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METHODS, TOOLS, AND SOFTWARE

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Modeling the circular economy in environmentally extended input–output

A web application

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Abstract

Global environmental and resource problems ask for new ways of managing the production and consumption of resources. The implementation of new paradigms, such as the circular economy, requires decision-makers at multiple levels to make complex decisions. For this, clear analyses and modeling of scenarios are of utmost importance. Meanwhile, as the sophistication of databases and models increases so does the need for user-friendly tools to use them. The RaMa-Scene web platform reduces these barriers by allowing users to visualize easily diverse impacts of implementing circular-economy interventions. This online web platform makes use of the multi-regional environmentally extended input–output database EXIOBASE version 3 in monetary units, which has been modified to show explicit transactions of raw materials from recycling activities.

KEYWORDS
circular economy, ecological economics, environmental input–output analysis (EEIOA), industrial ecology, internet-based modeling, scenario analysis

1 | INTRODUCTION

Environmental, economic, and social global implications of a transition to a circular economy (CE) remain to this day difficult to assess. Although scientists and practitioners have studied the benefits and drawbacks of scenarios of changes implementing CE strategies, results give conflicting information (McCarthy, Dellink, & Bibas, 2018 and the references therein; Donati et al., 2020 and the references therein). More research is needed to support decision-makers with robust advice (McCarthy et al., 2018). There are challenges in the incorporation of environmental impact assessment tools into decision-making (Jay, Jones, Slinn, & Wood, 2007), in the participation of stakeholders in environmental modeling (Voinov et al., 2016), in the sharing and handling of multi-disciplinary data (Davis, Nikolic, & Dijkema, 2010), and in the replicability of outputs (González, Gleeson, & McCarthy, 2019). These challenges and the lack of availability of user-friendly tools for the creation of global scenarios hinder the objective of providing clear and robust guidance on CE strategies.

Economists and environmental scientists have tried to overcome these barriers by developing tools for the analysis of the impact of policy interventions and technological changes. In particular, native (i.e., to be used on specific systems) and web-based tools for macro-level environmental impact assessment have been developed. As we will discuss later in this article, at this point in time none of these tools are well suited to assess environmental and economic implications of CE interventions.

Therefore, in order to support easy access to economic and environmental information and to reduce barriers for scenario creation, we developed a web-based application, *RaMa-Scene* (RAw MAterials SCENario Efficiency improvement assessment tool). RaMa-Scene combines strengths of previous platforms and provides additional features for analyzing and modeling scenarios in the monetary multi-regional environmental extended input–output (mrEEIO) database EXIOBASE.

The web platform is accessible by visiting www.ramascene.eu while its source code is stored in a permanent repository on *Zenodo* (Donati et al., 2020).

In the following sections, we describe the requirements we defined for such a web tool in relation to what existing platforms offer (Section 2); how the data, methods, and interface of the RaMa-Scene platform was constructed (Section 3); use cases to illustrate the use of the platform (Section 4); discussion and conclusions (Section 5).

2 | REQUIREMENTS, REVIEW OF EXISTING SOFTWARE, AND DESIGN CHOICES FOR RaMa-SCENE

The development of the software started with an inventory of requirements. A consultation with potential users highlighted the following as essential:

1. Ease of access and use were important factors for the facilitation of CE insights creation by multiple types of users;
2. The possibility for user modification of input data to see the effects CE interventions;
3. The ability to intervene also in secondary raw materials supply chains together with a high sectoral resolution, since CE focuses strongly on resource management;
4. Comparability of the current economic status to possible scenarios, as the CE is composed of multiple strategies and interventions (Donati et al., 2020).

To avoid repeating work, we initially screened a number of web-based and native software against these criteria (see Section 2.1). From there, we made decisions about the design strategy for the RaMa-Scene platform (see Section 2.2)

2.1 | Review of existing software

Our software review was created by online search and inputs from potential users. We investigated a variety of tools used in four main interest areas in the industrial ecology community, namely life-cycle assessment, material flow analysis, environmentally extended input–output analysis and, more generally, sustainability assessment tools. Additionally, under indication of users we added tools which they considered noteworthy. In this phase, we identified 27 applications (see Supporting Information S1). Of these 27 applications, 9 provided scenario creation features of which 6 included macro or structural economic data at the global level. The rest of the software had specific focus (e.g., construction or aviation sector), or did not provide the possibility to create global and national scenarios (e.g., trade data visualizers), or required users to provide product level information (e.g., life-cycle assessment tools). The following review describes six applications (web links available in Supporting Information, except EUREAPA), which could provide analysis of global economic data and environmental impacts, and features to create scenarios. The analysis focuses on the aforementioned criteria of availability of materials from secondary sources in the database, scenario-modeling features, accessibility, and user-friendliness.

Nazara et al. (2004) created a free and open-source python-2-based software named REAL pyIO. The software has multiple functionalities allowing users to analyze in depth IO data using advanced methods including the Ghosh model (Ghosh, 1958) and the RAS method (Stone, 1962, p. 227) which is used for balancing and projecting IO tables. Users can visualize and modify the IO database of their choosing provided that it can be copied into the software integrated spreadsheet. The software does not offer data visualization features and it is aimed at a specialized audience.

Carnegie Mellon's EIO-LCA (GDI, 2008) is a free and open-source web platform that can be used to analyze policy impacts using USA and international input–output (IO) datasets up to 2007. The tool allows for the estimation of environmental impacts and energy for national economies through a simple yet intuitive interface. The tool allows creating scenarios by editing both final demand and industrial transactions. Scenarios are obtained by defining a production recipe for a new product or modifying a pre-existing one. Users are presented with a list of all the inputs that can be modified in absolute terms and they can then visualize results by means of simple pie-charts.

EUREAPA (Roelich, Owen, Thompson, Dawkins, & West, 2014) was a free-access web tool employing IO data based on GTAP7 (McDougall & Golub, 2007) which is no longer accessible. It allowed for the analysis of pre-calculated future scenarios in the context of dietary, transport, and energy policies; affluence; and population changes. The different scenarios were created with the support of specialists. Thus, users had control over the intensity of a policy intervention based on expert information. It presented a simple and intuitive interface in which drop down menus allowed users to make selections of different elements for analysis to be displayed on a bar graph.

pyMRIO is a python package that allows using most available multi-regional EEIO databases to perform various types of IO analyses, including scenario building and visualizations (Stadler, 2018). Functionalities include aggregation, extension restructuring, and footprint analysis.

Pycirk (Donati, 2019, Donati et al., 2020) is a free and open-source python-3 package for the analysis and modeling of the mrEEIO database EXIOBASE after transformation from multi-regional environmentally extended supply-use tables (mrEESUTs). The package allows for creating scenarios by modifying values in any table in the database, including secondary raw materials transactions. Additionally, it allows for extensive selection of analytical parameters (e.g., extensions) for the result output. Thanks to a standardized format, scenario settings and results can be easily saved and replicated. Although without visualization features, users can easily compare different results by operating the software through a command line. Pycirk is aimed at mrEEIO practitioners with programming experience.

IOsnap (Jackson & Court, 2019) is a Windows-native commercial software for the analysis and modeling of USA IO data. The software interface allows the user to analyze economic impacts at different regional levels. Scenarios are created by absolute changes in the final demand of 11 available sectors. The software presents a simple interface aimed at a specialized audience.

IMPLAN (IMPLAN, 2018) is a widely used commercial web-based tool for the analysis of IO data. The tool has an advanced, however, simple interface for the analysis of economic impacts at the level of 400 sectors in the United States. The data is highly disaggregated at the regional level. The tool has functionalities for scenario making at both final demand and industrial level (i.e., production recipe), integrating also indirect impact assessment capabilities.

None of the tools offered a free and open-source online option for the analysis of the impacts of CE. In fact, only the Carnegie Mellon's EIO-LCA platform allowed for the modification of production recipes (GDI, 2008), but it was not in global multi-regional form. REAL PyIO and Pycirk, allowed for the modification of multi-regional IO databases of which only one (Donati et al., 2020) included the assessment of a diverse set of environmental extensions. UK's 2050 Global calculator and EUREAPA allowed for the analysis of pre-calculated scenarios for different types of policies (DECC, 2010; Roelich et al., 2014); however they did not permit interactive exploration or direct modifications of the database. Two tools, IOsnap (native) and IMPLAN (web-app), presented modeling features at final demand or final demand and intermediate level. However, both tools were commercial, which represents a barrier in accessibility of data and results by a broader community.

As previously discussed, these last two features are fundamental for offering users different options for the assessment and modeling of improvements of CE interventions.

2.2 | Implications and design choices for the RaMa-Scene platform

Given that no current platform met our requirements, the decision was made to develop a dedicated platform.

First, to ensure ease of access and use, we decided to develop a web platform with a user-friendly interface. The design of the interface and the visualizations are inspired by previously developed web tools such as the Atlas of Economic Complexity (Hausmann et al., 2019), thereby facilitating the use of results across multiple platforms providing different economic insights.

Second, visualization of results should be presented side by side so that users can rapidly see the difference from baseline and scenarios thereby facilitating comparability (see also Section 3).

Third, since a high sectoral resolution was essential to model CE interventions, we decided to use the EXIOBASE database. At the time of writing this study, EXIOBASE is the IO database with the largest number of available sectors and presents detailed environmental and socio-economic information of sectors and regions globally across multiple years (Stadler et al., 2018; Wood et al., 2015). The additional advantage of employing EXIOBASE is the presence of data concerning secondary raw-materials transactions (Merciai & Schmidt, 2018).

Last, in order to allow for the assessment of CE interventions, a dedicated feature for the modification of the underlying data should be present. The EIO-LCA tool (GDI, 2008) and Pycirk (Donati et al., 2020) are good examples of implementation of this feature.

3 | DATA, METHODS, AND USER INTERFACE

In this section, we describe the database and methods used in the calculation of the IO system, data selection, and scenario creation.

3.1 | Data

RaMa-Scene employs the monetary mrEEIO database EXIOBASE version 3.3.sm (Donati & Koning, 2019) in product-by-product industry–technology assumption format (Miller & Blair, 2009, pp. 208–210). It includes a 16 year time range (1995–2011), 49 regions, 200 product categories concerning commodity and services, 1 aggregate final demand category, and 60 environmental and socio-economic extensions characterized to 10 footprint indicators. This version of EXIOBASE differs from the official release of EXIOBASE v3 (Stadler et al., 2018) as some extensions have been excluded (e.g., water accounts) while others have been characterized into impact indicators. Additionally, the seven final demand categories of EXIOBASE were aggregated into one and the database was modified to make secondary raw materials (SM) available in the IO system. Typically, there is no SM sector in the product-by-product IO tables because the output of end-of-life recycling is aggregated into primary materials. This meant that the input–output lacked that information after transformation from supply-use tables (SUTs). Faced with this challenge, other authors have employed hybrid tables using a Waste Input–Output model (Aguilar-Hernandez, Sigüenza-Sanchez, Donati, Rodrigues, & Tukker, 2018). The decision to employ monetary data, instead of hybrid data, was based on technical constraints and information preferences. The difference in units among the different commodities of the hybrid tables of EXIOBASE increases complexity both for the technical display of data but also in the phase of scenario data collection as market information appears to be more readily available. Furthermore, the hybrid data does not contain information on value added and employment studies (Merciai & Schmidt, 2018) which are important indicators to ensure comparability of analysis to previous studies (McCarthy et al., 2018). Therefore, we employed EXIOBASE monetary IO tables which have been modified with the method presented by Donati et al. (2020) in Supporting Information S1. This method modifies the structure of the SUTs in a way that upon transformation to IO tables, SM (i.e., output from end-of-life recycling) become available. This database is named EXIOBASE V3.3.sm where "*sm*" stands for *Secondary raw Materials*.

3.2 | Methods

One of the requirements was that of being web based so that different types of users can easily access the tool. We could follow two development options: (a) pre-calculated scenario results; (b) on-the-fly calculation of results. The former requiring developers to create a number of scenarios from which the users could choose. The latter, provides the user with full flexibility of how CE interventions are implemented in the IO system. Given the variety in modeling CE interventions and in the analysis of CE dimensions, on-the-fly calculation of results was the preferred option. In this way, users can easily investigate and compare multiple dimensions of the database and CE interventions instead of being limited to options decided a priori by the developers. In particular, we allow for two types of analysis (hotspot and contribution analysis) and for the modification of IO transactions at the industrial and final demand levels. The following sections present these methods.

3.2.1 | The environmentally extended input–output model

The mathematical model at the core of the platform is the final-demand-driven environmental input–output model (Leontief, 1970) described by the following equation:

$$r = b'Ly \tag{1}$$

here endogenous scalar r represents the total amount of environmental (or other type of) impacts that results from the stimulus generated by the consumption bundle represented in column vector y. The parameters of the model are a column vector b (with $'$ denoting transpose) of intensities of the appropriate environmental extension (direct impact per unit of production) and matrix L, the Leontief inverse matrix. The latter is calculated by

$$L = (I - A)^{-1} \tag{2}$$

where I is the identity matrix and A is the technical coefficient matrix. Entry A_{ij} represents the purchase of inputs from i required to satisfy one unit of output of j.

The generalized Equation (1)can also be expanded to represent the mrEEIO system used in RaMa-Scene.

$$\mathbf{r}_1\mathbf{r}_2\ \mathbf{r}_3 = \begin{pmatrix} \mathbf{B}_{11} & 0 & 0 \\ 0 & \mathbf{B}_{22} & 0 \\ 0 & 0 & \mathbf{B}_{33} \end{pmatrix} \cdot \left(\mathbf{I} - \begin{pmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} & \mathbf{A}_{13} \\ \mathbf{A}_{21} & \mathbf{A}_{22} & \mathbf{A}_{23} \\ \mathbf{A}_{31} & \mathbf{A}_{32} & \mathbf{A}_{33} \end{pmatrix} \right)^{-1} \cdot \begin{pmatrix} \mathbf{Y}_{11} & \mathbf{Y}_{12} & \mathbf{Y}_{13} \\ \mathbf{Y}_{21} & \mathbf{Y}_{22} & \mathbf{Y}_{23} \\ \mathbf{Y}_{31} & \mathbf{Y}_{32} & \mathbf{Y}_{33} \end{pmatrix} \cdot \mathbf{i} \tag{3}$$

here, **Y** and **A** are matrices composed of multiple regions and i is a one vector of appropriate length used to transform **Y** into a vector y. **Y** and **A** diagonal transactions represent domestic consumption for each country and off-diagonal transactions are import (vertically) and export (horizontally). Each regional entry is composed of all product categories. For simplicity, all equations in the following sections refer to the generalized Equation (1), however, knowing that they can be expanded to represent the multi-regional system.

3.2.2 | Hotspot and contribution analyses

Consumption activities across all sectors and regions in the world cause environmental and socio-economic impacts. For this reason, it is often of interest to view in isolation impacts across only some of these dimensions. From the defined requirements we decided to allow for the visualization of the impacts of CE interventions using two standard analyses. In the *hotspot analysis*, impacts are discriminated based on the sectors and/or regions where they take place, irrespective of the final product delivered by the supply chain. In the *contribution analysis*, the total impacts occurring along the supply chain of a bundle of consumption products are discriminated by product category and/or the consuming region, irrespective of where those impacts occur along the supply chain.

Therefore, in the particular visualizations provided by RaMa-Scene, we are not interested in the zero-dimensional grand total r described in the previous equations but we want to have the one-dimensional breakdown of impacts by either the sectors/regions where impacts occur (hotspot analysis) or the products/regions with the highest embodied impact (contribution analysis). These are obtained by adapting Equation (1) such that the vector on either the left- or the right-hand side of the Leontief inverse matrix is diagonalized. That is, a hotspot analysis is obtained as

$$r_h = diag\,(b)\,Ly \tag{4}$$

and a contribution analysis as

$$r_c = b'\ L\ diag\,(y) \tag{5}$$

where *diag* represents a diagonal matrix.

3.2.3 | Sectoral and regional detail

As mentioned previously, we employ a mrEEIO model of the global economy which distinguishes a number of regions each with a number of economic sectors. In order to allow the user to investigate regional or a sectoral distribution of impacts, we provide an aggregation method for results with the complementary dimension (sectors or regions) being collapsed to a single item.

The multi-regional database is composed of n_R regions and n_S sectors per region. In either case, the result of IO calculations must be transformed so that a vector with n_D elements is displayed. These are obtained by applying an appropriate aggregation vector g and an appropriate selection matrix S. An aggregation vector is a column vector that has one or more entries with value 1 and the remainder entries zero. A selection matrix has n_D rows and either n_R or n_S columns, depending on the visualization detail, with one entry with value 1 per row, and at most one entry with value 1 per column and the remainder entries zero. The selection matrix defines the transformation between the full list of sectors or regions and the sectors or regions to display in the visualization. The aggregation vector defines the transformation of the full list of the complementary dimension (regions or sectors) to be the single item to display. Note that the control variable y in Equation (1) can be multiple things depending on the specific application of the model. However, in the construction of baseline scenarios it will be based on matrix Y, which is the matrix of final demand observed in the reference year, with n_R columns (one per region) and $n_R n_S$ rows (one per region and sector).

In the context of mrEEIO the impacts of consumption can be broken down along a total of three types of region and two types of sector coordinates. We summarized them by:

- the region where impacts occur;
- the sector where impacts occur;
- the region that delivers the product to final demand;
- the sector (or product) consumed by final demand;
- and the region of final demand.

RaMa-Scene allows for four combinations of analysis/detail, where each extracts a *vector* along a particular dimension among those five, with the complementary dimension characterized by a *set* along another, and *all* impacts are accounted for along the remainder dimensions.

TABLE 1 Break down of possible impacts of consumption

		Dimensions				
Analysis	Detail	*Sector (Impact occurs)*	*Region (Impact occurs)*	*Sector (Delivers product)*	*Region (Delivers product)*	*Region (Final consumption)*
Hotspot	***Sectoral***	Vector	Single	All	All	All
	Geographic	Single	Vector	All	All	All
Contribution	***Sectoral***	All	All	Vector	All	Single
	Geographic	All	All	Single	All	Vector

Table 1 summarizes this information. Note that, in principle, there is yet another dimension along which the mrEEIO impacts of consumption could be distinguished, the final demand category, but in the database underlying RaMa-Scene this dimension has been collapsed to a single value.

The four combinations of analysis/detail are obtained as variations of Equations (3) and (4) to account for the multi-regional nature of the system, combined with applications of g and S and appropriate reshaping of vectors and matrices.

To obtain hotspot analyses with a sectoral or regional detail, first Equation (3) is applied with the stimulus vector being the row sum of total final demand, that is $y = Yi$, where i is a column vector of ones. The resulting vector r_h is then reshaped to a matrix R_h, with n_S rows and n_R columns, such that the (ij) entry of R_h represents the impact in sector i and region j. The sectoral detail (θ_h^{sec}) is obtained by applying the aggregation vector to regions (right multiplication) and the selection matrix to sectors (left multiplication), thus:

$$\theta_h^{sec} = SR_h g. \tag{6}$$

The regional detail θ_h^{reg} of the hotspot analysis is obtained by swapping the left and right multiplication of the aggregation vector and selection matrix:

$$\theta_h^{reg} = g' R_h S'. \tag{7}$$

Note that the selection matrix is transposed since it is assumed that it has the desired classification in rows.

The contribution analysis begins through a multi-regional variation of Equation (4) but now the sequence of application of the aggregation vector and selection matrix is more complex. That is because the columns of final demand define the region of final consumption, whereas the rows of final demand define the sector.

The sectoral detail of the contribution analysis (θ_c^{sec}) is obtained by first applying Equation (4) where $y = Yg$, that is, aggregation along the complementary dimension occurs upfront. The resulting vector r_c is then reshaped to a matrix R_c, with n_S rows and n_R columns, such that the (ij) entry of R_c represents the impact of the consumption of sector i originating from region j. The sectoral detail (θ_c^{sec}) is then obtained by summing over all regions (right multiplication) and applying the selection matrix to sectors (left multiplication), thus:

$$\theta_c^{sec} = SR_c I. \tag{8}$$

The logical starting point for the calculation of the regional detail of the contribution analysis is to apply the selection matrix to the matrix of final demand, YS'. However, the resulting object is itself a matrix so Equation (4) cannot be applied. We need to write down a variation thereof:

$$R_c = diag\,(b'L)\, YS'. \tag{9}$$

Matrix R_c has $n_R n_S$ rows and n_D columns, and entry (ij) represents the impact of consumption in region $j$of product k purchased from region l, where $i = k + (l-1)n_s$, where it is assumed that counting starts at 1 and sectors are nested within regions. Matrix R_c has to be reshaped in two steps so that entries along the dimensions of region of delivery and sector are aggregated. Formally this can be performed as follows. R_c is transformed into R_c^*, with n_R rows and $n_S n_D$ columns, whose entry (ij) represents the impact of consumption in region l of product k purchased from region i, where $j = k + (l-1)n_S$. Aggregation over the delivering region is performed as:

$$(r_c)' = i' R_c. \tag{10}$$

This vector can now be reshaped as matrix R_c^{**} with n_S rows and n_D columns, with entry (ij) representing the impact of consumption in region j of product i. Finally, the regional detail of the contribution analysis is obtained by the aggregation over the complementary dimension as:

$$\theta_c^{\mathrm{reg}} = g' R_c. \tag{11}$$

This concludes the four sets of calculations used for the creation of visualizations.

3.3 | Baseline and counterfactual scenarios

The starting point to model a CE intervention is to have a snapshot of the real world, that is, a baseline scenario of a year chosen by the user. From that baseline, CE interventions are modeled by a series of changes in coefficients of the model, leading to a counterfactual scenario.

RaMa-Scene uses the monetary mrEEIO system for a specific year chosen by the user as base to create scenarios by changing transactions in **Y** and **A**. This means changing final consumption patterns (**Y**) or production recipes (**A**). The counterfactual (i.e., modified) mrEEIO system is then obtained by the following generalized equation:

$$\mathbf{r} = \mathbf{B}\,\mathbf{x}^* = \mathbf{B}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}^* \cdot \mathrm{i} \tag{12}$$

where * denotes a counterfactual matrix, $\mathbf{r}^*$ is the counterfactual vector of extensions obtained after the creation of the counterfactual final demand $\mathbf{Y}^*$and the counterfactual Leontief inverse $\mathbf{L}^*$. The former is obtained by modifying the matrix **A** to $\mathbf{A}^*$ and then calculating $\mathbf{L}^*$ as shown in Equation (2).

Users of RaMa-Scene have nearly unlimited possibilities for the creation of counterfactual scenarios. However, while it is easy to modify values in the IO system, the most challenging aspects in scenario creation are collecting and organizing the new input data. In particular, users are recommended to consider the following aspects:

1. Primary impacts of an intervention (e.g., increase in sharing activities may results in a change in sales of goods while also affecting the use of services).
2. Potential ancillary changes needed to support the implementation of said intervention (e.g., changes in recycling may need changes in labor or in scrap and waste collection).
3. Commodity prices and their geographic differences (e.g., 1 kg copper may have a different price than 1 kg of aluminum and these prices may change depending on the region).

As shown, the counterfactual scenario in which CE interventions are implemented is constructed by editing elements of the A and Y matrices. Any element thereof can be chosen and a relative change (increase or decrease in percent) can be implemented. While this gives many opportunities for scenario creations, users need to keep in mind that RaMa-Scene does not perform any automatic balancing. This choice was motivated by the need to offer a quick response time of the tool and balancing would have increased computational requirements. Thus, if the user wants to perform the analysis of a scenario resulting in one or more sums of the inputs being $\neq 1$, then the IO system would remain unbalanced. Therefore, while users enjoy large freedom in the changes they apply to the system, they also need to be mindful of the way they construct their scenarios. In particular, users should consider whether they have included all needed coefficient changes due to the intervention, potential price changes, and whether this difference is due to variation in value added. However, it is important to reassure users that while there may be a discrepancy between the sum of inputs and that of outputs, the total product output x is the reference vector for the recalculation of the extensions. This is to say that if an unbalanced system is presented, it will not affect the legitimacy of results of the environmental extensions. However, the categories forming value added—namely compensation of employees, subsidies, and taxation—would need to be analyzed critically to avoid over- or underestimation of the socio-economic impacts.

In the following section, we show how these methods were developed into the RaMa-Scene platform.

3.4 | The RaMa-Scene user interface

The user interface consists of six panels (Figure 1). The first five are used to generate and visualize the baseline and counterfactual scenarios, and the sixth is a hub connecting to other online tools. We now list the actions that can be performed in each of the first five panels.

The first panel is the *Baseline settings* menu, where the user defines the type of analysis (hotspot or contribution) and the detail (sectoral or geographic) of the visualization, as well the year considered for the baseline scenario and the sectors, regions, and indicator used in the visualization.

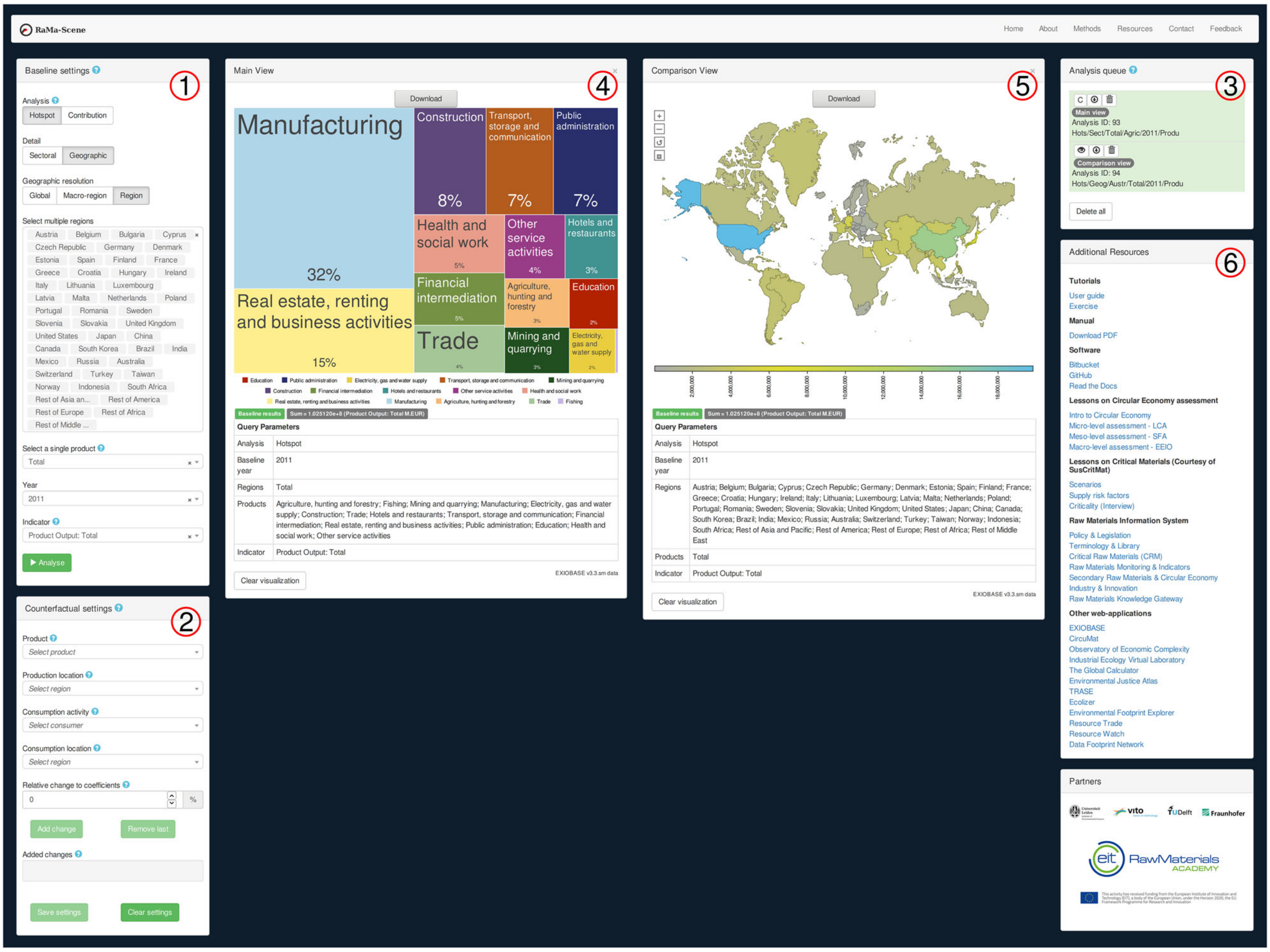

FIGURE 1 RaMa-Scene interface and panels

The type of analysis is selected in the field *Analysis*. The visualization focus is selected in the field *Detail*, where *sectoral* leads to a *tree-map* visualization and *geographic* to a *geo-map*. The *Year*, *Region*, *Product*, and *Indicator* fields are obvious. Note that depending on the detail of the visualization either one or several regions or products must be selected. Products and regions are characterized by a classification tree, such that it is possible to select items at different hierarchical levels (e.g., agriculture vs. rice or Europe vs. France). At the bottom of the panel the green button *"Analyze"* generates an analysis, which appears in the queue of panel 5, explained below.

The second panel is the *Counterfactual settings* menu, where the user defines the counterfactual scenario by editing specific parameters of the baseline scenario. Four fields allow specifying the row and column coordinates in the IO system, and a fifth field called *Relative Change to Coefficients* allows introducing the numerical value of the relative change (in percent) that the coefficient should be subjected to. The four coordinate fields are:

- *Product*, the input (or row) element to be edited;
- *Production location*, the region providing the product;
- *Consumption activity*, the sector or final demand (denoted as *Y* in the pull-down menu) which uses the product defined earlier as input;
- *Consumption location* is the region in which the sector using the product is located.

At the bottom of the panel, buttons allow to manage the edits: it is possible to add new edits and to remove the last inserted. Finally, green buttons to save and clear the settings.

The third panel, *Main View*, provides the visualization of the currently selected visualization configuration, with the details of that configuration at the bottom (under the heading *Query Parameters*), and at the top a download button.

The fourth panel is a *Comparison View* (similar to the *Main View*) provided to allow the user to compare the baseline and counterfactual scenarios.

The fifth panel is the *Analysis queue*, which contains the list of analyses that have been generated through the *Baseline settings* and *Counterfactual settings* menus. This queue allows the user to go back to previous assessments in the same session without having to rebuild them. To the right of each analysis there is a set of buttons: *Download*, *Delete*, *Eye*, *C*, and *M*. The meaning of the first two is obvious, the *Eye* button displays the configuration in the Main View, *C* displays the configuration in the Comparison View, and *M* applies the counterfactual changes defined in the *Counterfactual settings* menu and displays the results in the Main View. The *M* button only appears after the counterfactual settings have been saved.

The sixth panel, provides additional resources that could be useful to the users. In particular, we have created a series of video tutorials for the use of the platform (i.e., user guide and exercise tutorials), educational videos to understand the concepts related to the CE and the assessment tools (Donati et al., 2019) and a digital user guide (Donati, Graf, & Ko, 2019). In addition to these resources, through this panel users have a quick access to other web tools and information (JRC European Commission, 2016) that could be used to improve the depth of their analyses.

4 | USE CASES

In this section, we exemplify the use of the platform and the results from three use cases.

4.1 | Which country is responsible for the highest amount of material extraction due to their consumption?

For this analysis, we selected the contribution analysis at geographic detail. We choose "Domestic Extraction Used – Total" as the indicator, which is an aggregate of multiple metal and non-metal ores available in the database used RaMa-Scene. Figure 2 shows the baseline settings used and the resulting geographic visualization.

From the visualization, we can see that China holds the largest share of extractions due to consumption. By downloading the results through the download button and calculating each country's relative share (see Supporting Information S2, sheet a), we see that China is responsible for 37% of global domestic extraction used. This is likely due to its share in final consumption (including investment) of both manufactured and semi-manufactured goods, whose production in turn requires a high consumption of resources. This gives an indication of how much global extractive activities are stimulated by China. China is followed by the United State of America 10%, Rest of Asia and Pacific 7%, and Rest of Middle East 5%.

4.2 | Which sub-sectors are the top CO_2-eq emitters in Italy?

In this second use case, we investigated the sub-sectors (i.e., mid-level aggregate of product categories) with the largest greenhouse gas (GHG) emissions in Italy in 2011. Figure 3 presents baseline settings used, as well as two visualizations, the hotspot analysis on the left and contribution analysis on the right. As can be seen, the two visualizations present different results.

Starting from the sectoral hotspot analysis (on the left), we see that the production of electricity, gas, steam, and hot water supply is responsible for 20% of the GHG emissions in Italy. This category is followed by agriculture, hunting, and related services at 10%; manufacture of other non-metallic mineral products at 8%; construction 8%; and manufacture of electrical machinery and apparatus n.e.c. 7%; and the manufacture of coke, refined petroleum products, and nuclear fuels at 6%. For the other product categories, see Supporting Information S2, sheet b.

In the second visualization, we observe the global GHG emissions caused by consumption in Italy as opposed to the first visualization (hotspot) where we show the GHG emissions occurring due to production in Italy. The sub-sector that delivers the highest amount of emissions due to its consumption in Italy, is construction which holds a share of 13% of the total. This is followed by manufacture of food products and beverages at 11%; electricity, gas, steam, and hot water supply at 7%; health and social work 6%; manufacture of coke, refined petroleum products, and nuclear fuels 5%; manufacture of chemicals and chemical products 4%. For the full analysis, please see Supporting Information, sheet c.

4.3 | What global effects does the increase in secondary steel content in "Electrical machinery and apparatus n.e.c." (EMA) have on total greenhouse gas emissions?

We first analyze the total global GHG emissions due to production (Figure 4) through a hotspot analysis. We select a geographic detail so we can investigate the regional location of the impacts. By doing so, we will also be able to see where the majority of GHG emissions are emitted.

By hovering on the map—or by downloading the raw results from the analysis queue—we identify top three largest emitters: China 27.3% (1.05e13 kg CO_2-eq); USA 13.2% (5.07e12 kg CO_2-eq); India 6.8% (2.62e12 kg CO_2-eq).

We then perform a sectoral hotspot analysis for the whole world with a focus on the product output. We look for the values concerning primary and secondary steel in the visualization or the downloaded data. This analysis shows that of the 1.816 Billion € of all steel consumed (primary and secondary), 79% is due to the production of steel from primary sources and the 21% is due to production from secondary sources. While it is currently not possible to investigate directly the consumption of steel by *"Electrical machinery and apparatus n.e.c."* (EMA), we assume that the global ratio in product output is constant in the consumption of steel for the production of all products, including EMA.

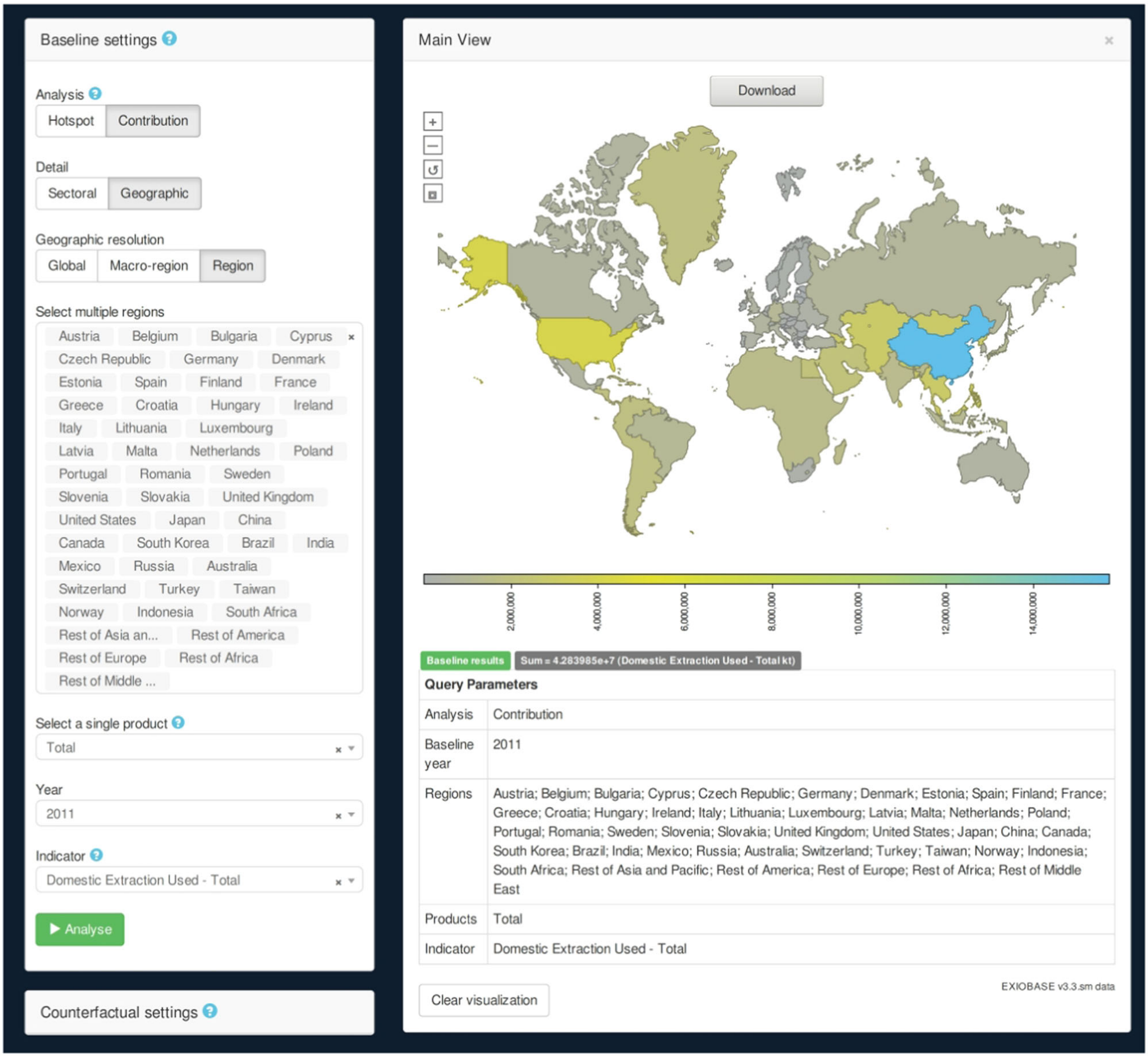

FIGURE 2 Regional contribution analysis of the total domestic extraction used due to regional consumption

After this analysis, we want to raise the share of secondary steel while lowering the share of primary steel, as recycled steel is less GHG emission intensive (Milford, Pauliuk, Allwood, & Müller, 2013). We rely on UNEP (2013) to identify the rate of change for both secondary and primary. We see that in 2050 steel recovery rate in EMA will increase by 30% in comparison to 2007 levels. For this simplified use case, we assume that scrap availability is directly proportional to the use of secondary materials in production.

Therefore, we increase by 30% the consumption of steel coming from secondary sources in EMA. Knowing that secondary steel amounts to 21% of the total steel consumed and assuming no price difference between primary and secondary steel, we calculate a reduction of 8% in the consumption of primary steel (Table 2 and Figure 4). The primary steel equivalent is calculated on the basis of global product output for the two categories. We assumed that the ratio at which the material from the two sources is used is constant across all sectors in the economy.

We save the counterfactual settings and click on the modeling **M** button on the analysis queue entry for the baseline settings shown in Figure 5. The results (Figure 5) show that global GHG emissions reductions would amount to 2494.24 Mt CO_2-eq, −0.02% from the baseline. In particular, if we hover over China, we would see that emissions amount to 10478.89 Mt CO_2-eq, which represents a 0.02% reduction from the baseline (Supporting Information S2, sheet f). The other regions showing important reduction of GHG emissions: Rest of Europe −0.03% (−180.38 Mt CO_2-eq) and Rest of Asia and Pacific −0.01% (−169.44 Mt CO_2-eq). However, some regions saw an increase in GHG emissions among which USA 0.01% (316.10 Mt CO_2-eq) and the majority of countries in the European continent, most EU member states, and advanced Asian economies such as South Korea,

FIGURE 3 Sectoral hotspot (on the left) and contribution (on the right) analysis of GHG emissions in Italy

TABLE 2 Modeling scenario settings for the replacement of primary steel for secondary steel in EMA

Field	Change 1	Change 2
Product	Secondary steel for treatment, reprocessing of secondary steel into new steel	Basic iron and steel and of ferro-alloys and first products thereof
Consumed by	Electrical machinery and apparatus n.e.c.	Electrical machinery and apparatus n.e.c.
Originating from	Total (i.e., all countries and regions)	Total (i.e., all countries and regions)
Consumed where	Total (i.e., all countries and regions)	Total (i.e., all countries and regions)
Technical change coefficient	30%	−8%

Taiwan, and Japan. This is likely due to an important presence of electric arc furnaces in these countries. For additional insights, the reader can refer to the Supporting Information S2, sheets e and f.

5 | DISCUSSION AND CONCLUSIONS

We presented a free and open-source platform, RaMa-Scene, that allows for the creation of complex scenarios using the multi-regional environmentally extended input–output database EXIOBASE. We also make available a new version of the monetary product-by-product IO database EXIOBASE where materials produced with secondary technologies (i.e., recycling industries) are explicitly represented. The platform and database

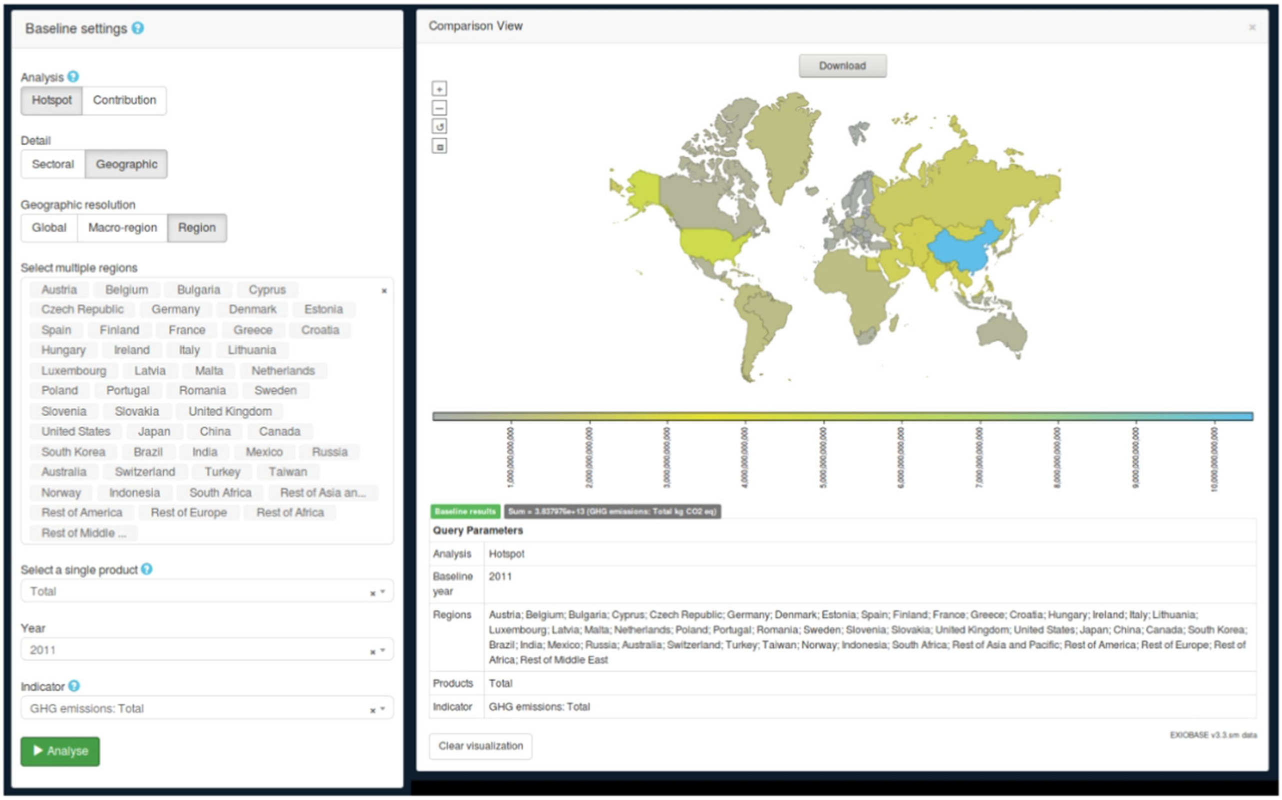

FIGURE 4 Baseline settings and regional distribution of total GHG emissions from production

are intended as an addition to environmental impact assessment tools available for policy makers and practitioners interested in the analysis of the current structure of the global economy or the creation of CE scenarios to support decision-making.

RaMa-Scene is the first free and open-source web application that uses a database with which users can analyze and modify the impact of CE interventions. In particular, it is the first web platform created with the intent of allowing the creation and analysis of complex counterfactual CE scenarios. Of the analyzed software, pycirk (Donati et al., 2020) was the only one that was also created with this intention. However, the pycirk python package is command line based and offers no visualizations. It is meant to be used by practitioners and students comfortable with programming. On the other hand, RaMa-Scene present visualizations and functionalities approachable by different expertise levels.

RaMa-Scene's visualizations and ease of use through easy to access buttons and drop-downs was inspired by the Atlas of Economic Complexity (Hausmann et al., 2019). We combined the user-friendliness and some of the visualization of the Atlas and combined scenario modeling features similar to pycirk. However, only relative changes can be applied. The combination of these features give users of RaMa-Scene great flexibility in the creation of any scenario of their preference. In this way, it distinguishes itself from EUREAPA (Roelich et al., 2014), where users could only choose the intensity pre-calculated scenarios. Similar to EUREAPA, RaMa-Scene employs footprint indicators but it also combines them with non-characterized extensions. This means that users can investigate variations in the extensions composing the footprints.

Other software presented more advanced features which could not be offered through RaMa-Scene. For instance, the native software REAL pyIO (Nazara et al., 2004) offers decomposition analysis and the commercial web-platform IMPLAN (IMPLAN, 2018) offers dynamic features for spending substitution. However, RaMa-Scene presents some exclusive features. Most notably, the analysis queue allowing for up to 15 analyses and multiple scenarios at the same time, and the analysis of secondary raw materials. These features give great flexibility in the investigation of circular-economy policy options and historical trends under multiple socio-economic and environmental indicators.

Besides the comparison to previous software, we acknowledge that there are other limitations from the perspectives of methods, technical implementation, and use of RaMa-Scene. From a methods perspective, RaMa-Scene uses only one transformation method from SUTs, the product-by-product industry–technology assumption. Multiple other methods and input–output configuration exist which may offer different results as the assumptions of the economic structure are different (Miller & Blair, 2009, ch. 5).

A few observations about the data are in order. First, the current available level of resolution of products in input–output data. For instance, current data do not distinguish between internal combustion engine and electric vehicles. This may prevent the modeling and assessment of some CE interventions. Second, in the modification of EXIOBASE as per Donati et al. (2020), we assumed that in each sector the consumption of secondary raw materials occurs at the same rate of primary sources. This may not be true in all cases. In the future, the database may benefit

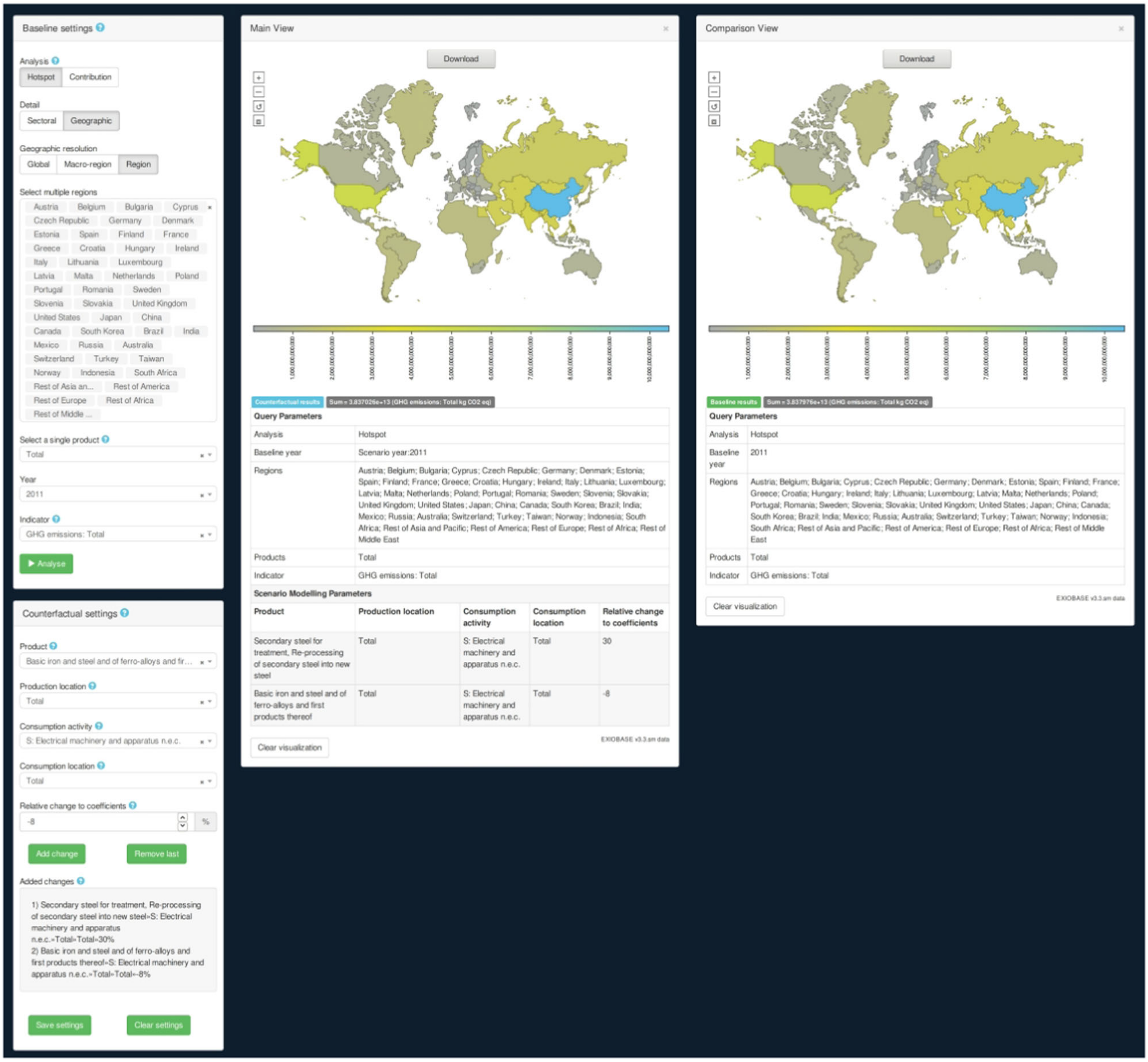

FIGURE 5 Total contribution of products consumption to global GHG emissions

from a formal separation of materials produced with different technologies (i.e., primary and secondary technologies). Third, the current database does not included final demand extensions, which may be critical for some product categories where the final-consumer use phase represents an important part of emissions (e.g., GHG emissions of personal vehicles).

From the implementation side, the Leontief inverse is computationally intensive. This is a challenge in the upscaling of the platform. One solution to this problem would be the application of formulas to avoid the recalculation of the Leontief inverse upon changes to the technical coefficient matrix (Hager, 2005).

Currently, users cannot visualize inputs to the recipes of product category. The integration of introspective features for production recipes may prove useful to users. Additionally, while it is indeed possible to analyze different years in the database, it is not made possible to create line graphs for time series, due to response time limitations, but users can choose two years shown simultaneously.

Last, the quality of a scenario is dependent on the quality of the data collection performed by the users. Therefore, the user is in complete control of the input–output coefficients and quality of scenarios. For this reason, users should make sure that their scenarios use realistic inputs keeping in mind technical and resource limitations, geographic differences, and plausible substitutability. Preformatted scenarios such as the ones in EUREAPA (Roelich et al., 2014) and 2050 Pathway Calculator (DECC, 2010) could facilitate users in these efforts, as well as help those interested in quick analyses.

In conclusion, the RaMa-Scene platform has multiple interesting and useful features that are currently not available on any other platforms we surveyed. At the same time, the live tests and courses conducted in the RaMa-Scene project with practitioners, scientists, and students, showed that there is still room to improve this version into a feature rich application that can be used by anybody working on environmental policy and scenario creation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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