Software and data for circular economy assessment
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SUMMARY

The circular economy (CE) is an industrial economic paradigm promoted with the aim to minimize the absolute consumption of resources, and the emission of pollutants while ensuring optimal socio-economic performance. This aim is pursued through multiple technical (e.g., business model changes and novel technology implementation) and policy approaches (e.g., changes in regulations to promote or limit certain activities). There is great diversity of circular economy strategies and the degree of implementation may vary greatly depending on the local industrial conditions, households behaviors and the ambitions of policy makers. Some of the key CE strategies include Product Lifetime Extension, Resource Efficiency, Closing Supply Chain Loops and Residual Waste Management. The structure of the global production and consumption system to which an economy or industry is connected plays an important role in how the impacts of implementation of CE strategies play out. For example, while circular economy strategies in the Netherlands could result in a longer product lives and more jobs in the repair sector, they may result in worse economic performance abroad in countries where primary production is located. Assessing the size of economic, social and environmental performances in exporting countries is helpful to understand the implications of implementation of circular economy strategies across the international system of consumption and production. Such insights are necessary to fully understand the benefits and barriers of policy and technical implementation, as changes in one sector or region will inevitably cascade across global supply chains. At the same time, environmental pressures are very diverse, and optimization to reduce emissions on one side could results in higher resource extractions or other unintended impacts (see chapter 2). In sum, economic, social and environmental impacts of CE measures in a specific country or sectors can be spread geographically, are interconnected and are diversified in type. Therefore, it is important to understand potential trade-offs of CE strategies. This thesis hence puts the question central how the economic and environmental effects of CE strategies can be assessed and the detailed data needed in such assessments can be obtained.

In chapter 2 we showed how the analysis of economic and environmental trade-offs may be performed for the agricultural sector. *Multi-Regional*

Environmentally Extended Input-Output Analysis (MR EEIOA) is a very suitable tool for this purpose, as it allows to perform analyses such as hotspot and footprint analysis of product groups and parts of the value chains which are responsible for high level of environmental impacts. The data underlying MR EEIOA (i.e., MR EEIO tables) is based on economic Input-Output (IO) tables. Such tables divide 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 by country defines the Gross Domestic Product (GDP). 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). So, a global MRIO covers global value chains, social information like numbers of jobs, economic information like value added. If a MRIO system (global, subnational or otherwise), comes with a set of environmental extensions, it is referred to as a MR EEIO system. This MR EEIO data in combination with analytical methods such as footprint and hotspot analysis are a suitable starting point for developing improvement options such as CE interventions.

There are however challenges in the employment of MR EEIO for analyzing the impacts of CE strategies. For example, scenario modelling software is not easily accessible. Scenario data often cannot be reused due to opaqueness of used inputs and how they are implemented to construct counterfactual scenarios. These challenges motivated the second study presented in this thesis in chapter 3, for which we developed a software in Python called pycirk, through which policy analysts can create complex scenarios and analyze their results. In addition to that, we provided a standardization of how CE strategies for product life extension and resource efficiency may be implemented as starting point to begin providing clarity and transparency on how these scenarios can be constructed. The tool allows for scenario settings in the software to be easily shared across different types of users and in publications thanks to their standardized structure and readability. For this study we also performed an analysis on product life extension and resource efficiency measures concerning the use and manufacturing of durable products (i.e., machineries and vehicles) and constructions. The presented software and methods were used to perform the analysis, which highlighted limitations and potential uses. For instance, assumptions had to be made in lack of detailed information on product categories that are typically aggregated in MR EEIO databases. Additionally, while standardized methods provided guidance in the modelling of the interventions, adaptation was still needed in some cases.

While the *pycirk* software facilitated various scenario analysis operations, it still had a high entry level for practitioners without a computer science background and lacked a graphical user interface for immediate visualization of results. For this reason, as described in chapter 4 the RaMa-Scene web-application was developed (https://www.ramascene.eu). The chapter presents a web-application with a graphical user interface that would be accessible by anyone with an internet connection and through which it would be possible to construct complex scenarios and quickly visualize and download their results, thereby lowering the entry level to access MR EEIO data. Since its deployment, RaMa-Scene has been used in classrooms and by consultants to study socio-economic and environmental impacts of products and potential policy implementations.

However, both in chapter 3 as chapter 4 we found MR EEIO data only allow modelling CE strategies such as Product Life time extension and Resource Efficiency strategies. MR EEIO tables currently are insufficient detailed to model Closing supply chain loops. This requires a very high product and even component level resolution to simulate the re-use of products and components central in this CE strategy. Furthermore, MR EEIO also describes the economy in monetary terms, while particularly for CE strategies such as Residual waste management a physical MR EEIO would give more insightful results. Product categories in MR EEIO data are often aggregates of different products (e.g. mobile phones, PCs etc. combined to electrical and electronic products) and, sometimes, their services. Circular economy interventions and their changes often affect specific relationships in supply chains and regions, which pushes the limits of applicability of input-output methods. However, as indicated MR EEIO tables have the advantage of giving a comprehensive representation of the interconnected relationships of economies and industries across the globe, something that is typically not possible to obtain from other types of databases such as those used for Life Cycle Assessment (LCA) or trade analysis. In other words, during the time span in which this thesis was written (2017-2022) the choice between databases for economic and environmental analysis presented important tradeoffs between detail and comprehensiveness of data. Some authors have tried to employ hybrid methods to compensate shortcomings in data and methods. Such hybrid LCA methods make use of the rather aggregated MR EEIO data as background data, and detailed Life Cycle Inventory data for foreground data. This type of hybridization is convenient as LCA and IO methods share similar computational methods, and LCI data in some cases is used to detail MR EEIO databases or to estimate environmental extensions. However, data collection at the level of detail required to assess impacts of existing supply chains and model the changes of circular economy interventions is a time consuming and labor intensive practice, which sometimes also may be limited also by data confidentiality.

In the fifth chapter of this thesis, we investigated these challenges and described how Computer Aided Technologies (CAx) have been used to obtain information that can be useful to complete LCIs; and how Artificial Intelligence (AI) methods have been used to support data estimation where direct data collection or simulation was not possible or impractical, and data conversion from a variety of sources. This work not only contributes to the expansion of LCI data, but it also promotes a stronger integration of LCA with open source software used for product design, and contributes to the development of digital twins of supply chains. These data and systems could then be used to increase the product and industry detail of EEIO databases, promoting an ever more seamless transition from LCI and MR EEIO data. However, while simulations of production systems and supply chains, and the conversion of heterogenous domain specific data and knowledge for LCA and MR EEIO can be an important source of data for CE, more coordination is needed to make the best use of the current digital infrastructure, expertise and automation methods to improve our ability to assess the socio-economic and environmental impacts of the circular economy. In this regard, the last paper of this thesis offers a perspective to the industrial ecology community on how to use digital technologies in combination with AI methods to support decision making for sustainability at all levels.

There are multiple limitations in the work presented in this thesis, which represent inspiration for future research. Firstly, while MR EEIO proved to be an effective tool to model CE interventions for Product Life extension and Resource efficiency strategies, as discussed above is not yet well suited to model Closing supply chain loops or Residual waste treatment options, recycling and changes in material stocks due to the lack of physical data on production and consumption, next to a lack of detail in product and component resolution. Hybrid MR EEIO and waste IO would allow to better capture physical aspects concerning the CE. Future research should expand the use of tools for CE assessment to include hybrid and more detailed MR EEIO data. Additionally, while many types of environmental, social and economic impacts can be assessed with MR EEIO databases, this framework has hardly been linked to the concept of planetary and social boundaries. That is important to understand if CE strategies bring us within an environmentally safe and socio-economically just space. Future research could investigate how to integrate quantifiable social and planetary boundaries into easy-to-use tools such as RaMa-Scene. Furthermore, the demand driven model at the base of our approaches 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 may provide additional insights into CE that are simply out of reach for linear models such as the Leontief model. While we investigated CAx and AI methods to increase detail in data availability for LCI and MR EEIO data, methods from other fields that could also be helpful were not included. Similarly, we did not research ways of increasing regional detail.

The recent developments from national statistical offices and supranational organization to increase diffusion and use of official statistics will likely continue and as the need for insights into the sustainability of our economy in relation to the ecological crisis, more and more effective tools for data and scenario exploration (e.g., for circular economy and sustainability assessment) will be need. 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, the European Strategy for Data and the New Circular Economy Action Plan, the European Commission is set to create CE dataspaces which will store information on circularity, potential for disassembly and sustainability of products. 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.