Software and data for circular economy assessment

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1 INTRODUCTION

1.1 CIRCULAR ECONOMY

In the current economy, we take materials from the Earth, transform them into products, use these products and then discard them as waste. This linear model is currently the main way of utility and value creation. The environment is only perceived as a provider of primary resources, and a place that should absorb waste and emissions. However, everything is an input to something else in a virtually closed system such as our planet. Considering the economy as a way to only produce utility and value is bound to result in overexploitation of resources, exceeding planetary boundaries and therefore threatening our natural living support system (Rockström et al., 2009).

The circular economy (CE) aims to mitigate this threat by considering the limitedness of our resources and the limited ability of the environment to work as a sink for waste and emissions from our industrial system. It promotes the use of resources in closed loops (e.g., re-use and recycling) which also implies the adoption of renewable resources extracted at a sustainable level, all the while ideally eliminating the use of exhaustible ones (Pearce et al., 1990, Chapter 2). This requires technological, organizational and policy changes aiming at the sustainable management of resources. Producer responsibility, servitization, business models innovation, sustainable consumption, eco-industrial parks, are among the many approaches that support a reduction of resource consumption and keep materials in closed loops (Ghisellini et al., 2016; Kirchherr et al., 2017b; Potting et al., 2016). Several scholars and organizations have tried to provide a clear definition of a circular economy (Calisto Friant et al., 2020; EMF, 2015b; Kirchherr et al., 2017b). Kirchherr et al. (2017) considered no less than 114 definitions, from which they suggested to define a circular economy as:

"An economic system that replaces end-of-life concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro-

level (products, companies, consumers), meso-level (eco-industrial parks) and macro-level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers."

In addition to the Micro-Meso-Macro subdivision which was originally offered by Ghisellini et al. (2016), strategies to realise a CE strategies can be grouped in different categories (Aguilar-Hernandez et al., 2018a; EMF, 2012; Potting et al., 2016). One of these consists of the so-called R principles that support a circular use of products, their components and materials (see Figure 1). Another is the so-called 'butterfly diagram' developed by the Ellen MacArthur Foundation (EMF, 2012), see Figure 2. Later, the EMF and McKinsey developed the so-called ReSOLVE framework as a tool for business and government to implement CE strategies (EMF, 2015a):

- REgeneration: technological and resource use changes that aim at retaining utility of resources
- Share: the sharing of resource and products
- Optimize: increase efficiency, remove waste, and leverage big data, automation and remote sensing and steering
- Loop: employing technologies and changing organization around the recovery and reuse of resources that have reached their end of life
- Virtualize: dematerializing products and services by offering them through a digital alternative
- Exchange: substituting material and technologies for more sustainable alternatives

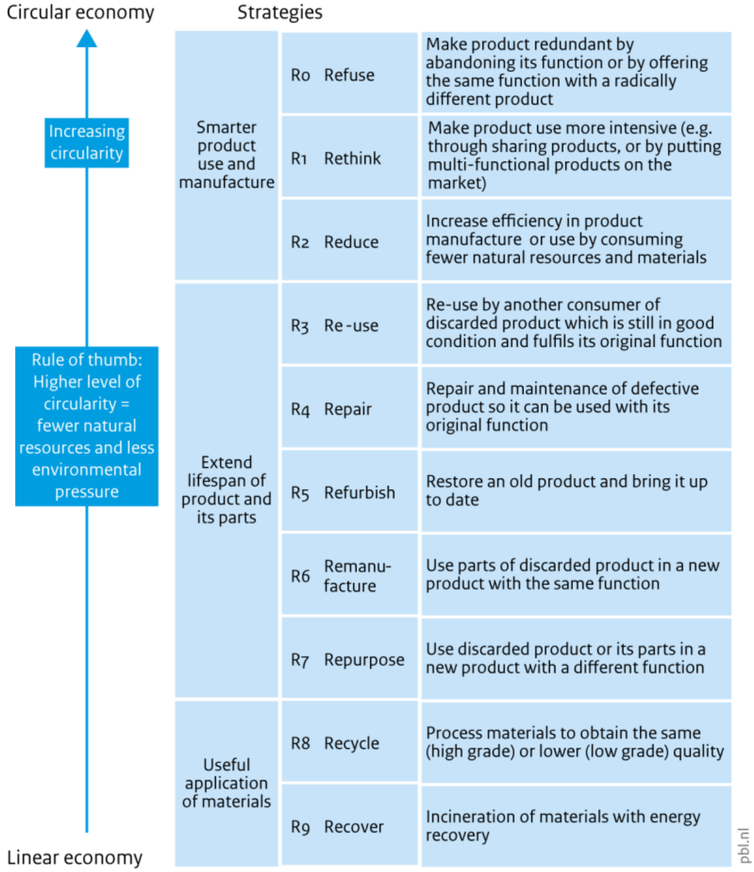

Figure 1: R Strategies (Potting et al., 2016)

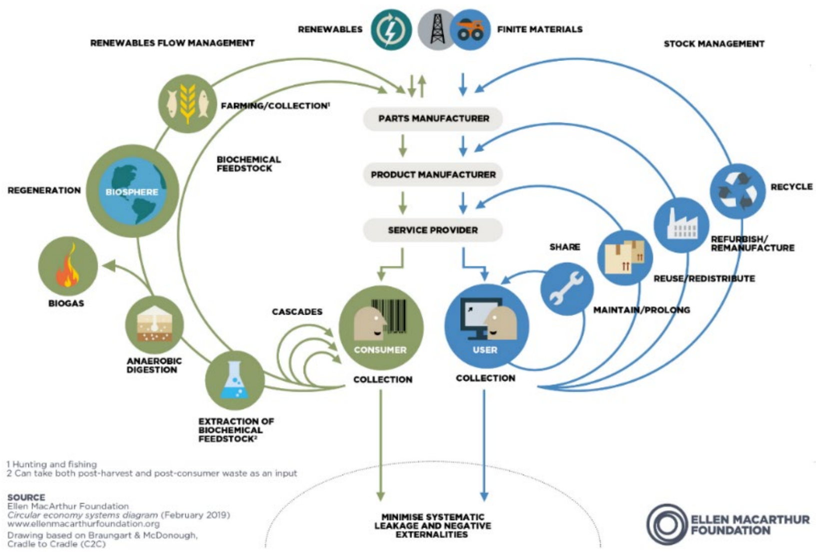

Figure 2: Circular Economy Butterfly Diagram (EMF, 2015b)

The main ambition of this thesis is to contribute to the development of assessment methods that analyze the economic, social, and environmental implications of CE strategies. This implies that an unambiguous grouping of CE strategies is required that can be used easily in socio-economic and environmental assessment methods. However, some of the groupings presented above leave room for unclarity. For example, does recycling fall under regeneration or loop? In order to assess the potential impacts of CE strategies, it is important to have a clear framework that is suitable for use in combination with assessment tools such as Environmental Input Output (IO) models – as explained in section 1.2 tools widely used by the scientific community to asses economic, social and environmental implications of sustainability policies. Through analysis of macro-economic studies on CE, Aguilar-Hernandez et al. (2018) showed that the following classification of CE strategies, essentially an aggregate of classifications mentioned before, is well suited to use in assessments based on IO and related models:

- Resource efficiency
- Closing supply chain loops
- Product life extension
- Residual waste management

The CE is in essence an aggregate of changes in technologies and policies in specific sectors and in the relationship among sectors aimed at reducing resource consumption and generating value. These changes by themselves may bring about marginal gains macro-economically but their compound effect in the avoidance of environmental pressures and socio-economic value generation could be substantial. In other words, the macro-level effects are the result of aggregate use and effects of micro and meso-level strategies. To assess the environmental and socio-economic performance of the CE, modelers have two choices: 1) Model aggregate effects of the strategies in production and consumption (e.g., global reduction of material consumption by 30% across all sectors); or 2) model detailed changes to simulate specific interventions (e.g., diversion of scrap metal from manufacturing). In the following section we discuss different modelling approaches that can analyze the social, economic and/or environmental impacts of CE strategies and interventions.

1.2 MODELS FOR CIRCULAR ECONOMY ASSESSMENT

To understand the social, environmental and economic effects of CE policies, the expected changes in the economy and technology need to be modelled. Different analytical tools are available for such modelling. Each of them has its particular strengths and weakness in capturing subtleties of the strategies as highlighted in the former section (e.g. Donati et al. (2021) and Walzberg et al. (2021)). In other words, questions concerning the modelling of circular economy can be answered through a variety of analytical tools from various fields of sustainability from industrial ecology to economics and complexity science.

Analytical tools can be divided depending on their focus of application: micro, meso and macro levels. The micro-level concerns models that focus on individual product systems (e.g., a consumer good) or specific technologies (e.g., industrial water filtration systems). The meso level may concern how a given supply chain is organized (e.g., industrial relationships, their inputs and outputs for the production of a given consumer good) or a given bulk material transformed across multiple industries and regions from extraction to disposal (e.g., copper extracted in a region and how its use in different equipment. The macro level mainly concerns how entire economies are represented and organized in their complexity, showing who is consuming or producing products and providing services, their requirements and effects (e.g., how all products are manufactured and consumed in Italy or globally). In the field of Industrial ecology, Life Cycle Assessment (LCA), Material Flow Analysis (MFA), and Environmentally Extended Input-Output Analysis (EEIOA) are key methods to assess the impacts of CE interventions (Aguilar-Hernandez, Dias Rodrigues, et al., 2021; Haas et al., 2015; Sassanelli et al., 2019).

LCA focuses on "compilation and evaluation of the inputs outputs and potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). LCA is regulated by ISO 14040 and is divided in 4 phases: 1) Goal and scope definition; 2) Inventory Analysis; 3) Impact assessment; 4) Interpretation. In particular, in LCA the inputs and outputs of technological processes (i.e., activities) are modelled. Activities are connected to each other by their inputs and outputs. Aggregates of activities form lifecycle stages, from the extraction to the end-of-life (EOL) (recycle/waste management). Flows that enter and exit unit processes are divided into economic and environmental flows. Economic flows connect activities and concern intermediate and final products and services of positive, negative or zero economic value. Environmental interventions are chemical, physical or biological anthropic interferences with the natural environment such as the extraction of resources or the emission of pollutants into nature. These quantified flows are inputs and outputs to the environment relative to the primary function(s) (i.e., functional unit) satisfied by a product system (Guinée, 2001). Given the high level of detail of discerning unit processes in LCA, it usually applied at individual product level. For this reason LCA has been promoted as an ideal tool for circular economy assessment. First, it is a recognized, standardized and scientifically based methodology in the field of sustainability (Pena et al., 2021). But second, it is a tool capable of looking in high detail at product specific CE strategies (e.g. re-use of components from end-of-life copiers). Therefore, many CE studies that focus at the micro and meso level have employed LCA (Sassanelli et al., 2019; Walzberg et al., 2021). Examples include the assessment of biobased products (Dahiya et al., 2020), closing material loops for metal packaging (Niero & Olsen, 2016), novel business models for consumer products (Hoffmann et al., 2020; Sigüenza et al., 2021), and closing loops in the construction sector (van Stijn et al., 2021). While LCA is very well suited to analyze environmental benefits of CE product systems, the foreground activities concern only one product system at a time and it typically requires substantial human and time resources to collect and compile the necessary data (i.e., life cycle inventories) for each analysis. Additionally, for LCA to provide insights other than environmental impacts, more data or methods hybridization are required to gain insights on social and economic impacts.

Also MFA has been used for circular economy assessments. It is an appropriate tool to follow materials and substances throughout their different life cycle stages from extraction to disposal, or through different regions (Ayres & Ayres, 2002b). Similarly to LCA, MFA traces the inputs and outputs through transformation processes but with a special focus on the material balance of a single or bulk material and the creation and development of its stocks through a region or industrial system (Ayres & Ayres, 2002b, Chapter 8; Ayres & Simonis, 1995). This makes MFA a suitable tool for the analysis of CE at the meso-level. The inclusion of stocks is important, as it help with forecasting at which moment end-of-life materials will become available for re-use and recycling in the future provided that average lifespan of products is known. For example, Millette et al. (2019) used MFA to investigate plastic management solutions to implement the CE in Trinidad and Tobago and Dong et al. (2020) assessed future scenarios of copper demand in China and how circular economy policies would effect demand.

So, while LCA and MFA are great for detailed CE analyses at product and material level, they do not cover the whole economy. They also look at the economy in physical terms, but do not include information on e.g. jobs, added value, or costs. LCA and MFA hence can provide excellent environmental impact analyses, but not economic or social analyses. EEIOA is more capable of covering social, environmental and economic impacts of CE interventions with a reasonable product and geographic detail. The basics of EEIOA are described in Box 1 (Leontief, 1941, 1970a). An IO table divides the economy of a country in a number of sectors (or products) and their inputs (e.g., services, goods and employment) required for the supply of goods and services to other industries and final consumers. The difference between the consumption of all products and services by an industry and its output is value added (i.e., .e. the sum of wages, taxes and subsidies and profit). The sum of all value added by industry defines the Gross Domestic Product (GDP). The IO table can further be ‘extended’ with environmental information such as the emissions and primary resource extraction of each sector, leading to an Environmentally Extended IO (EE IO). But there can also be other extensions, such as the employment numbers per sector. When IO tables of multiple countries are combined together connecting them through their trade relationships, this results in a multi-regional IO system, which in principle can cover all countries and all sectors in the global economy (i.e., Global MRIO). If a MRIO system, global or otherwise, comes with a set of environmental extensions, it is referred to as a MR EEIO system.

Box 1.1: Multi-regional Environmentally Extended Input-Output Analysis

Environmentally Extended Input-Output (EEIO) analysis (Leontief, 1970; Suh, 2009) is based on Input-Output (IO) analysis (Leontief, 1951; Miller and Blair, 2009) and deals with the quantification of environmental pressures that take place along the supply chain of goods and services, by assuming that production structure remains fixed. The basic Leontief demand-driven model can be framed such that a stimulus vector of final demand leads to a set of emissions occurring in each production sector as:

$$\mathbf{r} = \mathrm{diag}(\mathbf{b})(\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y} \qquad (1)$$

In the preceding expression $\mathbf{r}$ is the column vector of emissions occurring in each production sector (the response variable) and $\mathbf{y}$ is the column vector of final demand of products delivered by each sector (the control variable). The parameters of the model are the column vector $\mathbf{b}$ of environmental intensities (environmental pressure per unit of economic output) and $\mathbf{A}$ is a matrix of technical coefficients (i.e., direct requirements matrix) whose entry ij is the volume of inputs from sector i that are required to generate one unit of output of sector j.

diag stands for diagonal matrix and $\mathbf{I}$ is the identity matrix. The technical coefficient matrix is calculated as $\mathbf{A} = \mathbf{Z}\,\mathrm{diag}(\mathbf{x})^{-1}$, where $\mathbf{Z}$ is the matrix of inter-industry transactions and $\mathbf{x}$ is the column vector of total output of each sector, $\mathbf{x} = \mathbf{Z}\,\mathbf{i} + \mathbf{Y}\,\mathbf{i}$, the row sum of $\mathbf{Z}$ and $\mathbf{Y}$, where the latter is a matrix whose columns represent the final demand of different consumption categories (e.g., households, government, investment), and $\mathbf{i}$ is a vector column of ones.

Equation 1 can also be expressed in multi-regional form:

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

Here the subscript numbers in each matrix transaction indicates the region coordinates and the type of transaction. For instance, $\mathbf{A}_{11}$ indicates the direct requirement coefficient for the domestic production of region 1, while $\mathbf{A}_{12}$ is the direct requirement coefficient for production that is exported by region 1 to region 2. In other words, values on the diagonal of the $\mathbf{A}$ matrix represent domestic consumption and production, while transactions off the diagonal are import and exports to other regions.

MR EEIO databases (see box 1.2) contain data concerning global economic relationships (e.g., trade) and for each country and sector environmental extensions from extraction to greenhouse gas emissions. For this reason, it is often employed in the analysis of circular economy policies at the macro-economic level (Aguilar-Hernandez, Dias Rodrigues, et al., 2021; Walzberg et al., 2021). For example, Wijkman et al. (2015) explored the employment and GHG impacts of CE in the European Union economy, and Wiebe et al. (2018) investigated the global impacts of circular economy interventions to the year 2030. The advantage of EEIOA over e.g. LCA and MFA for the analysis of CE policies is that it covers the whole economy and covers next to environmental also socio-economic data such as employment, value added and taxation to name a few. The Leontief model makes it easier to process such large amount of data, on the other hand it limits modelers to static analysis. However, due to limits in computational power, there is a trade-off between data resolution and complexity of models. In fact, typically the more complex the interrelationship in the model the lower the data resolution. MR EEIO offers an effective trade-off between capturing many details about the economy and the environment while also being computationally and mathematically accessible by most analysts. Tools like Computable General Equilibrium (CGE) models capture more complex economic dynamics, but usually at the expense of data resolution. Given the fact that CE strategies can be highly product specific while we at the same time wanted to cover social and economic aspects, and also wanted to capture global trade-offs of CE policies, we decided upon using MR EEIO as the main tool in this thesis.

Box 1.2: Data for Multi-regional Environmentally Extended Input-Output

EE IO data is in many countries based on official data from the well-established System of National Accounts used by National Statistical Institutes (EUROSTAT, 2008). The accounts offer a rich variety of data which includes sectoral production statistics, households surveys, employment and in many cases environmental and waste data that may be collected by geological and environmental agencies present on the national territory (Beutel et al., 2018; EUROSTAT, 2008). Such an EE IO dataset allows to investigate socio-economic and environmental impacts of groups of products, materials, and sectors in an interrelated fashion. In essence, an EE IO dataset allows calculating how e.g., a change in final demand of a specific product leads to changes in production volumes in all economic sectors – and hence changes in emissions and resource extraction, value added creation, and job numbers (see Box 1.1). In most cases, IO databases are collected and disseminated by National Statistical Offices (NSOs) and supranational organizations such as European Statistical Office (EUROSTAT, 2022b), the Organisation for Economic Co-operation and Development (OECD, 2022) or the Asian Development Bank (ADB, 2022). Additionally, the databases provided by NSOs are made only for the country in which the NSO is based, and often have only a limited number of environmental extensions available. Since in many countries imports and exports play significant role for the Gross Domestic Product (GDP), it is important to include the supply chains to and from a country. This can be done by linking country IO tables via international trade, which gives a so-called multi-regional IO database. Making such MRIOs is complex: individual country IOTs must be brought into the same classification, trade data have to be added, etc. Since the total exports in all country IO tables differs from total exports, imbalances must be solved which inevitably implies adjusting national IO tables. For this reason multi-regional (MR) EEIO databases such as EXIOBASE (Stadler et al. 2018), EORA (Lenzen et al., 2013), GTAP (Peters et al., 2011) and others have been largely developed by the scientific community, in some cases adding sector detail in environmentally relevant sectors (Stadler, Wood, Bulavskaya, Södersten, Simas, Schmidt, Usubiaga, Acosta-Fernández, Kuenen, Bruckner, Giljum, Lutter, Merciai, Schmidt, Theurl, Plutzar, Kastner, Eisenmenger, Erb, Koning, et al., 2018).

1.3 SOFTWARE AND DATA FOR CIRCULAR ECONOMY ASSESSMENT

The models described in the previous sections rely on software and data to assess the potential effects of the CE, which are so complex they usually only can be applied by scientists and specialist practitioners. The analysis in the previous section indicates that tools and models for CE analyses are available, however, virtually all the analytical tools mentioned (LCA, MFA, EEIO) need involvement of highly skilled experts and substantial time investment. For policy makers this is a drawback. Similar to e.g. carbon footprint calculators that show how consumption changes could lower carbon emissions (Mulrow et al., 2019), it would be ideal if a simple to use scenario tool would be available, in which they could select CE scenarios for products and get a first impression of economic, environmental and social implications. However, in most cases analytical tools that could be used to create CE scenarios are either specifically developed for users with a programming background and/or available under paid licenses. This is an issue which affects accessibility of data of public interest concerning the economy and the environment, as well as limiting transparency and replicability of studies as implementations of scenarios may vary. For this purpose, easy to use software tools such as web applications are of great importance to ensure rapid and replicable development of scenarios, and access to the environmental and economic insights needed to promote the CE and sustainability at a large.

Data availability also plays a fundamental role in CE assessment as it can enhance models and validity of outcomes (Lahcen et al., 2022).However, due to the labor intensity of data collection and handling, there are challenges in timeliness and detail of data concerning products, activities, environmental impacts. Such challenges result in several limitations depending on the model choice. For example, IO data discern at best only a few hundred sectors or product categories, and in practice often only a few dozen. Hence data on production systems is much more aggregated than it would be in LCA or MFA studies where thousands of detail processes may be available. Past experience has shown that even the most detailed, global EE IO databases compiled by the scientific community have significant drawbacks in relation to the needs of CE impact assessment (Aguilar-Hernandez, Deetman, et al., 2021):

- Low resolution of product categories (I.e., families of individual products that have different functions, and more important, require specific technical approaches to realizing CE)
- Expression of transactions between industries in economic instead of physical terms. This is particularly important for CE modelling, since end-of-life components or waste have no, low and highly variable value so that economic value does not represent well physical flows.
- No or limited detail for specific re-use and waste management sectors, while they are the ones most relevant for CE
- No data on in use material stocks, while these determine future outflows of end-of-life products

In brief, there is also a need for an expanded and systemic data collection efforts for CE. This work needs to realize more detail in EEIO data and present sectors involved in re-use and recycling of products in physical terms. A common practice in the EEIO community for the development of databases with high product resolution is to gather LCA data such as Life Cycle Inventories. LCI data can be obtained from multiple sources, and each providing a different level of accuracy (Parvatker & Eckelman, 2019). For instance, while plant data provides the maximum level of accuracy, in many cases, this data is not accessible due to security and intellectual property concerns. Therefore, simulation tools are the next best option in lack of confidential industrial data (Parvatker & Eckelman, 2019). In this thesis we make a distinction between simulation software created to solve one or a limited number of specific problems, and standardized software tools such as Computer Aided Technologies (CAx). The former typically focuses on only specific applications and analysis, it may vary in quality as it may be developed by software developers with limited resources, and as a result the number of users may be smaller. CAx, on the other hand, generally enjoy a high level of standardization and support, general feature richness and a large user-base. This is software that is already broadly used by product developers and engineers.

In this thesis we focus on the former as replicability of results and standardization of practices is of great importance to create a reliable data pipeline for continuous data collection. However, simulating entire products and their production processes is also a labor intensive effort. Techniques from Artificial Intelligence and the use of digital technologies may be needed to promote automation in data retrieval and in estimation of missing data. Such practices in connection with the broad use of data collection efforts through digital technologies should then become pervasive systems of data collection for the fields of CE and Industrial Ecology.

1.4 Problem statement and research questions

In the previous section, we saw a number of issues. Firstly, we found that EEIO in principle is a good tool that can help to assess economic, social and environmental implications of CE strategies. Such assessments usually are supported by first analyzing the priority 'hot spots' of environmental pressures in a system, and then analyzing how CE interventions may reduce them but, secondly, we also found that methods like MR EEIO analysis require a high level of skills to make such scenarios, leading to the suggestion that a CE scenario tool may help policy makers and practitioners easier to gain insight in good CE options, and hence, CE dissemination. Thirdly, while MR EEIO maybe a very promising tool for CE analyses, it is likely that in future more detailed data will be required than what is currently available in existing MR EEIO databases. Since data collection is usually labor intensive, this leads to the question whether simulation tools, artificial intelligence methods and digital technologies can support these efforts.

Based on this problem statement, the main research question and related sub-questions are articulated in this way:

How can we facilitate and promote the environmental, social and economic assessment of Circular Economy interventions at the macro level?

- Sub-question 1 – How can MR EEIO be used for priority setting of CE interventions?
- Sub-question 2 – How can CE strategies be modelled with MR EEIO?
- Sub-question 3 – How can we create a user-friendly interface for modelling CE strategies with MR EEIO, easily accessible for non-specialists?

- Sub-question 4 - How can we use Computer-Aided Technologies (CAx) and Artificial Intelligence (AI) methods to increase data availability for the analysis of CE?
- Sub-question 5 - How can the IE community position itself with regards to AI and digital technologies to better support sustainability and CE assessment?

1.5 STRUCTURE OF THE THESIS

In relation to the questions above, this thesis is structured as follows.

Chapter 2 studies the environmental and economic impacts of final consumption of agricultural production due to imported consumption. The study is used to understand how MR EEIO can be used to support policy making and to highlight hot spots related to the impacts of international food supply chain.

Chapter 3 concerns the development of software and methods for standardized and replicable CE scenario making in MR EEIO. A case study is also presented on the global environmental and socio-economic impacts of the implementation of CE strategies.

Chapter 4 develops a web-application with the intent to facilitate low-threshold access to and use of MR EEIO data, in the form of a CE scenario tool that offers easy to interpret outcomes and visualizations.

Chapter 5 addresses the issues of data availability and resolution in MR EEIO. By performing a systematic literature review we show how computer-aided technologies and artificial intelligence methods may be used to generate and estimate data useful for LCIs, which in turn could be used to enrich LCI and MR EEIO databases.

Chapter 6 presents a vision of some key experts for the industrial ecology and circular economy communities on how to improve data collection practices by leveraging digital technologies (DT) and artificial intelligence (AI) methods. It discusses challenges and opportunities in the use of AI and DTs and presents recommendations for future steps.

Finally, chapter 7 provides answers to the research questions posed in the former sections, provides overall conclusions, and reflects on topics for further research and policy implications.

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