7 DISCUSSIONS AND CONCLUSIONS

7.1 INTRODUCTION

With this thesis we aimed to investigate multiple ways to facilitate and promote the environmental, social, and economic assessment of Circular Economy (CE) interventions at the macro level. The various chapters tackled different issues related to this topic. The second chapter concerned the investigation of the environmental, social and economic impacts of final consumption of imported and exported agricultural products by the Netherlands. This study was used to understand how EEIO can be used to advise policy makers in finding hot spots for reducing environmental impacts. In the third and fourth chapters we investigated methods for replicable scenario making, and tools to facilitate access and promote the use of EEIO data to analyze circular economy interventions. In the fifth chapter, we described the use of Computer-Aided (CAx) Technologies and Artificial Intelligent methods to improve data availability for LCIs and EEIO. Increased data availability can facilitate the assessment of circular economy by allowing the modelling of interventions at a detailed level to study their macro effects. Finally, in chapter six, artificial intelligence methods and digital technologies are discussed further to show ways forward for the industrial ecology community for the development of models, systems and collection of data to the benefit of sustainability and circular economy. All these chapters helped to answer the overall research questions and sub-research questions formulated in section 1.4 of this thesis, on which we elaborate in section 7.2 below. Then section 7.3 presents limitations of this thesis and future research directions while 7.4 discusses the implications for policy makers.

7.2 CONCLUSIONS

7.2.1 Introduction

In this concluding section, we address in the next paragraphs first the sub-questions as formulated in section 1.4:

- Sub-question 1 – How can MR EEIO be used for priority setting for CE interventions?
- Sub-question 2 – How can CE strategies be modelled in 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 CAx and artificial intelligence 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?

We then discuss the answer on the main research question, formulated as: How can we facilitate and promote the environmental, social and economic assessment of Circular Economy interventions at the macro level?

7.2.2 How can MR EEIO be used for priority setting for CE interventions?

Chapter 2 showed an assessment with MR EEIO of the environmental and economic performances of countries and sectors with regard to agricultural and food production. The assessment demonstrated that it was possible to identify where the highest environmental pressures take place and where the highest value added is created. Additionally, a multi-indicator analysis was performed in order to avoid biased priority settings toward a single indicator, which could lead to problem shifting in phase of policy implementation. To this end, chapter 2 provides results on multiple environmental pressures (i.e., greenhouse gas emissions, water consumption, land use, raw material extraction), and additional results for other indicators and their regional and sectoral breakdown can be found in a dashboard provided in the annex to the chapter. Besides the identification of hotspots, another aspect of priority setting concerns the assessment of

CE strategies. By modelling CE strategies in chapter 3, we showed how interventions can be prioritized to obtain the maximum mitigation of environmental pressures. Chapter 4 ties these two approaches together by providing a web-application where hotspot and footprint analyses can be performed for all products and regions in EXIOBASE for a multitude of socio-economic and environmental indicators, while also modelling complex CE scenarios. Scenarios can be compared against each other and the baseline to identify the most effective CE interventions. However, our conclusions also indicate that in many instances a mere computational approach is not sufficient and contextualization of results and value judgments (e.g., where to produce) play a key role in determining whether and how a sector or an intervention should be prioritized.

7.2.3 How can CE strategies be modelled in MR EEIO?

In the third chapter of this thesis, we investigated how CE scenarios can be implemented in MR EEIO and presented procedures that promote their replicability. The described framework had the intent to clarify terminology and structure behind modelling concepts by depicting an overview of the structure of CE strategies and their implementation in MR EEIO. Based on previous literature, we showed that taking CE as the economic paradigm to be implemented, different strategies can be applied (i.e., product life extension, resource efficiency, closing supply chain loops, residual waste management) (Aguilar-Hernandez et al., 2018a). Chapter 3 developed modelling blueprints by CE strategy, which are schemes depicting elements of MR EEIO that could be modified to simulate CE interventions. This supports building transparent and replicable scenarios. More specifically, the blueprints allow to indicate which values in the IO tables need to be modified and how (e.g., reuse of a product may result in final demand changes in terms of transactions for said product and supportive services to facilitate reuse). Such blueprints are not meant to provide a rigid application of modelling approaches but rather to indicate how the interventions may be modelled. The advantage of this approach is that the blueprints may be reused by CE analysts and serve as a first attempt to standardize how CE interventions are modelled in MR EEIO, so that studies become more comparable and replicable. This is further supported by the development of the open source software tool pycirk which facilitates organization of scenarios and modelling which can be shared in a standardized format (see Donati, 2021). It has to be noted that in chapter 3 blueprints were developed only for a number of CE interventions reflecting the product lifetime extension and resource efficiency strategies, leaving closing supply chain loops and residual waste management to future research. Closing supply chain loops was not investigated since the technical implementation is highly product specific. Modelling this strategy implies that new production recipes have to be included in the MR EEIO that have re-used components or recycled materials as inputs, and current MR EEIO tables simply lack this detail. For instance, the product categories of machinery and equipment, and electrical machineries and apparatus, are too broad to allow for a meaningful modelling of closing supply chain loops. Residual waste management could also not be investigated as the complex relationship between consumption, material stocks and waste generation is only captured by physical or hybrid IO databases with a detailed waste management sector, which currently are hardly available at the level of detail required.

7.2.4 How can we create a user-friendly interface for modelling CE strategies with MR EEIO, easily accessible for non-specialists?

CE assessment with MR EEIO could be highly facilitated and promoted if MR EEIO databases and modelling software for CE assessments were easily accessible by all potential users. For this purpose, the use of openly accessible software with standardized procedures and analysis is of fundamental importance. As indicated in in chapter 3, we developed pycirk, a Python package for the modelling of CE scenarios in MR EEIO which allows users with basic programming experience to easily access MR EEIO data and create scenarios that can be easily replicated. However, pycirk still requires a knowledge of Python or command line interface, which cannot be expected from the general public or analysts who have never had experience with coding. For this reason, and based on this experience, chapter 4 developed an online scenario web-application called RaMa-Scene (RawMaterial Scenario tool). RaMa-Scene presents a dashboard through which interactive visualizations are displayed according to the user selection, and it allows for the visualization of common analytical procedures performed with MR EEIO such as environmental footprint and hotspot analysis by product and country, or geographic region. Additionally, it provides a large variety of socio-economic and environmental indicators that can be used to assess the multidimensional aspects of the CE. Furthermore, RaMa-Scene allows users to create CE scenarios, and compare their performance against the baseline data and other scenarios. However, for the same reasons we explained in the previous section, RaMa-Scene is limited to the modelling of Product Life time extension and Resource Efficiency strategies. In order to allow for the assessment of additional CE strategies such as closing supply chain loops and residual waste management various modifications are needed, in part already discussed in section 7.2.3. First, a theoretical model for closing supply chain loop interventions should be developed and implemented as standard procedure, next to enhancing product and sector detail in IO databases to ensure a meaningful product-specific assessment. Second, hybrid, or physical waste IO data should be included in or replace the current monetary IO database to assess properly CE options related to residual waste management.

7.2.5 How can we use Computer-Aided Technologies (CAx) and Artificial Intelligence (AI) methods to increase data availability for the analysis of CE?

Chapter 3 and 4 showed current MR EEIO tables are not sufficiently detailed and lack physical data useful to calculate the implications of CE interventions that require detailed information on specific products (e.g., interventions concerning closing supply chain loops). To overcome such data gaps without excessive research time input, Chapter 5 analysed via a systematic literature review if CAx and AI methods can be used to obtain detailed Life cycle inventory (LCI) data.

CAx appear to provide most of their benefits in the of data for life cycle stages that require industrial processing (e.g, manufacturing of physical goods, chemical products, construction, and energy). This is an obvious result as CAx software and methods are most often developed specifically for the purpose of managing design and manufacturing activities. CAx can therefore offer relatively easy access to LCI data in the manufacturing stage, with some applications in estimating potential recycling and maintenance activities. This is made possible by CAx' ability to generate volumetric and material information of process inputs and outputs, and the creation of process flow diagrams for instance chemicals.

AI methods offer possibilities of converting or extracting data from different fields (i.e., domain specific data) and applications, which can be used in LCIs. This is of great relevance when heterogeneity and volumes of used data and databases goes beyond the ability of practitioners to execute the same task manually. For instance, there is data in large chemical databases and scientific articles that is currently not used in LCI databases. Through methods for natural language processing employing data mining and expert systems, it is possible to find information and relationship in data and written text that could be used in LCIs. Machine learning methods have also shown potential to facilitate the estimation of data where diversity of parameters in the product system and/or objectives are simply not possible for practitioners to perform manually.

In short, CAx have the ability of generating data and AI methods provide the ability to perform repetitive tasks beyond practitioners' ability. Our review showed their combined use is an attractive prospect that can also support LCA scenario studies for instance enabling 1) Optimization of simulated product systems; 2) Generation of a vast range of alternatives (which may or may not be optimal); 3) Estimation of values concerning component's performance over their use (e.g., estimating the life span of a product).

7.2.6 How can the IE community position itself with regards to AI and digital technologies to better support sustainability and CE assessment?

Chapter 6 discusses potential ways forward for a stronger integration of digital technologies and AI in industrial ecology. Industrial Ecology is the science that analyses the physical economy, so any data improvement benefits for the field of industrial ecology means also better tools for the assessment of circular economy. In this chapter, we showed how there are many opportunities to be exploited in the use of AI in combination with existing data and digital technologies. However, various challenges need to be overcome related to resource requirements, data accessibility and governance, explainability, interpretability, and causality. An effective mitigation of these challenges would allow for better exploitation of technological developments in AI for the purpose of promoting sustainability objectives. In particular, the IE community should establish working groups in the IE scientific community to investigate potential research directions to improve exploitation of opportunities while addressing their challenges and potential negative consequences. Such working groups could create inventories and benchmarks for data and models useful for common IE analytical tasks, promote best practices for the sustainable use of AI intelligence from the perspective of energy and material requirements, but also to mitigate potential issues related to the increase in digital divide and general misuses of AI. Generally speaking, the IE community has a responsibility to nurture and actively direct AI developments and should more purposefully engage in these activities.

7.2.7 Answer to the main research question

The former sections now allow answering the main research question:

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

Through the chapters of this thesis, we have presented methods and software for the assessment of circular economy interventions. The methods provided ways of standardizing procedures to enable replicability of studies and hence reuse of scenarios for CE assessment at the macro level. For this purpose, it was also important that easy to use tools such as pycirk and RaMa-Scene were created to standardize methods of analysis and enable the least experienced users to easily create scenarios and assess their environmental, social and economic impacts at the macro level. However, important data limitations still need to be overcome to allow effective analysis of CE interventions in macro level analytical tools. Currently, MR EEIO tables appear to be suitable to model the economic-social-environmental trade-offs of CE strategies such as Product Life time extension and Resource efficiency improvements. However, strategies of Closing Supply Chain Loops and Residual waste management are still challenging to model as MR EEIO tables are not sufficiently detailed or may lack information on the physical dimension of production and consumption in the economy. CE implementation will require many innovations and micro level changes throughout the economy. Such micro level changes need to be modelled to estimate their potential impacts at the macro level. For this purpose, increasing data availability is fundamental. Computer-Aided Technologies and Artificial Intelligence methods can play an important role in increasing data availability to support CE policy. However, coordination of research is required within the industrial ecology community to ensure effective exploitation of AI and mitigation of its potential negative effects. The IE community should engage in actively directing AI developments by creating working groups to investigate data and model benchmarks for common IE and CE analytical tasks in line with effective governance and ethical standards. In turn, this could benefit the community by ensuring a stable stream of data to enrich LCI and MR EEIO databases.

7.3 LIMITATIONS AND SUGGESTIONS FOR FURTHER RESEARCH

This section presents limitations of the studies performed in this thesis and indicates future directions for research concerning software and data for CE assessment. While chapter 2 investigated how MR EEIO could be used to identify hotspots across international supply chains and highlighted the importance of presenting a multi-variate analysis to policy makers, these methods are not strictly applicable for the identification of potential areas where CE interventions may be applied. In fact, chapter 2 employed well established IO methods such as the environmental Leontief model (Leontief, 1970a), regional footprint and hotspot analyses. In other words, although the CE is a new economic paradigm, we may not always need new analytical methods to assess its potential impacts. The tools at our disposal within the industrial ecology and sustainability community may be in many cases sufficient to perform CE assessments (Walzberg et al., 2021). However, we need to think critically in what combination these tools may be used, and which indicators are most appropriate depending on the research question. Wherever possible standardized combinations of tools and indicators should be integrated into software to facilitate the work of analysts to provide robust, comparable, and replicable results to decision makers.

This is not an easy task as circular economy indicators are more than plentiful, and their implementation is uncoordinated across the community. For instance, we see that even national circularity scores are measured differently across different actors and institutions (see for example Aguilar-

Hernandez et al., (2019), Colloricchio et al., (2023) and EUROSTAT, (2022a). Saidani et al., (2019) provided a taxonomy of circular economy indicators and their potential uses from micro to macro level applications. Such efforts of classifications of indicators should be applauded and followed closely. However, a continuous increase in number of methods and indicators is to some extent unavoidable as it is also shown by the vast number of beyond-GDP indicators (Hoekstra, 2019, Chapter 4) and the multiple analytical tools that may be used for circular economy assessment (e.g., Donati et al., 2021; Lange et al., 2021; Walzberg et al., 2021). Where possible, convergence of methods and indicators, and their integration in modelling software is desirable.

Nevertheless, a consensus is unlikely to be reached and it is also reasonable to expect analysts to use a variety of analytical tools depending on the research question. For instance, the demand driven model at the base of our approaches in chapter 2 through 4 is a linear model. We know, however, that socio-economic and environmental dynamics can be complex and non-linear. The hybridization of static with dynamic models, such as the use of Agent Based Modelling (e.g., Di Domenico et al., 2022) or Computable General Equilibrium Models using MR EEIO data (e.g., Winning et al., 2017), may provide additional insights into CE that are simply out of reach for linear models such as the Leontief model. As such, future research may also investigate how methods can be combined depending on the research question, their transparent application, and their replicability. This may be achieved by promoting the development of open-source software libraries and digital fora where the communities of CE scenario modelers and software developers can meet, share knowledge, and store software and methods. One example of such community can be found in in the *opensustain.tech* initiative (Augspurger et al., 2023) which keeps an inventory of all open source software for sustainability. Such initiative could be developed even further to include inputs from analysts, as well as permanent storage and online use of developed software.

As shown in chapter 3 and 4, the presented tools (i.e., pycirk and RaMa-Scene) allow for many types of environmental, social, and economic impacts using MR EEIO databases. However, the results these software output currently lack a broader context, so we do not know to what extent CE strategies bring us within an environmentally safe and socio-economically just space, or whether the modelled CE interventions need to operate within certain physical and social boundaries. Future research should seek the integration of material constraints, and other contextual information such as planetary and social boundaries into software for CE assessment (see for example O'Neill et al. (2018) or Di Domenico et al., (2022)).

Additionally, while in chapter 3 standardized methods of scenarios construction and the sharing of modelling assumptions were suggested and we see their current use by analysts (Colloricchio et al., 2023), they are yet to become common practice and they will need promotion of standards across the scientific community. The recent developments is ISO standards for measuring and assessing circularity (ISO, 2023) may represent a great opportunity in this regard, provided that they are also expanded to include guidance for the construction of CE scenarios. Such standards could then be integrated into software tools for CE assessment, thereby improving replicability and comparability of studies, and transparency of assumptions. Therefore, future research may also investigate effective ways of sharing data for scenarios construction, and the development of centralized systems to collect scenario data so that modelers can more easily access fundamental data for their analyses. For example, Creutzig et al., (2022) have conducted an in-depth review where they have collected, among others, data for CE scenarios. However, this is an annex to a scientific study, while the community of CE modelers could benefit from a web-based fora where the data could be more easily searched, reused, and expanded through time as new CE studies become available.

An important limitation found in the assessment of CE scenarios was the use of monetary MR EEIO data. In the studies performed in this thesis, there was conscious choice to use monetary data. This choice was driven by the desire to facilitate access to environmental data most commonly used by practitioners and data that is frequently curated. In fact, hybrid MR EEIO data containing physical information about the structure of the economy is uncommonly used by practitioners and analysts partly due to the lack of consistent curation by most National Statistical Offices and supranational organizations (Wiebe et al., 2018). However, CE interventions have an important physical component that is difficult to capture through monetary data. As a result, CE strategies such as Residual Waste Management and Closing Supply Chain Loops could not be modelled. Future research should integrate hybrid MR EEIO data into software tools to model circular economy scenarios, and additional efforts are needed in the promotion, expansion, and use of Hybrid MR EEIO by analysts and statical offices.

Through the modelling of CE scenarios, it also became clear that CE strategies are composed by micro-level changes across supply chains (see chapter 3). However, MR EEIO data only presents large aggregates of product categories. For example, it is often not possible to distinguish between subparts of a manufactured product (e.g., car, engine, wheels, etc). This is a big limitation in the modelling of CE interventions such as remanufacturing and repair. For this reason, chapter 5 and 6 explored potential opportunities to increase data availability on production systems. While we investigated CAx and AI methods to increase data availability for LCI and MR EEIO data, methods from other fields that could also be helpful were not included. For example, the field of operation research may offer techniques that could further expand possibilities for data generation, and the same could be said of subfields of AI that were not directly investigated such as image recognition. Moreover, CAx predominantly focuses on manufacturing of complex products and chemicals. Agricultural production is therefore not well represented in the analysis for CAx in chapter 5. At the same time, simulations tools specific for the agricultural sector do exist and should be further investigated to understand whether they could be used to generate data for LCI robustly. Also, chapter 5 did not include studies that showed methods of direct data collection from industrial actors. This was a conscious choice as we were interested in how to obtain data independently from direct collection from industrial actors. However, there are many interesting developments that could be of great benefit for data collection for circular economy assessment as shown also by Rusch et al., (2023). Future research should also be dedicated to finding how direct data collection may be possible from industrial actors, how National Statistical Offices may integrate this data for the purpose of CE, and how industrial secrecy and intellectual property rights could be protected. With regards to this last point, care should be given when simulating production systems independently from industries as some industrial actors may be litigious toward people who unravel details of their productions (Goldstein & Newell, 2019). Additionally, while we tried to investigate how to improve product detail of MR EEIO data through the expansion of LCIs, we did not research ways of increasing regional detail. Regional detail is important to identify where impacts may occur as a result of CE implementation.

At last, chapter 6 presented potential applications of digital technologies and AI from experts' knowledge and from partial scientific literature. Future research could provide more in-depth reviews (e.g., through systematic reviews) on these topics and offer exemplification of recommendations so that they can be more easily implemented by the scientific community.

7.4 IMPLICATIONS AND REFLECTIONS

In recent years there have been many policy developments at different levels aimed at increasing data availability, quality, and accessibility. For example, national statistical offices, EUROSTAT, and supranational organizations such as the Organization for Economic Co-operation and Development (OECD), United Nations Statistics Division (UNSTATS) and United Nations Environment Programme (UNEP) have supported the development of multiple platforms to facilitate the diffusion and comprehension of official statistics. Examples of this are the OECD data portal, UN COMTRADE and the World Environment Situation Room (WESR) respectively. This trend appears to likely continue as the need for insights into the sustainability of our economy in relation to the ecological crisis is crucial for science-based policy making and for informing the public. In the meantime, policies concerning CE are in the processes of being implemented, and they will influence the way we collect, store, and use data. For instance, in the context of the EU Digital Strategy (European Commission, 2022), the European Strategy for Data (European Commission, 2020) and the New Circular Economy Action Plan (European Commission, 2020), the European Commission is set to create CE dataspaces which will store information on circularity, potential for disassembly and sustainability of products. Additionally, the EU Carbon Border Adjustment Mechanism will also require the collection of data on material composition and GHG emissions of products and validation methods by authorities and specialists. These are just a few of the crucial environmental policies for which improved data is needed. However, these ambitions will fall short if insufficiently supported in terms of governance and funding. For this purpose, national and international organizations should be engaged in the process of harmonizing data practices across regions, in the institutionalization of data collection practices to support these ambitious policies, to provide a clearer picture of how we use natural resources and the impacts across the life cycle of products and services. This would greatly benefit society ability to tackle the ecological crisis and help us to transition to a sustainable and circular economic system. The path forward is not void of challenges, but the active management of these development should help us in mitigating these challenges and promote the benefits. The work presented in this thesis aims to provide a humble contribution to these developments.

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