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THE INPUT-OUTPUT METHOD AND ITS USE IN LCA

Scientific summary

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SUMMARY

This report is a summary of the *Input-output method and its use in LCA* project funded by SCORE**LCA** and jointly carried out by the CIRAIG at Polytechnique Montréal and the Industrial Ecology program of the Norwegian University of Science and Technology.

This study explores the principles of the economic input-output (IO) analysis method, its extension to environmental analysis (EEIO) and positioning with regards to standard LCA and the hybridization of the EEIO and LCA approaches. It also presents the results of two case studies on the application of the EEIO method and its hybridization based on two standard LCAs (a comparative LCA of electric car and conventional car in Europe and the LCA of a residential building in Québec). In these cases, the implementation differs in terms of tools, databases and practitioners. The findings are presented and compared (LCA/EEIO/hybrid) and conclusions and recommendations are drawn. Hybridization is applicable according to an iterative approach described herein that may be automated depending on the EEIO database that is used. An automation tool was developed.

KEY WORDS

Environmentally extended Input-Output Analysis (EEIO), Life-cycle assessment (LCA), Supply and use tables (SUT), Hybrid IO-LCA

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1 Glossary and abbreviations

CEDA	Comprehensive Environmental Data Archive CEDA is a suite of environmentally extended input-output databases that are designed to assist various environmental systems analyses and life cycle assessments, including carbon footprinting, water footprinting and embodied energy analysis. The CEDA quantifies the amount of natural resources use and environmental emissions of products throughout their life cycles by connecting input-output tables, which represent the entire supply-chain network of an economy, with a comprehensive list of environmental interventions including natural resource types (fossil fuels, water, metals ores and minerals), and various emissions to air, water and soil. For this study, the 2002 USA CEDA database (economic allocation version) has been used, which is included as a library in SimaPro (v8.05.13) LCA software.
CPA	Classification of product by activity A product classification and coding system (approximately 3 000 subcategories) used by Eurostat http://ec.europa.eu/eurostat/web/cpa-2008
EEIO	Environmentally extended input-output Economic IO tables extended of environmental flows, used as models in environmental analysis based on a life cycle approach driven by economic exchanges in interconnected sectors in a national or multiregional economy
GHG	Greenhouse gas
IO	Input-output Input-output tables, models and economic analyses
LCA	Life cycle analysis (process based)
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
SPA	Structural path analysis Analysis that determines the main channels of contribution to system impacts
A	Technical coefficients matrix (technology matrix)
Basic price	The amount receivable by the producer from the purchaser for a unit of good or service produced minus any tax payable, and plus any subsidy receivable, by the producer as a consequence of its production or sale. It excludes any transport charges invoiced separately by the producer.
I	Identity matrix
L	Leontief matrix (Leontief, 1970)

2 Study context

This study explores the potential and implementation of the input-output (IO) method and data to carry out environmental life cycle analyses. The objective is to provide an overview of the economic IO method and its extension to environmental analysis (EEIO) as well as of the state of the art in approaches to hybridize EEIO and standard LCA[1] and their ease of implementation. Two case studies serve to highlight practical findings that are applicable in analyses undertaken by SCORELCA members. Unlike LCA, the IO and EEIO databases do not apply cut-off thresholds or exclusions in economic exchange inventories (traded products, energies or services) and could therefore lead to more comprehensive environmental analyses. Hybrid LCA offers the complementarity of the two methods: details for products and technologies, and better coverage of environmental exchanges in LCA; no truncation nor exclusion in EEIO.

3 Economic IO analysis

IO analysis considers the entire economy as a group of industrial (or sectoral) stakeholders that purchase and sell goods and services (products). Input-output (IO) tables are constructed based on data from national and international statistical agencies and from academia, and refer to a specific year. The final consumption of the products by households and governments and the imports and exports are presented in separate tables. All the other flows that are not considered as product exchanges are represented in extensions. In an economic analysis, these exchanges are typically regarded as added values, specifically with regards to salary payment and profits.

IO tables are generally symmetrical in order to indicate which products are used to manufacture which products (**Z**, Figure 1). In other words, industries are taken out of the representation of the economy so as to focus on the interdependence between the different products. These constructions combine an allocation step (similar to partition and substitution methods used in LCA) that addresses situations in which an industry co-produces more than one product and an aggregation step to calculate an average global technology used to manufacture each product.

[€]		Manufactured products	Electricity	Services		Households		total
Manufactured prod.		0	20	45		35		100
Electricity	**Z :**	30	0	30	**h :**	140	**x :**	200
Services		0	80	0		70		150
Value added	**va.:**	70	100	75				
total	**x :**	100	200	150				

Figure 1: Simplified fictional example of IO table (not normalized) based on product classification.

Notes: The Electricity *column compiles the flows of various products (**Z**) and the added value (**av**) dedicated to electricity production in the economy. The* Electricity *row indicates the electricity consumption required in the production of various commodities (**Z**) and by the final consumers i.e. households (**h**). The column and row sums must be equal (**x=x'**).*

An IO table must then be standardized against the total production of each commodity. The column then becomes a sort of "recipe" to produce 1€ of a commodity (Leontief 1970). The matrix **Z** becomes the matrix of technical coefficients (**A**), which is used in IO analysis models with the Leontief matrix ($\mathbf{L}=(\mathbf{I}-\mathbf{A})^{-1}$) to introduce the life cycle approach. By multiplying a vector of final demand for commodities (e.g. household demand) by **L**, it is possible to calculate the total cradle-to-consumer production required for each product to meet demand. This so-called "quantities model" is at the core of all IO and LCA analyses, which share the same mathematical foundations and several

1 Thereafter, it is understood by « LCA » the standard life cycle analysis method based on unit processes to deliver products and whose inventory is generally truncated by the application of a cut-off threshold (e.g. inputs that represent less than 1% in mass of the total inputs of the process are excluded from the inventory since it is assumed that their contribution will not be significant to the impact) or the exclusion of certain activities (e.g. employee transport to the workplace). *ecoinvent* is such a database for process LCA.

presuppositions. Table 1 presents the key characteristics and simplifications of the IO analysis against LCA.

By combining all the IO tables available from different countries and reconciling their import and export declarations, it is possible to develop a table of the entire world in which each country is explicitly represented and each industry relies on domestic and imported inputs. Compiling multiregional IO tables is a very arduous task carried out by academics. However, using the tables is just as simple as using national IO tables. International tables pave the way for analyses that consider product origin.

IO tables are typically released every five years. The user must manage the temporality by adjusting inflation or deflation based on price indexes whenever necessary.

Table 1: Presuppositions inherent to IO analysis (unconstrained quantities model)

Characteristics and simplifications of IO	Shared by standard LCA?	Alternatives and solutions
Leontief functions: fixed technologies (the above-mentioned “recipe”), no input substitution	Yes	Other production functions, with elasticities, computable generable equilibrium model (CGEM)
Fixed prices (unaffected by the extent of the demand, invariable from one sector to the next), unlimited quantities regardless of demand	Yes	Linear programming models, operations research or CGEM
1:1 relationship between technology and product*	Yes*	Linear programming to work with a non-symmetric technology matrix (**A**)
Homogenous products: a given product has the same intrinsic characteristics regardless of the industry that produces or uses it	Yes	Disaggregation
Homogenous prices: a given product is priced the same regardless of the industry that purchases it	--	Disaggregation Use tables compiled in basic price to significantly reduce disparities between sector prices. Otherwise, use tables compiled in physical units

* The constraints can partially be lifted through the creation of several identical products that may be traced back to their original industries (e.g. electricity from wind, hydroelectricity, nuclear electricity, etc.).

4 Environmental IO analysis (EEIO)

IO analysis calculates the *total production* (from cradle to consumer) required for a given final consumption. EEIO analysis is chiefly used to calculate *total emissions* for a given consumption. To carry out these calculations, environmental extensions are added to economic inventory data. Mathematically, the environmental extensions are compiled and processed in the same way as added value (see previous section). The EEIO tables are therefore IO tables enhanced with a matrix of environmental flows expressed in physical units such as emissions to air in kg CO_2 or SO_2, m^3 of water withdrawn or kg of crude oil extracted. Each column (i.e. each production process and service activity—see Figure 1) therefore has an inventory of direct inputs and emissions. Some EEIO tables also provide the emissions during the product use phase as direct emissions by households per € of purchased product (e.g. CO_2 emitted by € of car gasoline).

The environmental extensions may be added to economic tables by statistical agencies. However, in such cases, the tables are often limited to GHGs and certain resources. The most comprehensive models have been developed by academic researchers. Significant efforts are often required to collect the data, estimate the missing data, scale up the figures and ensure data quality (identify biases, verify consistency, etc.) This explains the relatively limited availability of national and multiregional EEIO databases (e.g. EEIO tables). It is very important to note that, while EEIO analysis takes into account all relevant economic activities, the coverage of the environmental issues is only partial if the inventory is incomplete. However, a sufficiently detailed and comprehensive EEIO model may be used during the screening phase of an LCA to guide data collection and the further modeling.

5 Hybrid analysis

Despite certain analogies, the EEIO and LCA approaches are so fundamentally different that they cannot meet a same study objective and are therefore not substitutable. Hybridization enhances their complementarity (i.e. product and technology details, better coverage of environmental issues in LCA, no truncation and exclusion in EEIO). The theoretical argument for hybridization affirms that "*it is better to be uncertainly exact than accurately biased*".

An analysis is considered hybrid when it:

1. combines the detailed descriptions (i.e. inventory) of specific processes to an aggregated but complete description of the economy
2. avoids (or significantly offsets) the issues caused by the cut-off of detailed processes
3. corrects the double counting issues introduced when combining LCA and EEIO descriptions

Hybridization may be undertaken from two perspectives. The first aims to detail an existing EEIO model by introducing LCA process information, typically to disaggregate the sectors in the EEIO table and make it possible to distinguish different products within a same group (e.g. fluid milk and cheese within the dairy products group) or different technologies (e.g. electricity from wind, hydro or nuclear energy). The overriding objective is to model the economy as a whole by focusing on the roles of certain technologies or products in various economic sectors. The analysis is therefore macroeconomic. The perspective requires significant effort and data (prices, production volumes) but sustainably enhances the EEIO table and preserves its balanced feature.

The second perspective involves using a normalized EEIO table to complement one or several LCA processes. The approach requires minimal effort and data (the price of the product in the LCA process or the average prices of the sector to which it belongs) and aims to offset the limitations of LCA. Figure 2 illustrates the hybridization principle at the level of the LCA and EEIO unit process. This perspective is the most adapted to specific analysis for which most impacts should stem from detailed LCA processes and the generic complement should be as small as possible. If, during hybridization, the portion of impacts from the EEIO is too great and pertains to operations that may be modeled with LCA processes, an additional data collection or LCA modeling phase should be undertaken to extend the LCA part and reduce that of the EEIO in the hybrid analysis. A contribution analysis will reveal this and guide the practitioner in the iterative hybridization process.

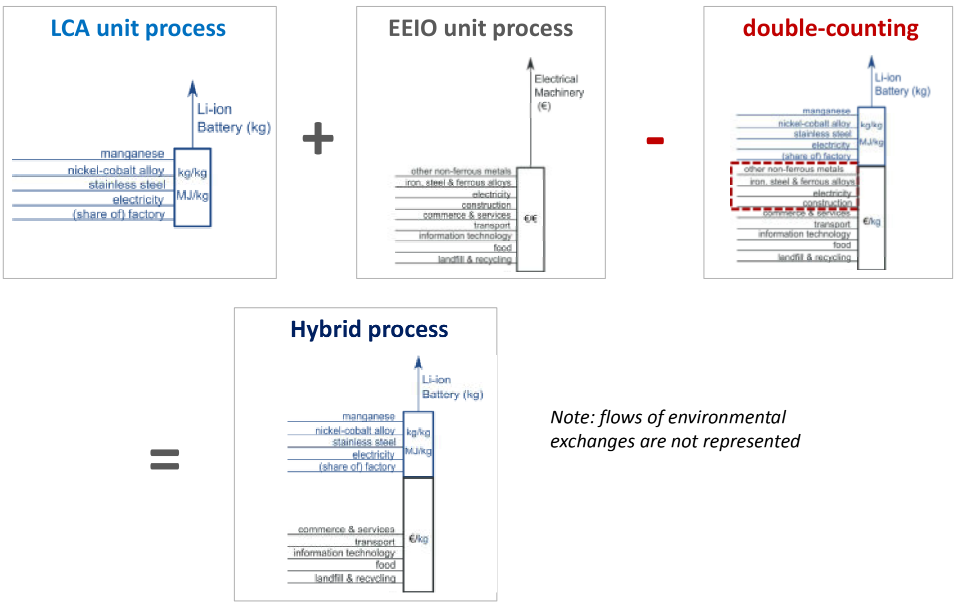

Figure 2: Principles of hybridization of an LCA process using a EEIO database process.

Notes: 1) the addition of the EEIO process requires knowledge of the average price of one kg of electrical machinery; 2) the environmental flows of the EEIO processes are removed during addition.

6 Hybridization illustrated through case studies

Table 2 describes the two hybridization case studies performed for the project: the comparative analysis of an electric car and conventional car, and the assessment of a multiunit residential building. In both cases, the starting point is an LCA. The EEIO is used as a generic complement to the specific foreground processes in the LCA model. The hybridization is tiered. The case studies were each performed by two distinct practitioners, using different EEIO database and tools. The car case study involves a large multiregional EEIO database which makes it impossible to rely on LCA software or spreadsheet (e.g. Microsoft Excel). A tool developed in Python was used. Figure 3 describes the iterative hybridization process.

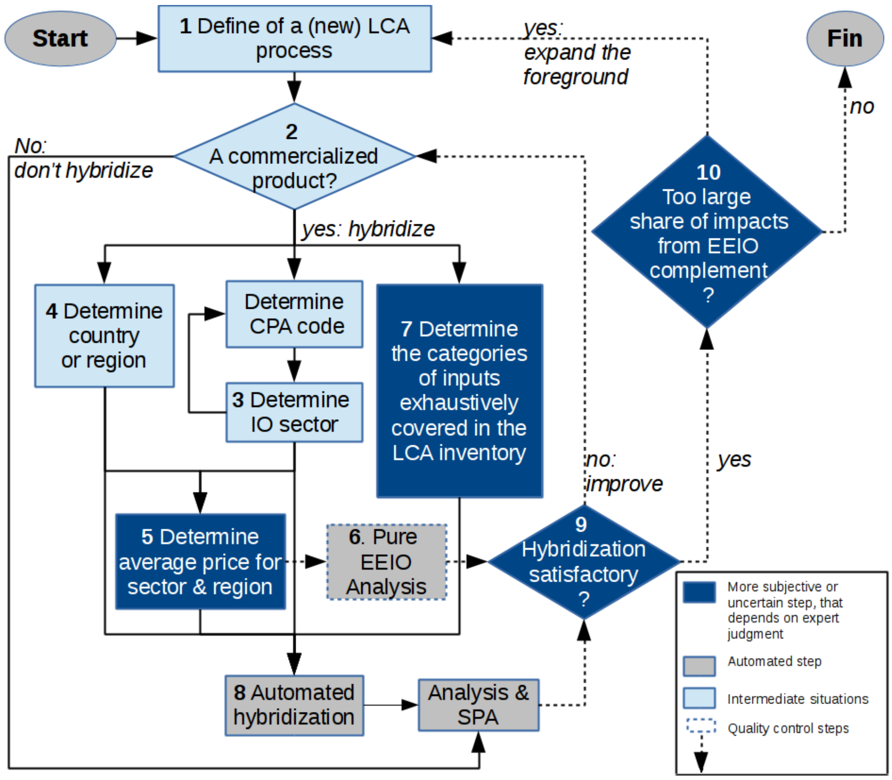

Figure 3: Iterative process implemented for hybridization.

Note: Automation refers to the hybridization of processes using the pyLCAIO tool; CPA: classification of product activity; SPA: structure path analysis.

Table 2: Description of case studies

	Electric versus conventional car	Building
Source of the case study	Two publications: battery LCA (Ellingsen et al. 2013) and comparative LCA of vehicles (Hawkins et al. 2013)	LCA currently being carried out by the CIRAIG, data collected
Functional unit	*Drive 150 000 km in Europe* (vehicle used for tourism)	*Ensure a comfortable living space for 75 years in a 4-floor, 20-unit residential building built in Québec in 2014*
Complexity	Cradle to grave: specific focus on the production phase (battery, engine, and car manufacturing)	Cradle to grave: simplified LCA (e.g. second iteration)
Foreground modeling	521 processes; EU and GLO regionalization	66 processes; Québec and GLO regionalization
Background (LCI database)	ecoinvent v2.2	ecoinvent v3.1
EEIO data	ExioBase v2.2 (multiregional, 2007); 44 countries * 200 sectors (ExioBase and CREEA 2014)	CEDA v4 (United States, 2002); 424 sectors
EEIO analysis	Regionalization of foreground ExioBase: CN, EU, CA Except for use and end-of-life phases: ecoinvent LCA processes	CEDA for all foreground processes except electricity supply, and energy combustion processes (heating, machinery), which are ecoinvent LCA processes
Price data	ExioBase compilation (basic price, €2007)	ExioBase compilation (basic price, €2007) Currency conversion: European Central Bank Deflation: producer price index (PPI), US Bureau of Labor Statistics (https://www.bls.gov)
Hybridization	Foreground process complementation (tiered hybrid), automated iterative approach	Foreground process complementation (tiered hybrid), manual iterative approach
Impact analysis	ReCiPe method (CML compilation for ExioBase)	ReCiPe v1.12
Tools	Specialized pyLCAIO tool to organize and manage tables, extract FCs for ExioBase and automate hybridization and double counting correction https://github.com/majeau-bettez/pylcaio	Standard LCA tools: SimaPro and spreadsheets
Practitioner profile	Analyst A: expertise in EEIO and hybridization, ExioBase, matrix calculation, Python programming	Analyst B: expertise in LCA and EEIO (none in hybridization)
Other		The case study was also used to assess the influence of adding LCA to the costs (100% EEIO modeled) incurred during the building's service life and relative to development expenses, taxes, insurance and management fees.

7 Results

7.1 Electric car case study

Both LCA and EEIO approaches led to very similar estimates for climate change for the cradle-to-gate assessment of the electric car. Still, contributions differ (Figure 4). Following hybridization, the climate change score rose by 30%. The hybrid analysis increased acidification score by 16%, marine ecotoxicity by 12% and eutrophic and human toxicity by approximately 8%. The emissions that contribute to toxicity impact categories are not as extensively inventoried in ExioBase as GHGs or acidifying substances.

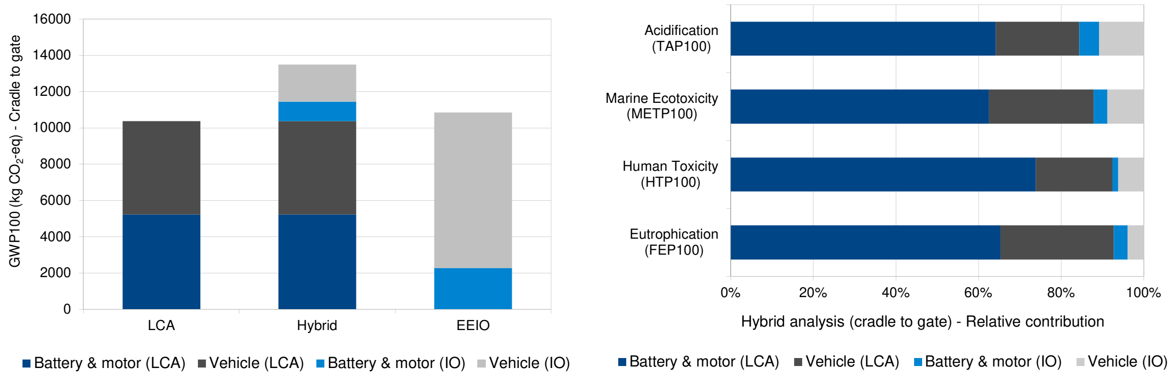

Figure 4: Impact scores of electric car production (cradle-to-factory gate)

Left: climate change assessed using LCA, EEIO and hybrid analysis. Right: other impact categories assessed using hybrid analysis. The hybrid analysis represents the relative contribution of the LCA (LCA) and EEIO (IO) processes.

The higher figures are explained by the series of value chains added through EEIO, which each contribute to an increase of less than 1%. The value chains that most contribute to the potential impact on climate change are *Business services, Wholesale and commercial services, Vehicle sales and maintenance, Retail sales and commercial services, Stationary, Research and development*, etc.

In the comparative cradle-to-gate LCA of the two cars, the conventional car's climate change score is lower (65%) than that of the electric car (100%) due to battery manufacturing. Hybridization helps close the gap (68% versus 100%) but the conventional car remains the better option. However, when looking at the entire life cycle, the impact score now favours the electric car thanks to the much lower contribution of the use phase (Figure 5). When comparing the two cars over the whole life cycle, the hybrid LCA does not lead to a different conclusion than LCA.

7.2 Building case study

The pure EEIO analysis developed from the LCA model yielded higher scores in the range of 5 to 10% for the climate change, ozone layer depletion, mineral and fossil resources, terrestrial acidification and human toxicity indicators as compared to the LCA. The most significant increase occured for the particulate matter formation indicator (40% additional impact). However, for the aquatic eutrophication and ecotoxicity indicators, the scores were 20 to 60% lower. For all indicators, the use phase's scores are quite similar to those of the LCA since the LCA processes for electricity production and the direct emissions from wood pellet combustion for building heating were used in both analyses.

Figure 6 presents the scores after hybridization. The figures rose by 2 to 5%. However, the overall increase is lower than what the pure EEIO analysis seemed to indicate.

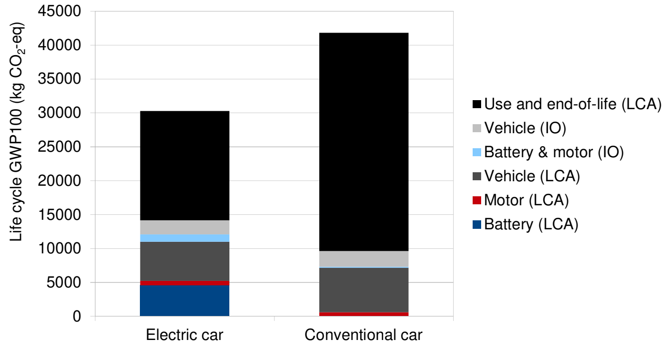

Figure 5: Life cycle comparison of the climate change impact score of an electric car and a conventional vehicle using hybrid analysis

Note: The use and end-of-life phases of the car (aggregated in black) were not hybridized.

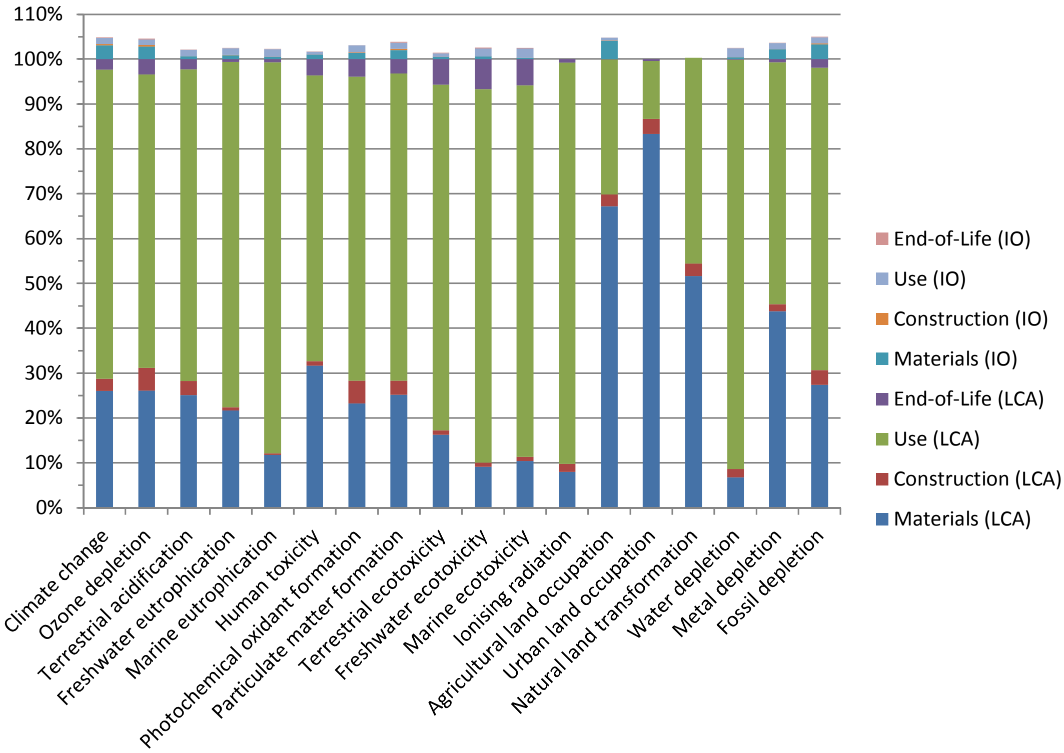

Figure 6: Contribution to the life cycle impacts of the building using hybrid analysis.

The scores are normalized on the contribution of LCA processes (LCA) to bring out the contribution of EEIO (IO) processes from hybridization.

Finally, EEIO has been used to improve the model by adding processes that were not considered in the initial LCA. These processes are modeled using pure EEIO processes (i.e. without hybridization) and expenses data collected during the study. Rather significant impacts are revealed: certain impacts increased by 11% (e.g. acidification, aquatic ecotoxicity), 17% (e.g. land use, climate change) and even 21% (e.g. water withdrawal).

8 Findings

8.1 EEIO analysis

The two case studies served to demonstrate that pure EEIO analysis is:

- a relatively **quick process**
    - that can still take significant time when the EEIO database is detailed (i.e. disaggregated, offering to the practitioner an extensive selection of products and sectors such as CEDA), and especially when the foreground system to be modelled is detailed.
- a useful tool to carry out a preliminary **assessment for contributions and hot spots** analysis
    - pertaining to materials and services
        - The higher the aggregation level of the EEIO tables, the more "average" will be the modelling for the material or the service. Multiregional tables offers less precision than the CEDA database.
    - **Confidence in indicators other than climate change and resources should be limited** because the EEIO tables do not provide comprehensive coverage of environmental flows (especially to toxicity-related substances). Practitioners must be aware of environmental issues that are not adequately covered when selecting a database and when interpreting the results.
- a tool that is:
    - not adapted to full life cycle studies when use and end-of-life phases require the addition of LCA processes.
    - **not accurate enough for comparative product studies**, especially when the products are similar or share numerous value chains.
    - **still useful to add specific services** that cannot be modeled in the foreground system because processes are not available in LCA databases or when data collection is not possible. However, it requires the collection of expenses data. Certain services may significantly impact the results, depending on the object analyzed (e.g. 10 to 20% increase in the building case study).

There is also a substantial gap between the EEIO tables in terms of sector/product disaggregation and environmental flow coverage. The initial selection of the EEIO database is therefore very important. If regionalization per country is not a criterion—unlike product, material and services details—then a national database such as CEDA is probably a better option.

8.2 Hybridization and its profitability

Compared to EEIO analysis, a hybrid analysis is a lengthy process. But it should be kept in mind that most of the burden of an EEIO analysis has to be assumed as well during the hybridization since it must involve 1) the scaling of the EEIO processes used in hybridization and 2) the gathering of price data and eventually other economic data related to price conversion. Both steps are required in an EEIO analysis. A hybrid analysis adds the hybridization step in which double counting must be managed.

The vehicle case study (partly automated analysis) required two days of work. The building case study was conducted manually using SimaPro and spreadsheets and took approximately four days. In both cases, an inexperienced analyst would probably take double the time.

The work required to carry out the hybridization for the building case study may seem to outweigh the benefits. When the correction for the double counting is partially automated (as was the case for the electric car case study using the pyLCAIO tool), the hybridization process becomes more accessible and the return on investment is proportionally more advantageous. The tools makes it possible to add several inputs that are difficult to inventory to the analysis in just a few hours, quickly solving the truncation issues, hence correcting for the underestimation of the impact. It also allows increasing the confidence in the comparative results of two products having several value chains in different economic sectors (e.g. battery and electric machinery manufacturing on one hand, and motor vehicle manufacturing on the other hand).

The full operational potential of hybrid LCA will only be reached when a whole LCA database (e.g. *ecoinvent* 3) is available in a hybridized version to correct the effect of the truncation of thousands of LCA unit processes.

8.3 Recommendations

Table 3 lists the main recommendations with regards to EEIO analysis and hybridization in an LCA study. They are related to each LCA phase and consider key points that must be considered when the study gets underway. The recommendation to work with basic prices reduces the sensitivity of the EEIO or hybrid model to price fluctuations over time. It also allows keeping the model usable with any updates of the EEIO tables, provided that the latter retain the same reference currency over time (e.g. €2007 for Exiobase).

Table 3: Recommendations for EEIO analysis and hybridization

Phase/criterion	Recommendation
When the study gets underway, at the Goal and Scope phase of an LCA	
Is an impact score for a specific product required?	If so, EEIO analysis alone is not sufficient
Is an estimate of a material's/service's contribution to the impact required?	Consider EEIO analysis *Price data collection and conversion may be labour intensive*
Is regionalization a criterion?	If so, use multiregional tables with an automation tool (pyLCAIO combined with pyMRIO)
Is it relevant to consider operations generally transacted as services in the foreground?	If so, include economic data collection for these services in the data collection process
Do the following products/concerns arise?	- Waste management/scenario analysis? - Biosourced products evaluation? The capacity to describe specific issues for these products/concerns varies significantly from one EEIO database to the next
Inventory	
If the mirror economy hypothesis is set out (EEIO table from another region)	Is the electricity grid mix of the other region acceptable? (or at least similar to that of the study region) If it is not, do not use an EEIO process (generally, *electrical power generation, transmission and distribution*) and select an LCA process instead (as was done here for the building case study) Determine whether recurrent operations within the economy may differ fromone region to the other (e.g. natural gas or heat supply)
Price data	Limit the number of price sources and prefer a single source of average basic prices. *Suggestion: ExioBase compilation (regional but low disaggregation)* Price conversion (buyer/producer/basic) *Suggestion: CREEA compilation (ExioBase and CREEA 2014)*
Impact assessment	
LCIA method	Ensure that the LCIA method and the inventory are consistent with respect to the names of the substances. In commercial software, LCIA methods are generally consistent with the *ecoinvent* database but not necessarily with the EEIO data (see below).
Tools	
SimaPro or other commercial LCA software	Advantages - Quickly validate the elementary inventory flows that are not characterized by the LCIA method - Rename series of elementary flows

	These advantages are relevant if the EEIO inventory database does not follow *ecoinvent* guidelines, which LCIA method developers generally follow (e.g. substance nomenclature) Drawbacks - Does not necessarily facilitate the import of EEIO databases by the users - Limited computing resources when the database is too large (e.g. the software cannot handle/support multiregional tables)
pyLCAIO	Advantages - Automation: eliminates repetitive steps and several sources of handling errors - Virtually unlimited database and table size - Hybridization process automatically documented in a log file for better transparency - Free, open source software Drawbacks - Minimal expertise required: it uses only a small number of commands but no graphic interface available yet - Does not include an harmonized library of LCIA methods matching current databases' nomenclatures

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