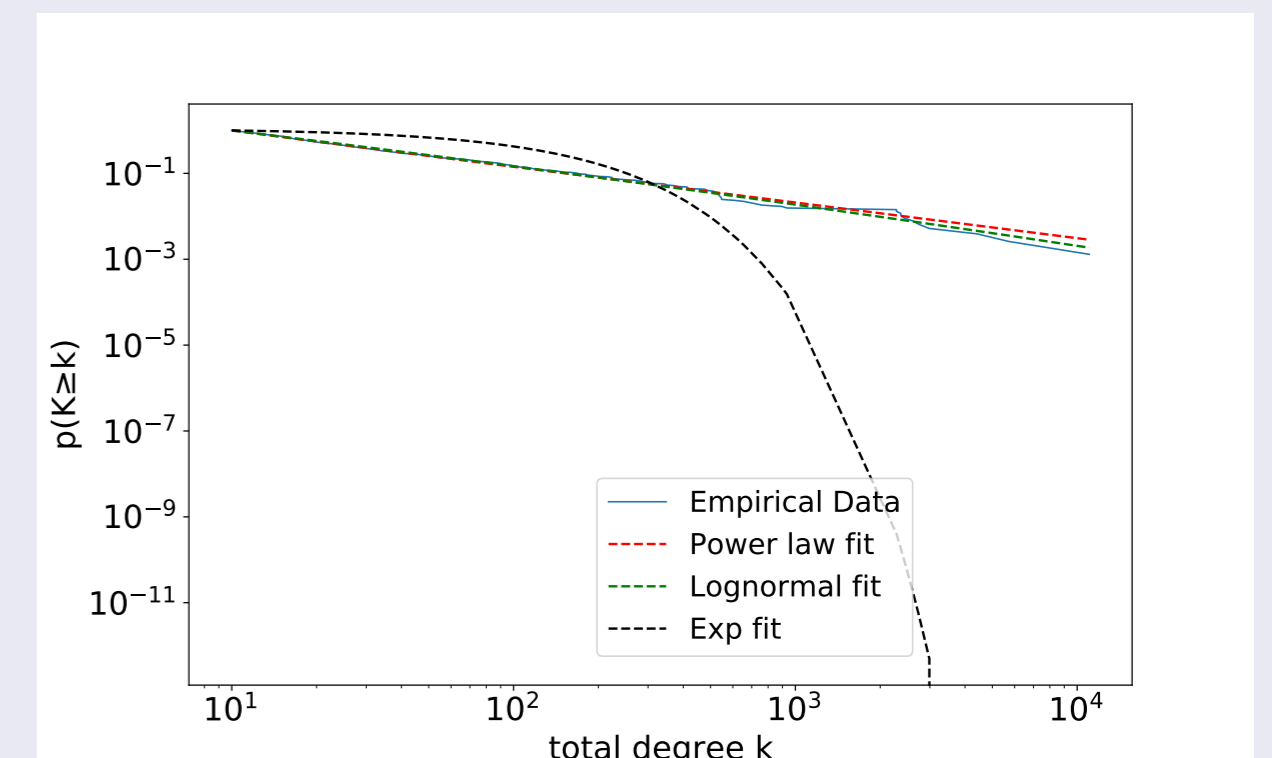


Figure: degree total flow powerlaw

- Fat tail in the technosphere.

Forthcoming

- Proper Bipartite analysis:
 - Null model [5].
 - Small-world $\langle d \rangle \approx \frac{\ln N}{\ln \langle k \rangle}$.
 - Clustering/transitivity.
 - Hierarchy: who is at the "top" of the network ?
 - Nestedness.
- Monopartite projection with statistical validation.
- Active processes for a "real" demand vector.
- Multi-scale representation:
 - LCI point of view: "aggregation", cut-off.
 - IO analysis: indirect effect.
 - Network side: renormalizable model, reduced google matrix.
- Other LCI datasets: Ecoinvent.
- Comparison to other bipartite nets.

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