An Input-Output Virtual Laboratory in practice –
Survey of the uptake, usage and application of the first operational IELab

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Abstract

The Industrial Ecology Virtual Laboratory (IELab) is a recently established collaborative cloud-computing platform for compiling large-scale, high-resolution, enviro-socio-economic accounts based on multi-region input-output (MRIO) tables and for conducting integrated sustainability assessment projects. These include, for example, published triple bottom line assessments of biofuels, low-carbon construction materials or high-resolution waste modelling. This contribution provides a structured review of IELab applications that were published in either peer-reviewed journal papers or in the form of conference proceedings. The main research question posed is "What are the specific features of IELab that were used in the research and could the research have happened without them?" It is thus investigated whether the IELab has actually and truly enabled new research. A detailed analysis of IELab characteristics and their usage is presented. The results can help with the design of new research projects and inform existing and prospective users of the IELab about the options for academic research and practical applications.

Keywords

Industrial ecology, virtual laboratory, survey, input-output analysis, multi-region input-output tables

1. Introduction

Achieving long-term sustainability requires regional and industry specialisation strategies and the development of and investment in energy systems, cities and transport infrastructure with very low carbon emissions and resource requirements. These issues are at the heart of Industrial Ecology, a rapidly growing field that systematically examines local, regional and global materials and energy uses in products, processes, industrial sectors and economies. With the publication of a special section in *PNAS*, Industrial Ecology has become a mainstream academic discipline Weisz et al., 2015.

As the research questions and applications in Industrial Ecology increase, so do the requirements for data and for more sophisticated methods, models and tools to enable decision-making based on quantitative assessments (Pauliuk and Hertwich, 2016). This in turn necessitates advanced computing and software. Pauliuk et al., 2015 recently proposed general principles and practical guidelines for open software development and distribution in Industrial Ecology. The authors also presented open source code for several often-encountered data handling and modelling tasks.

Two major methods in Industrial Ecology research are becoming increasingly useful in enabling multidisciplinary studies on the human impact and dependency on the natural environment: multi-region input-output (MRIO) analysis and Hybrid LCA (HLCA). The need for improved MRIO and HLCA development, synthesis and utilisation has been repeatedly expressed at international workshops and conferences, in scientific articles and by international organisations such as the OECD, UNEP and Eurostat (Hellweg and Milà i Canals, 2014; OECD, 2015; Wiedmann and Barrett, 2013).

Global MRIO models have evolved rapidly in the last 5-10 years (Tukker and Dietzenbacher, 2013; Wiedmann et al., 2011) and have enabled significant novel insights and applications, published in top-ranking journals, e.g. on the international responsibility for greenhouse gas emissions (Davis et al., 2011; Kander et al., 2015; Peters et al., 2011; Steinberger et al., 2012) and nitrogen pollution (Oita et al., 2016), on the true extent of nations' resource use (Wiedmann et al., 2015b) or on the ultimate drivers of global biodiversity loss (Lenzen et al., 2012b). Duchin et al., 2015 and Duchin and Levine, 2015 showed how static MRIO analysis can be extended into a dynamic framework, based on world trade modelling, that enables the exploration of alternative scenarios about possible future developments. Another development has been the analysis of embodied environmental impacts at sub-national scale, as for example illustrated by Feng et al., 2013 for inter-provincial flows of embodied CO_2 emissions in China. Bachmann et al., 2014 demonstrated the benefits of using multi-scale MRIO models where sub-national regions of a country are nested in a global MRIO table to achieve a better representation of trade flows between regions and countries.

There is also the need to integrate data from other domains or disciplines as promoted by Heijungs et al., 2013 and Cucurachi et al., 2014 for the case of impacts assessment in LCA.

All of these developments require improved computational structure and capacity, data management and model integration. In 2012, a radically novel and highly automated approach to MRIO compilation was introduced by Lenzen et al., 2012a as part of the creation of the Eora global MRIO database. This concept of automated MRIO compilation was adopted and further developed in the Australian Industrial Ecology Virtual Laboratory (IELab, https://ielab.info) which is a collaborative, cloud-based e-research platform for compiling large-scale, high-resolution, enviro-socio-economic accounts and for conducting integrated sustainability assessment projects for a wide range of topics (Lenzen et al., 2014). IELab has (a) unprecedented detail (up to 1,284 sectors within 2,214 regions) to enable more in-depth HLCA, (b) a flexible MRIO table structure, tailored to suit specific research questions and (c) highly automated workflows, greatly expediting runtimes on an open-access platform.

The IElab has succeeded in bringing together a diverse set of sustainability researchers and practitioners, enabling tangible, inter-disciplinary research outputs. These include published triple bottom line assessments of industrial biofuel production and large-scale biorefining, analyses of low-carbon construction materials, electricity supply and cities and high-resolution waste modelling, amongst others (see Table 1). The IELab also provides a much-used basis for data and analysis in industry-relevant, cooperative research, including integrated sustainability assessments and tools for the construction and water industries.

Perhaps the most significant achievement of the IELab to date is the ability to continuously synthesise and make available information that captures the interconnections between nature, economy and society with a high degree of diversity. It does so in the form of extended multi-region input-output tables (MRIOTs). IELab made a leap in the automated compilation of notoriously scant, heterogeneous, disparate, misaligned and often incomplete datasets, overcoming the significant limitations of similar databases (Wiedmann et al., 2011). Thanks to the efficiency of automated data feeds written by users themselves and the collaborative nature of IELab, sustainability research can become more efficient, timely and effective, enabling many more research applications than were previously possible. The 'analytical toolbox' in IELab includes sustainability benchmarking, embodied impact (environmental footprint) calculation and supply-chain analysis, all significantly enhancing the capability for an integrated assessment of new technological, economic or social approaches.

But how useful actually is the IELab for Industrial Ecology research and applications in general? This is one of the questions investigated in this paper. More specifically, this

contribution aims to explore what the specific features of IELab are that were used in research and whether the research could have happened without these features. It is thus investigated whether the IELab has actually and truly enabled new research. The next section explains the method used and the publications that were investigated. This is followed by a presentation and discussion of the results (section 3) and an outline of the limitations of this study (section 4). Section 5 concludes and provides an outlook on future developments of the IELab.

2. Method and studies

The method used in this paper is a survey amongst authors of publications that describe research undertaken with the IELab as well as a review of these publications. Most of them are in the form of peer-reviewed journal papers, some in the form of conference papers. In total, 30 published case studies were investigated (Table 1), referred to as "studies" in the following.

Table 1: Published work based on using the IELab and its special features (in alphabetical order of reference)

Topic (publication title)	Reference	Special IELab features used
Updating the WIOD database in a collaborative virtual laboratory	Abd Rahman et al., 2016	detailed sectors, balancing, heat maps, diagnostics
Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input-output analysis	Chen et al.,	regionalisation, non-survey methods, balancing, heat maps, standard deviation tables, satellite data, footprint calculations
Transnational city carbon footprint networks – Exploring carbon links between Chinese and Australian cities	Chen et al., submitted-a	detailed sectors, regionalisation, non-survey methods, balancing, heat maps, satellite data, footprint calculations
City Carbon Footprint Networks	Chen et al., submitted-b	regionalisation, non-survey methods, balancing, heat maps, satellite data, footprint calculations
Carbon Footprinting the Gold Coast City consumption of goods and built environment products	Ely et al., 2015	regionalisation, non-survey methods, satellite data, footprint calculations
A new subnational MRIO table for Indonesia	Faturay et al., 2016	regionalisation, non-survey methods, balancing, heat maps, diagnostics, satellite data, footprint calculations
An Australian Multi-Regional Waste Supply-Use Framework	Fry et al., 2015	detailed sectors, hybridisation, regionalisation, balancing, heat maps, diagnostics, satellite data, footprint calculations
Constructing a time-series of physical input-output tables for Australia	Fry et al., submitted	detailed sectors, heat maps, satellite data
Investigating alternative approaches to harmonise multi-regional input-output data	Geschke et al., 2014	detailed sectors, balancing, heat maps, diagnostics

4

Topic (publication title)	Reference	Special IELab features used
A Supply-Use Approach to Waste Input-Output Analysis	Lenzen and Reynolds, 2014	detailed sectors, hybridisation, balancing, heat maps, diagnostics, satellite data, footprint calculations
The Global MRIO Lab – charting the world economy	Lenzen et al., 2016	detailed sectors, hybridisation, balancing, heat maps, diagnostics, satellite data, footprint calculations, structural path analysis
Simulating the impact of new industries on the economy: The case of biorefining in Australia	Malik et al., 2014	detailed sectors, hybridisation, balancing, heat maps, satellite data, footprint calculations
Hybrid life-cycle assessment of algal biofuel production	Malik et al., 2015	detailed sectors, hybridisation, regionalisation, non-survey methods, balancing, heat maps, satellite data, footprint calculations
Triple bottom line study of a lignocellulosic biofuel industry	Malik et al., 2016	detailed sectors, hybridisation, regionalisation, non-survey methods, balancing, heat maps, satellite data, footprint calculations
The carbon footprint of Australia's health care sector (title tbc)	Malik, 2016a	detailed sectors, hybridisation, non-survey methods, balancing, heat maps, satellite data, footprint calculations
Input-output analysis for island economies	Malik, 2016b	detailed sectors, hybridisation, regionalisation, non-survey methods, balancing, heat maps, satellite data, footprint calculations
The EXIOLab in action – how virtual laboratories can help make IO-based research more timely and topical	Reyes et al., 2016	detailed sectors, balancing, diagnostics, standard deviation tables, satellite data, footprint calculations
A Waste Supply-Use Analysis of Australian Waste Flows	Reynolds et al., 2014	detailed sectors, satellite data
Estimating industrial solid waste and municipal solid waste data at high resolution using economic accounts: an input–output approach with Australian case study	Reynolds et al., 2015a	detailed sectors, satellite data
Evaluation of the environmental impact of weekly food consumption in different socio-economic households in Australia using environmentally extended input–output analysis	Reynolds et al., 2015b	detailed sectors, satellite data, footprint calculations
A sub-national Economic Complexity analysis of Australia's states and territories	Reynolds et al., in preparation	detailed sectors, regionalisation, non-survey methods, balancing, standard deviation tables
Sleep	Reynolds, 2015	detailed sectors, satellite data, footprint calculations
Accounting for Transport Impacts on the Economy: An Integrated Computable General Equilibrium and Transport Model	Robson and Dixit, 2016	regionalisation, non-survey methods, balancing, satellite data
Hybrid input–output life cycle assessment of warm mix asphalt mixtures	Rodríguez-Alloza et al., 2015	detailed sectors, hybridisation, regionalisation, non-survey methods, balancing, heat maps, satellite data, footprint calculations
Integrated Carbon Metrics and Assessment for the Built Environment	Teh et al., 2015	detailed sectors, hybridisation, balancing, satellite data, footprint calculations
Construction of Multi-Regional Input–Output Tables Using the Charm Method	Többen and Kronenberg, 2015	regionalisation, non-survey methods, balancing, heat maps, diagnostics, satellite data

Topic (publication title)	Reference	Special IELab features used
Constructing a Time Series of Nested Multiregion Input–Output Tables	Wang et al., 2015	detailed sectors, balancing, heat maps, diagnostics, standard deviation tables, satellite data, footprint calculations
Multi-regional sub-national MRIOs for policy making in China: Using the Chinese MRIO Lab	Wang, 2016	detailed sectors, regionalisation, non-survey methods, heat maps, satellite data, footprint calculations
The Concept of City Carbon Maps: A Case Study of Melbourne, Australia	Wiedmann et al., 2015a	regionalisation, non-survey methods, balancing, heat maps, satellite data, footprint calculations
Carbon Footprint Scenarios for Renewable Electricity in Australia	Wolfram, 2015; Wolfram et al., 2016	detailed sectors, hybridisation, balancing, satellite data, footprint calculations

A questionnaire (see Supporting Information, SI) was sent to the first authors of all publications listed in Table 1. The response rate was 100%. Authors were asked about their usage of features that are typical for, and specific to, the IELab, namely (Lenzen et al., 2014):

Detailed sectors: the possibility to expand the number of sectors beyond that officially published by statistical offices (e.g. in Australia, the IELab allows disaggregating the 111 sectors published by the Australian Bureau of Statistics (ABS, 2015) to up to 1284 sectors, based on published detailed information on the use of products (ABS, 2012).

Hybridisation: the option to insert new columns and rows in MRIOTs with specific data derived from process or company information.

Regionalisation: the capability to create sub-national, fully populated multi-region input output tables (MRIOTs) or supply-and-use tables (MRSUTs)[1] for small-scale regions (e.g. with a population of about 10,000 people in the IELab-Aus; 2,240 regions in total). In Lenzen et al., 2014 tailored, sub-national MRIOTs were called "Mother Tables" that could be further modified to result in "Daugther Tables". The IELab community has since changed these expressions to the more neutral terms "Base Tables" and "Branch Tables" (see https://ielab.info).

Non-survey methods: the possibility to choose from a number of non-survey methods for regionalisation. Currently, eleven non-survey methods are offered in the IELab, including location quotient, cross-hauling and other methods (Lenzen et al., 2014, SI p.4).

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[1]   In the following, the umbrella term MRIOT is used when referring to either symmetric MRIOTs or MRSUTs.

Balancing: the option to re-balance MRIO Base Tables with constrained optimisation based on a RAS variant method.

Heat maps: also called topographical maps, show the absolute values of MRIOT elements in coloured shades according to a logarithmic scale (e.g. Lenzen et al., 2012a, Fig.3, p.8377). Heat maps can be used for a quick quality check after table balancing.

Diagnostics: a number of diagnostic tools has been implemented in the IELab based on statistics or visualisations that were originally developed for the Eora global MRIO database (Lenzen et al., 2013; Lenzen et al., 2012a). These diagnostics can be used to assess the performance of MRIOT optimisation and uncertainty of MRIOT elements. Four tools were investigated:

- *Size distributions* of constraints and MRIOT elements count the number of values by $\log_{10}$ section (Lenzen et al., 2013, Fig.12, p.38).

- *Optimiser performance histograms* show the frequency distribution of constraint adherences before and after optimisation (Lenzen et al., 2013, Fig.11, p.38).

- *Rocket graphs* show how well the final, optimised MRIOT satisfied all constraints set during its creation (e.g. Lenzen et al., 2012a, Fig.4, p.8378 or Lenzen et al., 2013, Fig.4, p.29).

- *Hillside graphs* plot the relative standard deviations (RSD) of MRIOT elements against the absolute value of the elements (Lenzen et al., 2013, Fig.6, p.32). As in rocket graphs, small elements have a relatively large uncertainty as they are less well constrained compared to larger transactions. In hillside graphs, RSD therefore rapidly becomes smaller for large MRIOT values and the graph takes the form of a hillside or hockey stick (which is why some authors refer to the graph as '*hockey graph*', e.g. Wang et al., 2015, Fig.3, p.15)

Standard deviation tables accompany each set of results in IELab, i.e. for each cell in an MRIO table there is a SD value.

Satellite data: any additional, non-IO data such as environmental (GHG emissions, energy, water, etc.), social data (labour, hours of sleep, etc.) or economic data (including those from the Value Added block of IO tables, such as wages/salaries, taxes etc.).

Footprint calculations: the possibility of calculating total (supply-chain) factor requirements for final demand.

Structural Path Analysis (SPA): the identification of significant individual paths showing the connection between the industry origin of a pressure/impact and the final demand destination where this pressure/impact becomes embodied in.

Finally, survey participants were asked whether they think their research could have happened without using any of the IELab features listed above.

3.   Results and Discussion

A wide range of research questions was addressed in the studies, including detailed carbon footprint analyses of Australian cities and their industries (Chen et al., ; Chen et al., submitted-a; Chen et al., submitted-b; Ely et al., 2015; Wiedmann et al., 2015a) or selected sectors such as electricity (Wolfram, 2015; Wolfram et al., 2016) and health care (Malik, 2016a); hybrid life cycle assessment of construction materials (Rodríguez-Alloza et al., 2015; Teh et al., 2015); sustainability assessments of biofuel industries (Malik et al., 2014; Malik et al., 2015; Malik et al., 2016); environmental impact assessment of household food consumption (Reynolds et al., 2015b); refining waste input-output calculations (Lenzen and Reynolds, 2014; Reynolds et al., 2015a) and analysis of embodied waste flows (Fry et al., 2015; Reynolds et al., 2014); constructing a time series of physical input-output tables (PIOTs) and analysing the flows of construction materials (Fry et al., submitted); strategic transport appraisals (Robson and Dixit, 2016); economic complexity analysis to assess competitiveness and innovation at the sub-national level (Reynolds et al., in preparation) and even investigating the economic cost of a good night's sleep (Reynolds, 2015). The last three application show that IELab is not only used for environmental input-output analysis but that economic and social research questions are also being addressed. Most studies focussed on applications in Australia, but the Australian IELab concept was also applied to global MRIO initiatives (Lenzen et al., 2016); used to optimise MRIO construction (Geschke et al., 2014) and non-survey methods (Többen and Kronenberg, 2015) and to construct and use MRIO tables for individual countries (Faturay et al., 2016; Malik, 2016b; Wang et al., 2015; Wang, 2016) or to replicate MRIO datasets (Abd Rahman et al., 2016; Reyes et al., 2016).

3.1.   Usage of IELab features

Results of the survey are depicted in Figure 1. The majority of the studies (23, 77%) used the more *detailed sectors* provided by IELab, i.e. information that is more disaggregated than the standard set of sectors in input-output tables routinely published by statistical offices. This turned out to be a very useful, if not essential feature, when research questions were aimed at particular products or processes, e.g. construction materials, biofuels or

waste treatment. The Chinese studies emphasised the usefulness of having tables with 135 sectors for regional research and policies. Reynolds et al., in preparation relied on the full disaggregation of the Australian economy to 1284 sectors as the key feature in their analysis of how economic complexity influences regional competitiveness and innovation.
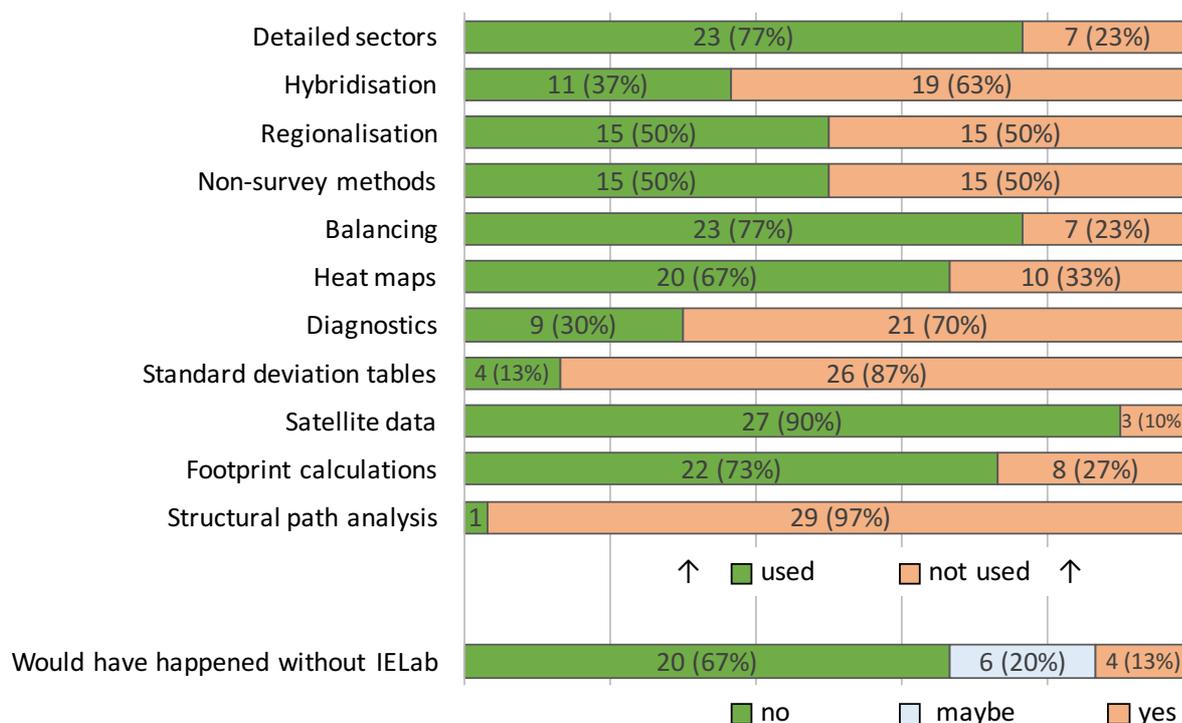
Feature	used	not used
Detailed sectors	23 (77%)	7 (23%)
Hybridisation	11 (37%)	19 (63%)
Regionalisation	15 (50%)	15 (50%)
Non-survey methods	15 (50%)	15 (50%)
Balancing	23 (77%)	7 (23%)
Heat maps	20 (67%)	10 (33%)
Diagnostics	9 (30%)	21 (70%)
Standard deviation tables	4 (13%)	26 (87%)
Satellite data	27 (90%)	3 (10%)
Footprint calculations	22 (73%)	8 (27%)
Structural path analysis	1	29 (97%)

	no	maybe	yes
Would have happened without IELab	20 (67%)	6 (20%)	4 (13%)

Figure 1: Usage of IELab features in published studies

Often, detailed sectors were either augmented or disaggregated even further by using non-IO data from life-cycle inventories or specific engineering processes. This *hybridisation* procedure was used in 11 of the 30 studies (37%), e.g. to distinguish 16 electricity sectors (from the original three) and nine types of concrete (from the original one) or to create new sectors that represent the production of biofuels from sugarcane, algae or forestry biomass; the production of warm-mix asphalt mixtures or activities of the health care sector. Malik, 2016b used hybridisation to augment Australia's input-output table with that of Norfolk Island's to analyse environmental impacts of small businesses on the island.

Using detailed sectors seemed to be more important for most research questions than the possibility of creating and using sub-national regions. Only half of the studies (15) made use of the *regionalisation* feature in IELab. This is slightly surprising since the prospect of enabling regional analyses with sub-national MRIOTs was one of the main reasons –

together with detailed sectoral analysis – to create the virtual laboratory in the first place (Lenzen et al., 2014). The studies that made extensive use of tailoring Base Tables were those exploring the carbon footprint of Australian cities. The Australian Government recently announced plans to expand its carbon neutral certification system – which so far recognises carbon neutral businesses, products, services and events – to also include cities, precincts and buildings (Department of the Environment, 2016). With Adelaide and Melbourne competing to be the first carbon neutral city in Australia, there is a need for a clear, comprehensive and consistent evaluation of all the direct and indirect greenhouse gas emissions that are associated with the activities of cities. Sub-national MRIO analysis with cities nested in other regions of the nation is particularly suited to respond to this demand since it allows for the unambiguous quantification of emissions embodied in imports and exports of cities.

Regionalisation was also used to create MRIOTs for Indonesian and Chinese provinces, counties and districts. Similar to Australia, these countries have very diverse and distinctly different regions, the analysis of which requires specific regional data in order to be relevant. The regionalisation of transport demand was the most important factor for the study by Robson and Dixit, 2016. These authors went to the extreme of reducing the numbers of sectors in the MRIOT down to two, in order to achieve the maximum number (249) of regions with a population of 10,000 people in the metropolitan area of Sydney. All sectors other than transport were aggregated into a single sector, such that there were two sectors: transport and all others. This was to enable fast running of the model for demonstration purposes. The studies on biofuels used regional input-output tables for the analysis because these regions offer ideal conditions for particular biofuels, namely Western Australia for the cultivation and growth of algae and South Australia for hardwood and softwood plantations.

Using sub-national regionalisation requires the use of a *non-survey methods* to disaggregate and distinguish sub-national regions in the MRSUT framework. IELab offers eleven different non-survey methods (Lenzen et al., 2014) of which the Adjusted Flegg's Location Quotient (AFLQ) method was the most used (in 13 of 15 studies that used regionalisation). Presumably, this is because AFLQ is the default method in the IELab user interface and researchers who have no particular preference for the regionalisation method are likely to just accept this default; however, this was not further investigated in this study. Faturay et al., 2016 used the simple location quotient (SLQ) method and Többen and Kronenberg, 2015 used the IELab for a generalisation and refinement of the cross-hauling adjusted regionalisation method (CHARM) to compile a MRIOT for Germany's federal states.

Once MRIOTs have been constructed with a specific number of sectors and regions, the IELab's reconciliation algorithm provides the option to *rebalance* the tables based on constrained optimisation (Lenzen et al., 2012a; Lenzen et al., 2013; Lenzen et al., 2014). Most studies (23, 77S%) made use of this feature which is essential to achieve consistency in the balance of monetary flows (e.g. for the calibration of computable general equilibrium models, as used by Robson and Dixit, 2016) and allocated environmental impacts in footprint calculations (e.g. without balancing, total global production-based and consumption-based impacts would not be the same). The studies by Reyes et al., 2016 and Abd Rahman et al., 2016 aim at replicating the multiple-step balancing procedures used for EXIOBASE and WIOD in the one-step procedure provided by the IELab.

The majority of studies (20, 67%) used *heat maps* to ascertain the general correctness of MRIOTs and satellite accounts; often this visual aid is also shown in publications to illustrate the structure and dimensions of the data. Wang et al., 2015, for example, use a heat map to show how Chinese provinces are embedded in the global Eora MRIOT, making it possible to discern trade of provinces with each other and with all countries in the world. Chen et al., and Wang, 2016 show the structure of city-level SUTs and how they link to other regions.

Only few studies however (9, 30%) made further use of *diagnostics* which illustrate quantitative information on uncertainty. The is likely due to the fact that diagnostic images only became available to IELab users later in 2015. Underlying the diagnostic tools are *standard deviation tables* (SD tables) that accompany each set of results in IELab, i.e. for each cell in a MRIOT a standard deviation value is provided, indicating the range of 68% of values in a normal distribution.

Few studies made active use of these tables, but for those that did the error data provided valuable information. Reynolds et al., in preparation used the SD tables for their economic complexity project to trace uncertainty in export data and investigate differences between IELab data and official statistics. Chen et al., and Wang et al., 2015 used SD data to show the uncertainty of the MRIOTs constructed in their studies. In the case of Wang et al., 2015 this was done by calculating the relative SD of Chinese MRIO data for each table element for three typical years that have different types of constraints.

Uncertainty information provided by the IELab also proved essential in replicating EXIOBASE in the study by Reyes et al., 2016. These authors mostly used the hockey-stick-shaped diagram provided as part of the diagnostics that plots the relative SD of MRIOT elements against their absolute value. The IELab uses the same compilation and error calculation routines as developed in the global MRIO project Eora (Lenzen et al., 2012a; Lenzen et al., 2013). SD information from the latter was essential to complete an error analysis for a recent global nitrogen footprint study published in *Nature Geoscience* (Oita et al., 2016),

although this study did not use the IELab directly and was therefore not included in the survey.

Satellite data were used by the vast majority of studies (27, 90%). In fact, research questions focussed on the analysis of satellite data. Twenty-two of the studies (73%) calculated *footprints* of satellite indicators, i.e. consumption-based accounts or supply chain data (cradle-to-shelf life-cycle inventory results) for environmental (GHG emissions, energy, waste), social (employment, sleep) or economic (value added components) impacts. In two cases the waste data from IELab was used to cross check own estimates by the authors (Reynolds et al., 2014; Reynolds et al., 2015a).

The main advantage seen in using satellite data was that IELab automatically provides a breakdown by root classification, i.e. satellite indicators are allocated pro-rata to industry size for all detailed sectors and regions. Such fine-scaled data is not available in any of the countries studied and turned out to be particularly useful for environmental footprint studies of cities or regions and specific technologies or products. As Wolfram et al., 2016 point out, in some cases a manual correction of the IELab default allocation might be necessary, as was done for the electricity transmission sector in that study. Fry et al., submitted used the waste satellite accounts from IELab in the construction of physical input-output tables (PIOTs). IELab was not used, however, to balance the tables. The EXIOBASE comparison study from Reyes et al., 2016 will utilise further satellite data from the CREEA project such as raw material extraction and volume of blue water used.

Footprint results can be broken down further by performing a *Structural Path Analysis (SPA)* that identifies the main supply chain routes that connect the origin of main impacts (e.g. the industry where GHG emissions are released) and the destination of final demand of a good or service. SPA as not generally available in IELab when the surveyed studies were carried out but the SPA code is part of the IELab Matlab script repository. Lenzen et al., 2016 have adopted and adapted the original architecture and workflow code of the Australian IELab in order to retain and make available all IELab features to the Global MRIO Lab.

With the IELab it is also possible to generate *time series* data by providing constraints with information that distinguishes a particular year from the base year for which the initial estimate is built. This feature, whilst implemented in the IELab, was not yet fully operational for Australia at the time of writing because data feeds for years other than the base year 2009 were not fully finalised yet. Some researchers, however, generated time series for other countries by completing the necessary data feeds such as Faturay et al., 2016 for Indonesia and Wang et al., 2015 for China.

3.2. IELab as a research enabler

The previous section highlighted the use of specific IELab features but the decisive question is whether the research could actually have happened without the IELab. Was the IELab just a convenient way of getting data quicker than otherwise or was it a true 'enabler' of novel research that would not have been possible without at least some of the features specific to the IElab?

Most respondents (20, 67%) answered this question with 'no' (the research would not have been possible). Especially where regional and sectoral detail was important, the IELab architecture and workflows enabled new applications. This is true for the carbon footprint studies of cities that relied fundamentally on the regionalisation to create city-level IO tables nested in regional counterparts (Chen et al., ; Chen et al., submitted-a; Chen et al., submitted-b; Ely et al., 2015) and for the economic complexity study by Reynolds et al., in preparation where the ability to harmonise various data sources, estimate data to a high resolution, and account for different regions were important parts to facilitate that analysis. Other regionalisation approaches exist and could have been used in principle (e.g. Jackson and Schwarm, 2011; Oosterhaven et al., 1986; Junius and Oosterhaven, 2003; Wenz et al., 2014), but implementing these approaches in practice would have been outside of the scope of work for most studies, in particular where researchers are not familiar with regional IOA and would have had to learn it as a new field of research first.

In the transport study (Robson and Dixit, 2016) IELab helped in providing a consistent method and data format for creating the IO tables used for the calibration of the integrated spatial computable general equilibrium (CGE) and transport model used. Without IELab, it would have been necessary to manually disaggregate the published national IO table using publically available economic data, which is not nearly as detailed as what is available through the IELab. However, post-processing of the data was still required to incorporate transport-specific data in the IELab.

Többen and Kronenberg, 2015 developed a new regionalisation method that was subsequently used to construct a subnational MRIOT for Germany. In his questionnaire reponse, J. Többen stated "In general, the compilation of a MRIO for Germany's federal states would have been possible without IELab […], but the compilation would have been much more costly. The main reason is that I used excessive amounts of additional data (in total about 15k data points, survey data on manufacturers and households) with a large number of information conflicts that would have required manual adjustments. Therefore, the use of [IELab] greatly decreased the costs of compilation." The German MRIOT was used to quantify the regional economic impacts of the 2013 flood in Germany (Schulte in den Bäumen et al., 2015).

For a larger number of sub-national regions as in the Indonesian (Faturay et al., 2016) or Chinese (Wang et al., 2015; Wang, 2016) studies or for the global MRIOT compilations (Abd Rahman et al., 2016; Reyes et al., 2016) a manual or less automated approach of regional and sectoral disaggregation compared to IELab is hardly imaginable. In order to create an MRIOT with the WIOD regional and sectoral structure plus some of Eora's countries plus some of EXIOBASE's sectors, employing a virtual lab with a one-step optimiser as used in Eora and a global root structure following the IELab's root-base-branch concept currently seems the only workable solution (Lenzen et al., 2016).

Studies that inserted new sectors and/or hybridised MRIOTs with additional data sometimes did so outside of the IELab's cloud environment (e.g. Teh et al., 2015 and Wolfram et al., 2016 exported Base Tables and tailored these further in Excel). All authors of hybridisation studies, however, stated that they would not have been able to construct the necessary sectoral and/or regional detail without the convenient function of the IELab. As was the case with regionalisation, the automated sector configuration within using IELab enabled Wolfram et al to finalise their carbon footprint scenarios of electricity supply as part of a Master's thesis within five months' time (Wolfram, 2015).

One third of respondents answered with 'yes' (4) or 'maybe' (6), i.e. their studies would have been possible without the IELab. In some cases, IELab simply accelerated research by providing data that would have been otherwise time consuming (but feasible) to compile (e.g. in Fry et al., 2015 and Lenzen and Reynolds, 2014) or IELab provided a convenient platform to integrate and test new root and data feed structures and MRIOT compilation techniques (Geschke et al., 2014; Lenzen et al., 2016).

The studies by Malik et al., 2014 and Reynolds et al., 2014; Reynolds et al., 2015a; Reynolds et al., 2015b used national tables and satellite data from the Eora database and only used certain functions or data from the IELab which where convenient but not necessarily essential, such as balancing, hybridisation, employment, value added and waste data. Reynolds et al., 2014 and Reynolds et al., 2015a used IELab waste to data cross check own estimations. Respondent Reynolds stated "This research [Reynolds, 2015] could have occurred [without the IELab], but it would have been much more intense data work to use just the Eora model. The IELab provided us with a level of confidence and controllability in this research." Finally, Fry et al., submitted constructed their PIOT time series outside of the IELab, but used the waste satellite accounts from IELab where the data is aligned and harmonised – something that is not the case with officially published waste data (at least not for Australia). The authors found the ability to align data using concordance tables a very useful feature of the IELab.

4.   Limitations of this study

A review like this is by definition a snapshot in time and it was not possible to capture current research that was not published at the time of writing. Some authors have published more than others on related or similar topics; therefore, some results might be biased towards the usage pattern of the most prolific authors. Yet, the total of 30 publications should provide a sufficiently diverse overview of IELab usage to draw general conclusions.

Some of the IELab features described in this review – such as footprint calculations, hybridisation and SPA – can currently only be performed by expert users. The implementation of these function in a web-based user interface that can be used by non-experts was ongoing at the time of writing. Expert users either used supplementary code on the research cloud or transferred Base Table data to a local workspace and performed the analysis offline. The usage of these specific features was therefore limited to experts with the appropriate knowledge.

5.   Conclusions and Outlook

Thirty published studies were investigated in this paper to shed light on the question whether the Industrial Ecology Virtual Laboratory provides elements that support or enable input-output-related research in a novel or even unique way. Two thirds (20) of the studies would not have been possible without the IELab and a further six would have required considerable extra resources to complete. The use of detailed sector information and the balancing function were the two most-used features of the IELab. Satellite data and footprint calculations were often used to address the specific research questions in the cohort of studies that was investigated. Perhaps surprisingly, only half of the studies made use of regionalisation (and underlying non-survey methods). Again, this was due to the particular research questions addressed. Only a few studies made use of uncertainty information and diagnostic tools; some authors might have been unaware of these features or didn't see the need to include error information in their publications. With a call to make such information in MRIO analysis more widely available (Wiedmann et al., 2011) and some high-profile journals requesting error estimates to be published, one should expect a higher use of uncertainty data in the future.

Some critical notes are in place. The IELab is currently still more a tool for experts and not fully developed yet for non-expert users. Whilst this does not diminish the potential usefulness for those who are willing and able to learn the exact workings of this e-research tool, it does severely restrict the number of potential users. Until the user-friendly interface

is fully developed that allows non-expert users with limited training to run analyses, the uptake of the the IELab will be limited. One example for an existing function of the interface is the possibility to select regions from a geographical map rather than having to create and use concordance matrices that aggregate all possible regions from the root classification into the ones used in an analysis.

Another potential barrier to a more widespread use to the IELab is its collaborative character. This idiosyncrasy was intentional and part of the framework's specific design from the beginning (Lenzen et al., 2014) but the last couple of years' experience has shown that data feeds are only written by researchers if they are either paid to do so or if they directly need the results for their own research and therefore have a benefit for their personal career. This is not surprising since the competitive character of research in modern times does not leave any place for altruistic motivations, but it also proved a problem for the further development of the IELab. In some rare cases, researchers did not fully complete data feeds that were initially assigned to them because they either underestimated the effort and simply ran out of funding or they moved on to other fields of research or roles in their lives. Luckily, these cases are the exception and continued funding enables the completion and further development of data feeds. But this shows that the unconventional setup of the IELab is as dependent on ongoing interest of researchers and funders as any other conventionally managed project. In that respect, the IELab is as much a social as a technical experiment.

There is an enormous potential for IELab to enable an even wider collaboration of diverse disciplines, to explore more complex sustainability issues and to provide improved outcomes for research, industry and governments. But this will not be possible without ongoing support and development. New project ideas and applications are increasingly being formulated by the IELab community, requiring more sophisticated analytical capabilities and tools. A new project funded by the Australian Research Council (ARC)[2] started in May 2016 to increase the processing capability of the IELab needed for large-scale modelling and optimisation analysis (as part the Global IELab development, Abd Rahman et al., 2016; Lenzen et al., 2016; Reyes et al., 2016) as well as to expand its functional capability. In detail, this will (i) boost the number of countries and hence improve the resolution of trade analyses, (ii) enhance the analytical toolbox for better product and process-level resolution and improved sustainability benchmarking, and (iii) integrate an econometric module that will allow scenario-based simulations of demographic changes and investment options. IELab developers hope that these major new elements will benefit

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research and applications in the areas of industrial ecology, regional economics, transition analysis, triple-bottom-line and sustainability assessments.

6. Acknowledgements

7. References

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Supporting Information

for

An Input-Output Virtual Laboratory in practice –
Survey of the uptake, usage and application of the first operational IELab

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Questionnaire on the usage of IELab

Sent out in March 2016

Please fill in the fields highlighted in blue; the more detail you can provide the better. "Usage of IELab" refers to using ANY feature of the IELab in the widest sense.

Details of the research in which you have used the IELab (topic, year, team etc.). Insert citation if publication exist.

What was the main research question you addressed in this research (one sentence)?

Which of the following features of the IELab did you use in our research and why?

Detailed sectors (i.e. any sectors BEYOND the standard number of sectors published by statistical offices; e.g. 111 sectors in Australia published by the ABS)

> yes/no

> Which type of sectors were of particular interest (particularly useful in the research)?

> Any other comments (e.g. did you aggregate sectors)?

Regionalisation, i.e. the ability to create sub-national, fully populated MRIOTs (e.g. in Australia for 2,240 regions with a population of about 10,000)

> yes/no

Which type of regions were of particular interest (particularly useful in the research)?

Any other comments?

Non-survey methods, i.e. the possibility to choose from a number of non-survey methods for regionalisation (currently about one dozen)

yes/no

Was any of the methods of particular interest (particularly useful in the research)?

Any other comments?

Balancing, i.e. the option to balance MRIO Base Tables

yes/no

Any other comments?

Satellite data, i.e. any additional, non-IO data such as environmental (GHG emissions, energy, water, etc.) or social data (labour, hours of sleep, etc.) or economic data (including those from the Value Added block of IO tables, such as wages/salaries, taxes etc.)

yes/no

Which data exactly did you use?

Any other comments?

Hybridisation, i.e. the option to insert new columns and rows in the MRIOTs (incl. MRSUTs) with specific data derived from process or company information

yes/no

Please describe briefly what exactly you did and what data you used

Any other comments?

Footprint calculations, i.e. the possibility of calculating total (supply-chain) factor requirements for final demand

yes/no

Please describe briefly what exactly you did and for which data you calculated footprints

Any other comments?

Structural Path Analysis (SPA), i.e. the identification of significant individual paths showing the connection between the industry origin of a pressure/impact and the final demand destination where this pressure/impact becomes embodied in.

yes/no

Please describe briefly what exactly you did and for which data you calculated paths

Any other comments?

Heat maps, diagnostic tools and standard deviation tables.

Please describe briefly what you used.

Any other feature?

Please describe any other function or feature of the IELab that you might have used but is not mentioned above.

Please answer the following question in any case:

Could this particular research have happened without using any of the IELab features (please explain why not if 'no' and why and how if 'yes')?

Thank you very much for your help!