Interactive visualization and industrial ecology: applications, challenges, and opportunities

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Summary

The emergence of increasingly complex data in industrial ecology (IE) has caused scholarly interest in interactive visualization (IV). IV allows users to interact with data, aiding in processing and interpreting complex datasets, processes, and simulations. Consequently, IV can help IE practitioners communicate the complexities of their methods and results, shed light on the underlying research assumptions, and enable more transparent monitoring of data quality and error. This can significantly increase the reach and impact of research, promote transparency, reproducibility, and open science, as well as improve the clarity and presentation of IE research. A review of current IV applications reveals that, while data exploration has received some attention among IE practitioners, IV applications in scientific communication are clearly lacking. With the help of a working example, we explore the value of IV, discuss its operationalization, and highlight challenges that the IE community must face during IV uptake. Such challenges include technical and knowledge limitations, limits on user interaction, and implementation strategies. With these challenges in mind, we outline key aspects needed to lift the IE field to the forefront of scientific communication in the coming years. Among these, we draft the basic principles of a "Hub for Interactive Visualization in Industrial Ecology" (HIVE), a point of encounter where IE practitioners could find an array of data visualization tools that are geared towards IE datasets. IV is here to stay, and its inceptive stage presents many opportunities to IE practitioners to shape its operationalization and benefit from early adoption.

<heading level 1> Introduction

Policy makers and the general public seek accurate quantitative information on the flows and stocks of materials and energy, supply chains, and their associated environmental impacts. Industrial ecology (IE) research on such topics, however, has traditionally struggled to be both noticed and understood due to, among other, open access, transparency, and reproducibility issues (Hertwich et al. 2018; Davis et al. 2010; Pauliuk et al. 2016). Moreover, while the complexity of environmental information has increased substantially over the last decade (Xu et al. 2015), the way scientific information is communicated in academic journals has remained relatively unchanged (Weissgerber et al. 2016). Despite many leading publications, including the Journal of Industrial Ecology, now publishing issues electronically, researchers seldom take advantage of the opportunities a digital platform can provide (Rogers 2016). One such opportunity is interactive visualization (IV), which enables readers to interact with visual representations of data (Zudilova-Seinstra et al. 2009). For instance, IV allows to compile custom-made cross-sections of complex datasets and display background information via web-based applications (see, e.g., Carbon footprint of nations (Hertwich and Peters 2009) [http://carbonfootprintofnations.com] and Environmental footprints (Stadler et al. 2015) [http://www.environmentalfootprints.org]). As such, IV can potentially help researchers communicate the complexities of their methods and results, shed light on the underlying research assumptions, and enable more transparent monitoring of data quality and error (Weissgerber et al. 2016; Perkel 2018).

New IE methods and tools generate more and more complex data, making IV an increasingly valuable tool to process such data. For example, recent advances in data compilation and modelling have produced large and complex datasets, containing country, product, and industryspecific data, that are difficult to understand without further data processing (Xu et al. 2015; Dijkema et al. 2015; Davis et al. 2010). Such complex data can aid IE practitioners in various ways: from facilitating virtual collaboration through internet-based platforms (Kraines et al. 2001; Cooper et al. 2013; Davis et al. 2010) to the development of more realistic models, for instance using user behavior data (Axtell et al. 2008). Similarly, the increased detail and scope of environmentally-extended input-output and life cycle assessment databases also challenge data exploration and coherent communication of results. Additional challenges for IE practitioners involve the increasing complexity of results from the application and developments on the topics of uncertainty (Heijungs and Huijbregts 2004) and scenario analysis (Pauliuk et al. 2017; Spielmann et al. 2005). In parallel, recent developments have made highly functional and easy-to-use IV tools readily available to researchers (Perkel 2018). Such advancements offer a unique opportunity to incorporate the use of IV into IE and improve data exploration, analysis, and communication of results. This forum article is addressed to all IE practitioners, irrespective of their knowledge and/or skills of IV and related fields such as computer science. We mainly aim to discuss on the value of using IV in IE research, leaving on a secondary level other aspects including recent developments in the IV field and the creation of IV content. We first describe IV principles and general applications (section *Main features and applications of interactive visualization*), followed by IE-specific current and potential applications (section *Current and potential interactive visualizations to illustrate society's metabolism*). Next, we outline future challenges in the IE field while providing some initial solutions (section *Challenges ahead*), including a dedicated web-based platform (section *Outlook: A Hub for Interactive Visualization in Industrial Ecology*), and section *Final remarks* concludes.

<heading level 1> Main features and applications of interactive visualization

The explosion of information technologies in the 1990s was accompanied by increasing amounts of data. To aid users in exploring and interpreting this data, the field of IV emerged with the basic idea of fully utilizing the human sensory system in processing and interpreting complex datasets, processes, and simulations (Keim 2001; Friendly 2008; Young et al. 2006). The IV process can be understood as a two-way communication between the user and the visualization system, where the user uses his/her interaction capabilities to interrogate and navigate through data (van Wijk 2005). Concretely, IV systems allow users to interact with information through the following functionalities (Zudilova-Seinstra et al. 2009):

- **Refine** visualization parameters/attributes such as shape, color, boundaries, and sample rate.
- **Interact** with the visualized objects through basic manipulation tasks such as selection, translation, rotation, scaling, aggregation, and follow a time path.
- **Filter** a dataset by extracting desired parts of information, for instance through probing localized visualization and measurement) and clipping (cutting away selected parts).

- **Transform** between multiple alternatives (e.g. changing underlying assumptions) and/or representations (e.g., from input-output matrix to a directed network or a geographic flow map) of a same dataset.

The value of IV has been extensively discussed (Kosara and Mackinlay 2013; Zudilova-Seinstra et al. 2009) and empirically demonstrated (Costanza et al. 2012; Rosling and Zhang 2011). It is argued that IV can strongly influence the users' perception and understanding of information, empowering them to discern relevant patterns in complex data, identify key points that require further analysis, and make sophisticated decisions (Zudilova-Seinstra et al. 2009). IV may also promote deeper comprehension of data and information, as the increased interaction and attention they command could enhance memory and long-term learning (Pike et al. 2009). In addition, IV could potentially make complex information more palatable to the general public, by making critical topics such as environmental footprints more engaging.

The operationalization of IV focuses on two key applications: data exploration and data communication (Heer et al. 2008). Data exploration via IV allows to inspect complex data in various ways. For instance, it allows for (1) sensitivity analysis, exploring the influence of various parameters, alone or in combination, on specific results, (2) contextualizing information, e.g. by focusing on the country, region or neighborhood where certain data (e.g. air pollution) is associated with, and (3) entering user's data and exploring its influence on an existing dataset. On the other hand, communication of results using IV has multiple purposes according to the target audience. For example, IV targeted to the general public can be used to support the storytelling when complex data is involved (Kosara and Mackinlay 2013), whereas targeting scientific audiences often involves more guidance and analysis to convey a specific finding.

While the basic ideas behind IV (refine, interact, filter, and transform) have remained relatively unchanged for more than 20 years (Friendly 2008; Young et al. 2006; Murray 2017), recent developments have spurred the use and diversity of IV applications (Perkel 2018). Such developments include those in computing power and graphics, data visualization software (e.g Tableau [https://www.tableau.com]), and visualization technologies (e.g. virtual reality), but especially those in web technologies, such as SVG, CSS, and HTML standards (e.g. scalable vector graphics support in HTML5) and dedicated libraries (e.g. D3.js). Web technologies and related IV applications have traditionally been developed and used by web developers and users with advanced knowledge/skills on programming, computer graphics, etc. In recent years, however, scientists have had increasing access to IV resources thanks to the growth in popularity of high-level programming languages, especially Python and R (Piatetsky 2017). High-level languages are easier to use since they have concise and expressive syntax and focus on readability by having a strong abstraction from computer language. Moreover, high-level languages allow users to use libraries of lower-level languages via so-called wrapper functions, namely routines used to call third-party functions for programming convenience. For example, a Python user with no knowledge of JavaScript can use D3, a powerful library dedicated to create IV in web browsers, via a wrapper function that translates rather intuitive commands into more complex language. Some popular wrapper functions can be found in the libraries ‘Bokeh’ (Python), ‘htmlwidgets’ (R), ‘pygal’ (Python), and ‘Shiny’ (R) (Perkel 2018).

Current applications of IV span from simple tools that allow users to manipulate basic graphical parameters to more complex multisensorial visualization systems (Zudilova-Seinstra et al. 2009). Basic interaction is commonly used in the fields of journalism and education, where users interact with large datasets through basic commands: selection, scaling, aggregation, filtering, etc. Examples worth highlighting are, among many other, the Washington Post's 'A world apart' (http://www.washingtonpost.com/sf/local/2013/11/09/washington-a-world-apart/), on income and education data by US zip code, and the 'Gapminder' on socio-economic statistics (https://www.gapminder.org/tools/). More advanced IV applications allow to utilize the full spectrum of the human sensory system, and include virtual reality (VR), multimodal visualization systems (MSS), and augmented reality (AR) (Zudilova-Seinstra et al. 2009). In the following section we describe current and potential applications specific to IE.

<heading level 1> Current and potential interactive visualizations to illustrate society's metabolism

<heading level 2> Current applications

Illustrating society's metabolism is an ambitious goal involving complex methods, multiple choices, and large databases. Early examples, such as the "Urban metabolism of Brussels" by Duvigneaud and Denaeyer-De Smet (1977), already showed the complexity of visualizing numerous material and energy flows and stocks of a given urban system. To aid in communicating and interpreting such complex results, IE practitioners and others have used various IV tools and platforms. A non-exhaustive overview of relevant IV applications in the IE and related fields can be found in table S1 in the supporting information. In the following we discuss these applications in terms of focus, technical characteristics, and functionality.

A main focus has been the visualization of regional environmental resource use and footprints, such as the Carbon footprint of nations (http://carbonfootprintofnations.com) and the CoolClimate Network (http://coolclimate.berkeley.edu/index). Another important focus has been on inter-regional economic and physical flows, such as the Zeean database (https://zeean.net/) and IEA Sankey diagrams (https://www.iea.org/sankey). All of these visualizations entail a sizeable amount of data and possibilities in terms of indicators, time and spatial scale, etc. Less explored areas of interest include visualizations of topic modelling (http://isdata-org.github.io/industrial-symbiosis-literature/topic-modelling-visualization/index.html) and co-occurrence analysis (http://isdata-org.github.io/mapping-the-bioeconomy/CoOccurrenceAnalysis/CircleCoOccurLayout.html).

Regarding the technical characteristics, IV applications are generally hosted in dedicated websites, and are rarely accompanied by a repository where the code and data are made available and/or discussed. The latter is key in the context of open and reproducible science, a topic we will discuss later on. The use of JavaScript is widespread as the core programming language, as it offers a flexible and widely-supported platform with multiple libraries available. JavaScript is sometimes used in combination with high-level programming languages, such as R, via 'wrapper functions', thus allowing non-advanced users to create and enrich IV.

The functionality of IV tools is generally rather basic, namely it does not require prior skills and/or knowledge to use them. Common IV functions are interaction by 'data on hover' (hovering over a point with a mouse), selection, and zoom, as well as filtering through drop-down menus. Valuable functions that are less widespread include those related to refining and transforming visual information. Refining functions can help to improve the visualization experience of users by customizing how the information is shown. For instance, hiding non-essential information can make graphs simpler and more concise, while changing the coloring can help users with vision deficiencies (Plaisant and Catherine 2004). Transformation between types of graphs may also be a valuable feature, as relevant patterns can emerge more easily. While the majority of applications focus on data exploration and analysis, few focus on scientific communication in peer-reviewed research. One of the few examples is given by Davis and colleagues (2017) while exploring automated data analysis approaches to explore potential waste pathways, and this work is complemented by IV tools based on topic modelling and co-occurrence analysis. These tools are available in a separate website and offer readers the opportunity to interact with the complete set of results.

<heading level 2> Potential applications

<heading level 3> Data exploration and analysis

A major challenge for IE practitioners is how to efficiently deal with increasingly large databases. Multi-regional input-output (MRIO) databases are being developed with an increasing level of spatial, temporal, and economic detail (e.g. Exiobase 3 and Eora), including sub-national data (Su et al. 2010; Lenzen et al. 2014) and product-level classifications (Tukker and Dietzenbacher 2013). Life cycle inventories (LCI) are similarly increasing in coverage. For instance, the widely used ecoinvent 3 database includes more than 14,000 unit processes, more than 4,000 environmental flows, 3 different system models, and more than 700 impact assessment indicators (Wernet et al. 2016). Furthermore, both MRIO and LCI databases have recently been used to assess local impacts at the basin, region, or grid level, thus generating localized data (Moran and Kanemoto 2016; Lenzen et al. 2013; Pfister et al. 2009). Other recent developments include global material flow databases (Lutter et al. 2014; Schandl et al. 2016, 2017), geodemographic and social media data (Hubacek et al. 2014), and travel data (Gonder et al. 2007).

In light of the multiple possibilities to explore and analyze these databases, in the following we identify some potentially valuable uses of IV:

- Matrix-based data (i.e. MRIO and LCA) can be transformed into multiple types of visualizations (heatmap, network graph, geographic map, etc.), each providing different insights into their structure. With the help of IV functions, such as zoom, coloring according to threshold values, and 'drag-and-drop', users can more easily identify 'impact hotspots' in supply chains, regions, etc.
- With the emergence of increasingly localized impact assessments, for instance through regionalized characterization factors (Verones et al. 2012) and scarcity-weighted footprints (Lenzen et al. 2013; Font Vivanco et al. 2017), quantifying impact results at the level of products, countries, etc. is becoming more and more complex. To aid in interpreting such results, IV can be used to visualize local data through interactive maps, for instance, regarding local scarcity indicators. Also, to explore results in light of the

multiple possible supply chain paths (e.g., competing suppliers), for example via ‘drag-and-drop’ type tools.

- Material and energy flow analyses are also becoming increasingly detailed, with data on new and more detailed material and energy flows, agents, etc. (Schmidt 2008). A way to better visualize such flows is by combining data-visualization techniques with Sankey diagrams, through so-called ‘hybrid Sankey diagrams’ (HSD) (Lupton and Allwood 2017). Adding interactive features to HSD presents multiple opportunities to explore its full potential (see, e.g., the ‘floweaver’ tool [https://github.com/ricklupton/floweaver]). Another application of IV is the visualization of the development of material stocks and flows over time with animated graphics.

The careful application of the above-mentioned IV techniques by study authors, consulting experts, and lay people can help to identify previously overlooked patterns in the results, sharpen the messages distilled from the research, and spawn new research questions.

<heading level 3> Scientific communication

A currently underused application of IV is to aid in the communication of results published in online scientific journals. While access to scientific publications increasingly relies on electronic devices, the interactive potential of these technologies remains largely unexplored (Weissgerber et al. 2016). A number of academic fields are already taking advantage of IV, such as Biology (e.g., interactive phylogenetic trees (Marinho et al. 2012)), Medicine (e.g., 3D neuroimaging visualizations (Papp et al. 2014)), and geosciences (e.g., interactive geospatial data (Podolak et al. 2017)). IV is also increasingly the focus of scientific publications, where IV tools are developed and described (see, e.g., (Price 2007; Carver et al. 2005)). Some publishers are starting to deploy some interactive features, showing that it is both technically possible and valuable to integrate IV in online journals. For instance, the publisher Elsevier recently launched a series of Interactive Data Viewers, including interactive viewers for plots and maps (Elsevier 2017). Similarly, F1000Research, an open-access publishing platform for life sciences and medicine research, offers the possibility to publish interactive figures in the online version of publications (Ingraham 2018). While the interactive features of these tools are still limited, these first steps are an opportunity for the IE community to actively contribute and shape the future of IV in scientific communication.

IV presents IE practitioners with great opportunities to (1) increase the reach and relevance of their work, (2) promote transparency, reproducibility and open science, (3) improve the clarity and presentation of their results, and (4) develop IV tools that are central in the presentation of results (Perkel 2018; Weissgerber et al. 2016; Talluri et al. 2017). With current IE-related databases, researchers can generate much more results than can be evaluated in scientific publication. This wealth of new information should be made available to both experts and the general public to (1) facilitate the dissemination of IE research, (2) allow people to connect their own research questions to the existing quantitative information, (3) put the available results and underlying data on display, (4) develop new research questions, and (5) contribute to the critical review of the information in the databases.

Using two working examples, following we highlight some valuable features that IV can bring to the communication of IE research. It merits noting that these examples are merely illustrative and, for the sake of simplicity, do not show the full capabilities of IV (see section *Challenges ahead* for a discussion on publishing complex IV figures). The examples are based on data from Fishman et al. (2014) on time series of materials trends that have multiple dimensions: three time series (inflows, outflows, and stocks), each with four material categories (timber, minerals, iron, and other metals) and two scenarios, all for two countries (Japan and the USA), amounting to 48 individual time series sets. The first example corresponds to material stocks in the USA and is shown in Figure 1 together with the original graph. The proposed IV can also be found on https://jsfiddle.net/cml_sidney_niccolson/w6qvqp1j/. In this example, we propose interactive features that include **data on hover** (yearly values are shown when hovering over the data points), **on-click data breakdown** (a breakdown of specific materials is shown when the user clicks on a given data point), and **variable selection** (it is possible to select/unselect the series that are shown in the graph). The latter feature allows to include a third scenario, not published in the original article, which is unselected by default yet the user can select it in the web version. This example contains the same information as a static graph, and can be readily used with minor changes in printed versions. For instance, additional instructions would support the interactive features in the graph legend or the graph title.

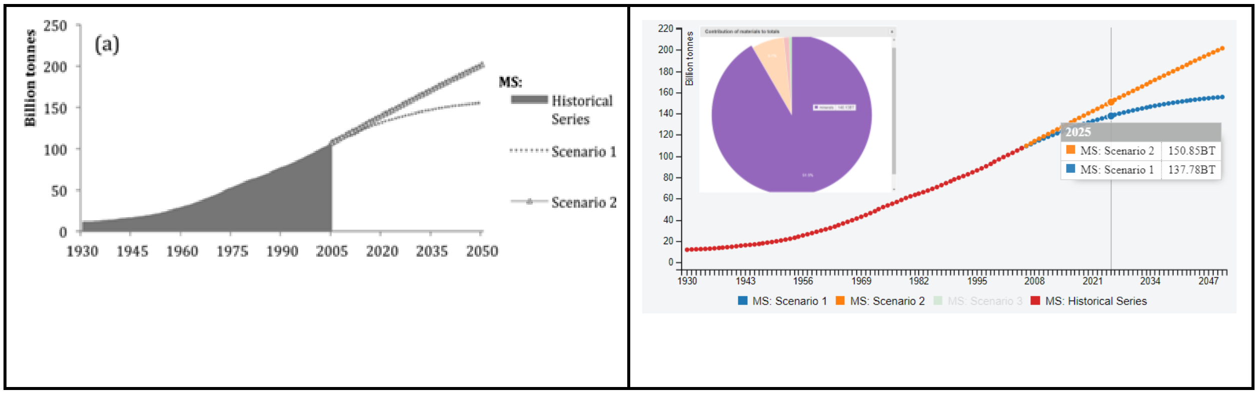

Figure 1. Original graph (left) and proposed interactive graph (right) based on the results by Fishman et al. (2014). The interactive graph can be found in https://jsfiddle.net/cml_sidney_niccolson/w6qvqp1j/.

Moreover, in socio-economic analysis, the absolute magnitudes of flows and stocks tell only parts of the story. The data in the original article was also analyzed as growth rates, per capita values, and per units of GDP to reveal their underlying aspects, culminating in a total of 192 sets. These sets were presented through 7 figures, many with multiple panels as the limits of monochrome prints at the time hindered the possibility of combining several of those figures. However, all these figures share the same horizontal axis (time), and many are numerical variants of the others. For example, sums of all materials or per-capita ratios, which change the vertical axis' units of measurements and scales. In a second example, shown in figure 2 and available in https://jsfiddle.net/cml_sidney_niccolson/gw0ddmop/, we propose to merge these figures into a single one while also making clearer the relationships between the data sets by allowing the reader to manipulate them on their own and watch the changes animate on-screen. The proposed IV is based on the original article's styles and present by default a combination of figures 2 and 3 in Fishman et al. (2014). Using a simple interface, the user can switch between countries, focus on specific materials, and change views from absolute numbers to any of the aforementioned variants. This new flexibility enabled to add a further variant (shares of the total) whose numbers were mentioned in the text but for which there was no room in the original article to visualize. In addition to the interactive features of the first example, this second one includes the option of **filtering** variables such as country and materials. The increased complexity of this second example, however, may present challenges of interpretation, as well as when presenting the results in the printed version (see section *Challenges ahead*).

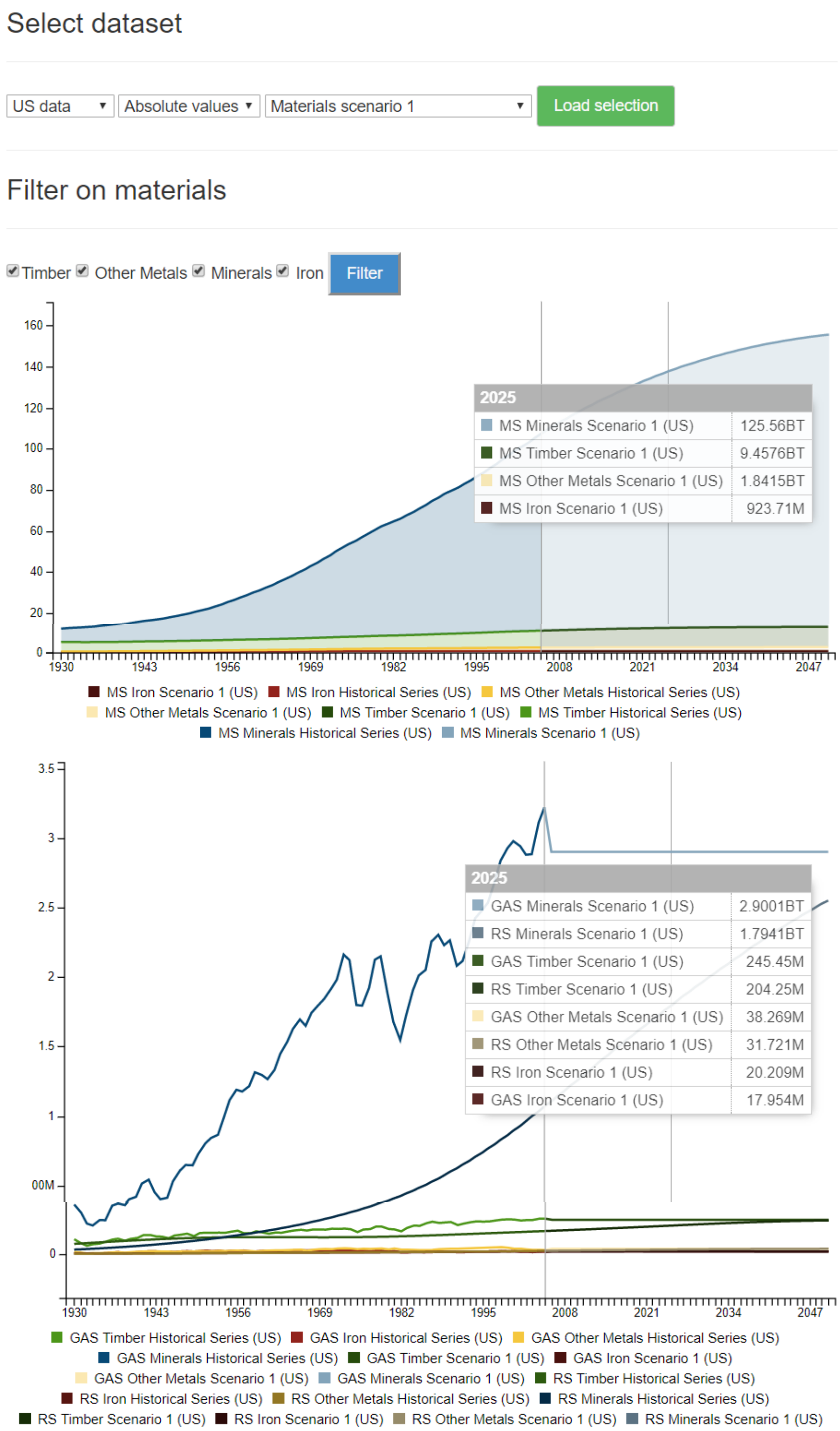

Figure 2. Proposed interactive graph based on the results by Fishman et al. (2014). The interactive graph can be found in https://jsfiddle.net/cml_sidney_niccolson/gw0ddmop/.

The proposed interactive features in both examples increase the transparency and clarity of the results, while at the same time improving the accessibility of information that would otherwise be placed elsewhere via additional graphs and/or supplementary materials. The proposed interactive features require no specific skills or knowledge to be used and can be considered not to interfere significantly with the user experience. More advanced solutions could, for instance, include the possibility to change the underlying assumptions behind the scenarios. Lastly, it is important to note that not only the results are more transparent, but the underlying Javascript and html code is also available in the provided web links, thus allowing full reproducibility.

<heading level 1> Challenges ahead

The introduction of IV in the IE field and in scientific communication in general will probably not be short of challenges and contention. While traditional data visualization enjoys basic guidelines (Kelleher and Wagener 2011; Rougier et al. 2014), similar guidance is missing for IV. Authors, users and journals will thus have to agree on basic aspects related, among other, to the technology, ethics, and licensing of data and IV applications. To help in guiding such a discussion, we outline below some key issues and offer some initial solutions.

- **How to encourage authors to create IV:** Creating IV to accompany a research publication requires additional time and often specialist knowledge, while the benefit may not be imminent. There are a large number of tools and software packages available to generate IV and developing IV often requires certain coding experience. The large variety of tools can be daunting, as it also carries a risk of choosing a technology or platform that may soon become obsolete. It is also difficult to know which software is most suitable, and it takes time to learn how to use these tools. Moreover, in the scenario that IV becomes popular in online scientific publications, there is a risk that an increasing number of basic users may need to resort to visualization software and services. While there are many of such services offering powerful features for free (e.g. Google Fusion Tables (Gonzalez et al. 2010) and Tableau Public), some others require a fee for the full range of features, even for non-commercial uses. Financial and knowledge limitations could thus put some users at a disadvantage. A key aspect to minimize this hypothetical disadvantage is to provide easy-to-use tools (see, e.g., Elsevier (2017)) as well as publishing advice to authors, including a list of resources available (Machlis 2017) and tutorials. Unexperienced users are encouraged to resort to high-level programming languages and wrapping functions, as these use more natural language and are easier to understand. Tutorials for both general and IV programming for Python and R can be found in Codeburst (https://codeburst.io/), Dataquest (https://www.dataquest.io/blog/), and Enhance Data Science (http://enhancedatascience.com/), among many other sites.

- **Balancing user freedom with the desire to communicate clear messages:** IV allows to create “maps” of complex datasets where the user can explore through the nuances of the data. One could argue, however, that such freedom conflicts with sending clear messages to readers. Indeed, scientific communication involves summarizing insights and condensing information and observations. In this sense, too many ways to manipulate a given graph can conflict with effectively communicating a clear message (Rougier et al. 2014). Following our examples in the subsection *Scientific communication*, we can observe that the first example conveys a clear message, while the second one gives the user much more freedom to explore the data and draw own conclusions. While such freedom can be desirable to explore a given dataset, it can lead to confusion when communicating results as too many trends may be observed. Other examples include the possibility to hide objects, change thresholds and the sample size, weightings, and graph transformations. While a general 'less is more' rule seems appropriate when communicating through IV, more specific guidelines need to be agreed upon between authors, users, and journals. In the meantime, the traditional solution of placing distilled results in the manuscript and more complex results in the supporting information is still valid for IV. Therefore, 'bounded' IV, with limited functionalities, and 'unbounded' IV, where users have more freedom to explore the whole set of results, can be placed, respectively, in the manuscript and supporting information.

- **Dividing responsibilities between authors and journals:** The implementation of IV in online journals could follow two different, albeit not necessarily conflicting, strategies. Author-level solutions would allow authors to include IV files as supplementary data, links to external repositories, etc., and even make specific IV tools the focus of publication. Journal-level solutions would allow journals to include IV in the web versions of published articles (Weissgerber et al. 2016). The first solution involves little to no changes for both publishers and readers, as IV files could be accessed and executed through web browsers (e.g. downloadable or online html files) and are supplemental rather than part of the article itself. A potential challenge would be, in cases where IV is presented as supporting information, whether reviewers have the expertise/skills to fully review the underlying data. Moreover, y not being an integral part of the article and/or easily reproducible, there is the risk that many users would choose not to access such supplemental IV files. There are tools to ease peer review and reproducibility, such as notebooks (documents that combine text, code, and data) that can be readily executed and viewed on any computer in a reproducible manner (Shen 2014). Popular notebooks include Jupyter for Python (https://jupyter.org) and R Notebooks for R (https://rmarkdown.rstudio.com/r_notebooks.html). Some examples are Jupyter-based IV tools for astronomical catalogs (Yu et al. 2017) and geospatial data analysis (De Marchi et al. 2017), among many other (see https://github.com/jupyter/jupyter/wiki/A-gallery-of-interesting-Jupyter-Notebooks).

Integrating IV files in the online article might entice more users to make use of such files, but in turn involves changes in authoring tools, editorial workflows, and infrastructure (Perkel 2018). For example, publishers would need to make sure their web-based authoring tools allow to embed and execute IV scripts (e.g. JavaScript) and adapt editorial tasks: content request, proofread and review, maintenance, etc. Moreover, it might be difficult to break users' habits of dealing with static graphs. Such changes can be easier to implement in online-only journals, which have strikingly increased in recent years. Nonetheless, it is evident from current publishers' experience that integration of IV in online journals, while still limited, is both technically possible and valuable (Perkel 2018). This experience also shows that a compromise solution between both approaches could be to let the users choose between static and interactive graphs, provided that the later does not convey key messages but rather additional insights (e.g. point values) or increased clarity (e.g. hidden objects).

- **Ensuring the access and permanence of IV data on the web:** It is important to ensure that IV resources (hyperlinks, data, code, etc.) will not only be easily accessible, but also available long-term. Long-term data hosting is an issue that is increasingly approached in the context of big data (Lynch 2008). In cases where IV figures are part of journal publications, either in the manuscript or as supporting information, the publisher should be responsible to ensure their access and permanence. Ensuring access and permanence is straightforward when the publisher is the sole responsible for the necessary infrastructure, as is the case of Elsevier (2017), but less so in cases where publishers rely on third-party companies, such as F1000Research partnering with Plotly (Ingraham 2018). In cases where IV figures are hosted in third-party repositories, there are multiple open-source solutions (Perkel 2018), for example open-source repositories such as GitHub (https://github.com). These open source platforms might offer some degree of longevity when it comes to code availability, but it must be acknowledged that they generally do not have the permanence of record that publishers provide. To further facilitate reproducibility and ease of use, there are open-source tools, such as Binder (https://mybinder.org), that can turn repositories of notebooks into a live interactive environment that users can run from their own browsers.

- **Ensuring data rights and cybersecurity:** Risks related to data copyright and computer security are not exclusively associated with IV, but its naïve or malicious application can increase such risks for both readers and publishers. Regarding data rights, authors should be careful not to publish sensitive proprietary data in front-end visualizations as well as prevent users the access to background data. It is the responsibility of authors to check the terms of service and/or privacy policies of third-party content hosting services to comply with data copyrights. In cases where IV is hosted directly by the journal publisher, the publisher should make sure that the author is aware of any potential copyright issues. Regarding cybersecurity, IV are generally produced by executing code (e.g. JavaScript), and so malicious code could be interweaved to cause undesired effects, security breaches and/or system damage to both users and publishers. Users are encouraged to treat IV resources (applications, scripts, etc.) as any other potentially harmful executable file or script and have standard protection to web application vulnerabilities (e.g. computer antivirus software). Publishers hosting IV content are encouraged to develop and apply specific security guidelines to find security flaws, such as source code analysis tools, to avoid endangering users.

<heading level 1> Outlook: A Hub for Interactive Visualization in Industrial Ecology

In addition to acknowledging the benefits and challenges of IV, we also want to look towards specific steps that could be taken within the IE community to encourage uptake of IV in this field. Accordingly, we suggest designing and creating a "Hub for Interactive Visualization in Industrial Ecology" (HIVE) as a point of encounter where IE practitioners can find an array of data visualization tools that are geared towards IE datasets. The proposed HIVE distinguishes itself from other initiatives that are geared towards general IE resources, such as the Industrial Ecology Dashboard (https://github.com/IndEcol/Dashboard), as well as platform-based tutorials (e.g., D3 [https://d3js.org/]) and profit-based initiatives (e.g. Plotly [https://plot.ly/]). The Supplementary Information (Figures S2, S3 and S4) provides sample screenshots of what the HIVE interface could look like. This hub could provide own and third-party easy-to-use front-end interfaces that take away the need for researchers to know how to code, while at the same time allowing IV tools and applications to be hosted within the same platform and linked from academic research and popular media alike. For example, while there are online generic 'IV makers' where users are only required to import data files, such as the Plotly Graph Maker (https://plot.ly/create/), IE practitioners may require additional chart types, functionalities, etc. not readily available (e.g. Sankey diagrams allowing circular links). This issue has driven other disciplines to create specific web-based IV creation tools, for example for time-geography research (Kim et al. 2017), molecular interaction maps (Dorel et al. 2017), and topological analysis (Theodosiou et al. 2017). To fulfill similar needs in IE, the proposed HIVE could function as a platform to foster the creation of IE-geared tools. The mission of this initiative is to strengthen uptake of IV in IE, to provide standardized tools, and to encourage IV innovation in our field.

We envision the development of HIVE to be guided by the following principles:

- **Ease of use**: the system is geared towards users with little to no coding experience and should allow them to upload spreadsheets or link datasets and develop an IV with great ease.
- **Education and outreach-oriented**: IV tools offer a platform to learn basic concepts of computer science, such as computer programming and human-computer interaction. In particular, a core aim should be to help people understand how to make their data machine-readable for IV tools through both original content and third-party web resources.

- **Flexibility**: researchers that do have the skills to modify code should be able to clone the IV tools without any restrictions and change them as they see fit.
- **IE-specific**: the tools developed should address specific data visualization needs that have emerged in the field of IE.
- **Open access, open source**: all software should be provided under a permissive, open source license. Access to the IV should not be restricted.
- **Community contributions**: the initiative should be open to contributions to IV software adjustments by community members and actively pursue constant feedback from its users.
- **Integrated with the Open Data initiative**: an institutional link should exist with the Open Data initiative (Hertwich et al. 2018), to strive towards common guidelines and where possible compatible protocols around IV.
- **Long-term availability**: journals provide a long-term historic academic records whereas websites come and go. The hub should provide an intermediate solution, acknowledging that maintaining old software is difficult but providing long-term storage solutions in internet time (e.g. 10 years).

Despite its potential, we acknowledge that there are various hurdles to overcome. Some of the principal challenges include the following:

- **Organizational responsibility**. What entity should be behind this initiative? Should it be a consortium of university departments? Is this a role for the International Society for Industrial Ecology? How independent should this initiative be? Should this become community-driven and/or integrated in community-based repositories such as the IE Dashboard?

- **Funding**. Funding will be required to kickstart this initiative. Work needs to be done on taking existing IV tools, tailoring them to IE, and to make user-friendly front-ends. In addition to this initial work, hosting and maintenance expenses will be incurred.
- **Roll-out**. Within the field of IE, the needs for and availability of IV tools varies strongly. More work is done and available within some sub-fields. How should this initiative divide its resources? What is the best way to ensure that this meets the needs of researchers? How should these tools interact with existing software and projects? These are key issues to ensure a successful roll-out.
- **User acceptance and persistence**. HIVE needs to attract a critical mass of data and users to become successful. Users need to see a clear benefit of using HIVE and supplying data to it. The software solution needs to be persistent so that continuous operation can be ensured as IV software solutions evolve.

<heading level 1> Final remarks

In light of the increasing complexity of data, IV can significantly increase the reach and relevance of research, promote transparency, reproducibility and open science, and improve the clarity and presentation of IE research. Yet unlike other research fields, and despite of the wealth of quantitative results that are generated, IV has received little attention within the IE community. A review of current applications reveals that, while data exploration has received some attention among IE practitioners, IV applications in scientific communication are clearly lacking. Other fields are ahead in terms of adoption, and some publishers are starting to integrate IV tools in online journals. What is thus needed to lift the IE field to the forefront of scientific communication in the coming years? Following we highlight some key points to answer this question.

First and foremost, it merits noting that there is no need to ‘reinvent the wheel’, as there is a vast pool of resources and knowledge available that can be readily harnessed. This includes the experience of current applications in IE research (see section *State of play*) and other fields as well as journal solutions such as online data visualization tools. Such ‘knowledge transfer’ can be sped up with a better interaction with other disciplines with larger IV uptake, for example via interdisciplinary projects and publications, participation in scientific conferences, etc. Publishers can also foster IV uptake by providing incentives to authors. For example, the publishing platform F1000Research reduces open access charges for articles containing IV (Ingraham 2018). From a normative perspective, dialogue and agreements on IV standards for data exploration and communication are needed to ensure that IV uptake is in accordance with transparent, reproducible and open science. From a technical point of view, we need to explore innovative ways in which IV technology can aid in transforming complex sustainability issues into situations that can be explicitly comprehended in words or the so-called “sensemaking process” (Weick et al. 2005). This includes identifying how IV technology can be applied in the various stages of intelligence analysis, or how to process information: from data gathering to scientific communication (Pirolli and Card 2005). Technical solutions should also facilitate the access to the data underlying IV, including users own tools, to avoid “captive user interface[s]” (Gancarz 2003). Lastly, the use of IV has the potential to enhance the transdisciplinary nature of

IE (Ehrenfield 2000) given that it can engage a wide range of stakeholders, thus increasing the relevance and reach of IE research. For example, more transparent results allow researchers from other disciplines, as well as journalists to understand the underlying assumptions and check for errors. In addition, intuitive and flexible IV tools can make topics such as environmental footprints and social metabolism more attractive to policymakers and the general public.

While there's no telling what the future holds in terms of IV technology and uptake, we boldly envision some valuable applications in IE. For example, the use VR technology in poster and oral presentations to better visualize complex data (e.g. material/energy flows and supply chains) and the use of 3D environments to better understand industrial processes in IE education (NMC 2017). Lastly, it is our belief that the proposed HIVE could promote the uptake of IV in our field and start a conversation about its challenges and opportunities. We do not consider the outlined proposal to be a definitive solution, but rather aim for these concepts to be used as a starting point for discussion. In any case, we encourage IE practitioners to explore how IV can have an impact in their research and its communication as well as share their findings and expertise in the context of a sound, transparent, reproducible, and open science.

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