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Creating and evaluating a metric for circularity and data security in the context of circular economies

– A work based on the Onto-DESIDE project

Evaluering av en skapad metrik för cirkuläritet och datasäkerhet inom cirkulära ekonomier

Vilgot Åström
Albin Norén

Supervisor : Niklas Carlsson
Examiner : Marcus Bendtsen

Linköpings universitet
SE–581 83 Linköping
+46 13 28 10 00 , www.liu.se

Abstract

In the present-day context it has become apparent that the current economical system, which is based on the "use and discard" attitude, is unsustainable. An alternative to the current system is a circular economy (CE), where all material is used as much as possible by recycling and reusing. Establishing communication between producers is necessary to enable a CE by facilitating information sharing about production and waste.

The purpose of this thesis is to explore CEs, information sharing and the relationship between the two. The research is divided into two specific but interconnecting parts: a literature study and a simulation. The goal of the literature study is to investigate and evaluate metrics regarding CEs and information sharing. Apart from researching metrics, the literature study also explores the Onto-DESIDE project, which is working on creating a platform for sharing information between actors partaking in a CE. In parallel to the literature study, a simulation is created that can emulate a basic CE where resources and material can be traded between producers. To give a more versatile result, the initial values are changeable.

From the literature study, several metrics are presented that measure aspects of a CE, of which the Global Circularity Metric (GCM) is chosen as particularly useful for its ease of implementation. As for information sharing, a new metric called "Sharing Index" is created. The results from the study are then applied to the simulation to create diagrams that showcase the tradeoff between how circular a system is, compared to how much information each producer needs to share. The results from the simulation show that producers who share information and resources benefit the economy. Depending on initial values the outcomes may vary, but a general conclusion is that a producer only need to share their resources with a specific percentage of other factories partaking in that economy to keep the circularity of the economy at a satisfactory rate. In a wider context, this thesis contributes to the understanding of CEs and the significance of information sharing for their success.

Acknowledgments

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1 Introduction

The purpose of this project is to research and produce metrics that can aid in measuring a Circular Economy (CE). This chapter starts by presenting the motivation behind the thesis. After that, the aim is presented, which is followed by the two research questions. Next, the delimitations of the project are presented, where all the initial restraints are set. Then, the contributions of the thesis are presented which is followed by the outline of the thesis.

1.1 Motivation

As the world seeks to face the challenges of resource scarcity and climate change, new methods of tackling these problems are needed. One of these ideas are CEs, a system in which resources are reused and passed around rather than the traditional linear approach [1]. While CEs have great potential for economic, ecological and social development, it is imperative to measure their effectiveness and progress [2]. Depending on how a CE is measured, results can vary widely, which can hinder informed decision making by stakeholders and policy makers.

Utility metrics can provide a way of measuring efficiency and impact of a CE as well as tracking circularity of products and resources in a system. There are many aspects to consider, such as economic growth, information exchange and environmental impact. As different stakeholders may have different perspectives on what constitutes as a valuable metric, it can be difficult to define one that is applicable in broad areas.

One aspect which needs to be considered in this day and age is data security and the availability of data. A CE relies heavily upon the sharing of resources and information about them. The flow of information would optimally be shared amongst all who need it. However, in an economy that favors competition over cooperation, this assumption can not be made. Thus, determining the tradeoff where the CE is working at a good rate but a minimum amount of information is being shared should be done.

1.2 Aim

This thesis aims to define and evaluate a utility metric for CEs in relation to information sharing and data security.

1.3 Research Questions

Through the combination of a systematic literature review and a simulation of an abstract version of a CE, this thesis answers the following questions:

1. What should be included in a utility metric for a circular economy?
2. What tradeoffs between data sharing and privacy are needed to ensure a well-functioning circular economy?

1.4 Delimitations

There is a large amount of proposed solutions towards implementing a CE. To be able to write a comprehensive thesis in an acceptable timespan, a lot of limitations needs to be set. All of these are set to create reachable goals.

Although a CE is supposed to work in all fields, this thesis is focusing on the textile industry. Despite different sectors being affected in different ways from a CE, by choosing one specific case it is possible to draw a broad conclusion in the context of this thesis' aim. Additionally, the textile industry is easy to reduce to a manageable amount of data where the waste that is being produced can be used by other factories in the same sector.

This thesis does not consider the appliance of blockchain technology in CEs. Although the research on this has good prospects, it is considered to be outside the scope of this project.

This project has created a simulation of a CE. This simulation does not focus on establishing a real world reflection of said economy. Instead, the purpose of it is to aid in creating and testing the utility metric.

Finally, the concept of CEs are treated as a net positive concept. The goal of the thesis is to strive towards a system that is as "circular" as possible. Therefore, negative aspects of CEs, such as transport costs or environmental impacts will not be accounted for. This includes the simulation, where a favorable result is indicated by a high amount of circulated products.

1.5 Contributions

This thesis provides an initial simulation framework for measuring the circularity of a system where the amount of products which is shared between producers is taken into consideration. Apart from that, two new metrics are presented: "Sharing index", which is the percentage of producers that share their resources with other producers and "Sharing for Stable Circularity index", which describes the level of information sharing that is required to achieve and maintain stable circularity in a system.

1.6 Thesis outline

The reminder of this thesis is structured in the following manner. The next chapter provides relevant information to understand concepts on which the thesis is built upon. After that, a chapter discussing related work is presented. It also introduces findings from the performed literature study and discusses relevant metrics for a CE. The fourth chapter presents the simulation, its architecture as well as several limitations. In the fifth chapter, the results from the simulation are presented. The chapter is sectioned into three distinct parts, each exploring different simulated cases. Following this, the next chapter provides thorough discussion of the method and results. It also places the work in a wider context. Finally, a conclusive chapter presents a summary of the work and states answers to the research questions. It culminates by discussing future work in the area.

2 Background

This chapter provides the reader with relevant information to gain a comprehensive understanding of underlying concepts, ideas, and theories. Firstly it introduces CEs, their importance, proof of concept, some obstacles and its relevance in the textile industry. After that, some concepts, projects and terms are explained, setting the stage for the thesis.

2.1 Circular Economy

The underlying concept of this project is CEs, it is therefore crucial to have a basic understanding of their purpose and why they are important. The past century has made it clear that earth is not an endless resource and that the current "linear" economical system is unsustainable [3]. In a linear system, the producers of goods act in isolation by obtaining, using and then discarding material without communicating with other parties. This is a result of the concentration of wealth combined with the cheap cost of material [3].

An alternative to this unsustainable economical structure is a CE. The main purpose of a CE is to reduce waste from producers by establishing a distributed network where these producers can share information specifying what waste they are creating and what resources they need [4]. This works in many areas, including raw material, energy and heat [5]. The resulting effect of doing this is that waste which otherwise would be discarded can be reused.

The European Union (EU) has been actively promoting the transition towards a CE in recent years [6]. It has launched funding programs, such as the Horizon 2020 program, which supports research and innovation on CEs on a regional level. Furthermore, the EU is actively encouraging business owners, governments and civil society organizations to collaborate and promote CEs. The long term goal is to reach climate net neutrality by 2050, and to be able to reach this, CEs play a prominent role [7].

Proof of Concept

There has been extensive research on the subject of CEs, spanning from possible application areas to actual proof of concept. One organization that has dedicated significant resources to researching CEs is the Ellen MacArthur Foundation, which has generated several promising statistics. It has, amongst other things, presented two possible scenarios for implementing a CE, a "transition scenario" and an "advanced scenario". A "transition scenario" is a theoretical scenario that depends on moderate assumptions regarding how well-established the CE has become. In contrast, in an "advanced scenario", the calculations account for a world that has undergone more radical changes towards a CE, such as cross-sector collaboration and legislation. It is estimated that the implementation of a CE would save the EU 340-380 billion USD per year in material cost in the case of a "transition scenario". By broadening the perspective to an "advanced scenario" the expected savings increase to 520-630 billion USD, which represents 3-3.9% of the total GDP of the EU in 2010 [8].

Aside from economical speculations, there are several real-world examples of CEs in work. One of these is in the city of Kalundborg in Denmark. In this city, five different companies, including a power plant, an oil refinery, a biotech and pharmaceutical company, a producer of plasterboard and a soil remediation company, take part in what can be seen as a CE [9]. One of the shared resources is the cooling water, which is produced by the refinery, where 95% of the water that is sent to the power plant comes from said refinery. Another shared byproduct is the heat coming from the power plant. The heat, which otherwise would have been discarded, is distributed between the Kalundsborg residencies. This redistribution has replaced 3500 oil-fired residential furnaces and provided heating for a fish farm [10].

Obstacles

A major element required for CEs to work is the communications network. The challenge in establishing this type of network is not only the interaction between people, but the standardization of a wide array of databases. In contrast to the human language, which has been uniformed over thousands of years, "computer language" is still in its infant stage of standardization. The data standardization issue is a known problem which is displayed in many fields, including ecology and economy [11, 12]. This problem will be amplified when trying to connect entire industries across different sectors.

Furthermore, it is impractical to rely on total cooperation between all affiliated parties. There may be conflicts of interest between different companies, restricting the amount of information that they want to share with each other. This aspect needs to be considered and a trade-off between how circular the economy is compared to how much data is shared needs to be done.

Textile Industry

The textile industry is one of the largest industries in the world, and it is growing [13]. Between 2000 and 2014, clothing production doubled [14], and today production has passed 80 billion garments each year, an increase of 400% in 20 years [15, 16]. This increase can be somewhat explained by the global population growth, but it is also believed to be largely due to the fast fashion cycles of the textile industry [17]. Due to fast fashion and higher production rates, textile waste has increased significantly [18]. This textile waste is usually separated into two categories: pre-consumer and post-consumer textile waste [19].

Pre-consumer textile waste is defined as the waste generated during production, which is estimated to be around 12% in the industry [20]. This also includes overstock, when factories produce more than necessary and sell off products to incineration plants. In a perfect CE, this waste during production would be sent somewhere it could be used or recycled. However, today it is mostly incinerated or sent to landfills [20].

Post-consumer textile waste is defined as the waste generated by consumers. This includes damaged and unwanted clothing [21]. Globally, it is estimated that around 84% of used textiles ends up incinerated or at a landfill, while less than 1% is recycled and used again in the same industry [20].

2.2 Metrics

Metrics define how the world is seen, and affect decisions and actions made in it. This makes it essential to reflect on which measures are included in a metric. For example, if an organization includes two measures in a metric while leaving out two others, the included measures will be the ones the organization tries to optimize. The people producing the best results in accordance to these measures will be favored for new positions, and soon everyone will be working towards optimizing the measures included in the metric while other measures are abandoned. In this way, the organization shifts into doing only what is measured in its metrics. This is why it is important to choose metrics carefully [22].

Circularity

Today, a wide range of metrics are used to measure circularity in a CE since no standards are set [23]. Some indices focus on how much material in an industry is first-use feedstock and ends up as unrecoverable waste, compared to the total amount of material flowing in the industry [24, 25]. These metrics mostly focus on how the flow of products move between agents in the context, while excluding any impacts outside of the current industry. Other circularity metrics try to cover more measures to assess circularity in a wider context, including economic increase, environmental impact, energy usage, and resource depletion [26, 27, 28]. While these metrics are broader and therefore may produce more accurate indices, their extensive nature might make them more difficult to implement and measure.

Information Sharing

In any supply chain, a compromise needs to be made between how much information each participant shares and how optimized the flow is. The type of shared information can include production levels, inventory status, maximum loads and capacities, current connections, waste output, and more. This would be considered an "absolute sharing" scenario, whereas the opposite would be a scenario where each participant only shares their actual orders with immediate neighbors in the supply chain. Usually, levels of shared data will fall somewhere in between the two scenarios [29]. To measure this, relevant metrics are used. A variety of metrics exist and they each include different measures. Some are more focused on the type of information shared by agents, how valuable that information is to both the sending and receiving party and what it can be used for, while others measure how far shared information reaches in a supply chain [30, 31]. It is also relevant to measure how much control each participant has in governing how different levels of access is distributed among other participants.

2.3 The Solid Project

The Solid project is an attempt to "re-decentralize" the internet [32]. The web has gone through a shift of power in recent years, the control of information and data that is shared across the internet has been assumed by large companies such as Alphabet, Meta and Amazon [33]. This goes against the founding principles on which the internet was built [34]. To counter this, the Solid project has been introduced as a possible solution.

Solid is built through pods (personalized online data stores) . A pod works as a private data storage and can be located anywhere. The Solid project website has some recommended hosts which can be chosen from, but users can also host their own pod. The host can monetize their servers through monthly subscription or ads. In the pods, data is stored which would otherwise have been stored on cloud services that large companies provide. Apart from that, users can store account information and login credentials. This enables users to log in through Solid when encountering new services requiring an account.

One important aspect of the Solid project is the extensive control of data which the user has. A user can specify different access rules to different companies by, for example, sharing their photo library with Instagram while restricting it to Twitter. Apart from defining access rules between different companies, a pod-owner can also differentiate access rules between other users [35].

2.4 Onto-DESIDE

This thesis will look at the Onto-DESIDE project. The project is researching the possibility to develop and utilize a semantic data standard for industries in a CE [36]. As stated previously, one of the main obstacles towards creating a functional CE is the communication. To manually combine data from different industries having various ways of storing and classifying information would be a massive undertaking with difficulty for expansion. Having a network of ontologies makes it convenient for companies to add their own databases. The Onto-DESIDE project started in June 2022 and is set to finish 2025, which means that this thesis only will cover its first stages. The project is funded by the EU Horizon group and works together with companies like Ragnsells and Lindner.

2.5 Discrete Event Simulation

In many fields, testing new ideas or processes can be time-consuming. In such cases, using a simulation as a testing environment can be a beneficial approach. A simulation refers to a program that mimics real-world situations, allowing users to study, analyze, and test different scenarios in a controlled and safe environment [37]. A simulation can either be created from scratch or downloaded as a program, depending on how narrow the use-case is.

There are many types of simulations, this report will focus on employing a Discrete Event Simulation (DES) [37]. In a DES, the simulation can advance through iterative steps. Steps can either depend on a set time, such as days or months, or be set to stop after a special condition has been met. For example, if the performance of a car needs to be tested, each step can depend on every lap in a racetrack.

A simulation can not always be interpreted as a real world representation of what it is trying to reflect. In many cases there are plenty of factors which may affect the result that the developer can not account for. What the simulation actually provides is a controlled environment with a few variables which gives the user total control of its world.

One relevant way of designing simulation experiments is using "one factor at a time" (OFAT). This is a model where all variables except for one are set to standard values, enabling results showing detailed effects of specified variables. This can make the simulation faster and more robust, but can also lead to misinterpretations as interactions between variables cannot be estimated.

One obstacle with simulations that needs to be accounted for is the transient period, which is the initial startup time for the simulation. During this period the simulated results may vary more then in a steady state, this makes it difficult to extract useful information from the period [38]. One methodology to fix this is to plot out the simulated results with each iteration on the x-axis and then see how many iterations it takes to reach a steady state. After that, the iterations before this steady state can be excluded when doing calculations.

2.6 Data Security

Data breaches are a significant problem among businesses and have been responsible for the loss of billions of US$. The cause of these breaches can vary from careless employees to active attacks from a third party. Because of this, businesses invest a large amount of resources to be able to prevent or mitigate these attacks [39].

Security in a CE

Despite the fact that the concept of a CE relies partly on trust and teamwork, it would be naive to disregard the fact that the structure is built upon an economical system that favors competition. When you cannot trust other participating members of the CE it is imperative to have a distributed communications network where data security is in focus. The network needs to balance the amount of available data between companies with how well the CE is functioning.

Access Rules

Access rules define who and what kind of data an entity can access, in for example a corporation, different access rules may be applied between employees and their supervisors. To ensure this protection, an access control list (ACL) can be utilized. An ACL is a list of IP addresses or other identifying information that associates users or groups with data and defines what access rule that relation has. A typical access rule is the read/write rule, where some users may only be able to access the data (read) while others may modify it (write).

What makes access rules and ACLs relevant to this thesis is that the Solid project has implemented a similar function into their pod system, called web access control (WAC) [40]. What differentiates WAC from normal access control is that WAC works over the web and is implemented using the HTTP protocol.

If a pod user is an entire factory instead of a single person, this factory can define the access rules for other factories with data spanning from production information to waste. This can then be implemented over a CE to create a global database with a standardized network but a decentralized data storage.

3 Related Work and Performance Metrics

To be able to create results that are applicable to the real world, a literature study was conducted with the purpose of finding relevant metrics that can be applied to the simulation. This chapter aims to present several of the metrics that are related to the research area and present two metrics that are applicable to the simulation. Furthermore, relevant work from the Onto-DESIDE project is presented.

3.1 Literature Study Approach and Workflow

A large part of the thesis consists of a compilation of diverse sources that are relevant to accomplishing the goal of the project. During the first stage of the process, a literature study was conducted where a number of papers were examined.

After a proper understanding of the subject area was attained, a template of the report was drafted with its corresponding subsections. A good template makes it easy to split up the workflow without risking an overlap of information. It also allowed for an iterative process, where new information easily can be added if needed. The information gathering was always a significant part of the project, and did not conclude because the writing of the report or creating of the simulation began.

As the simulation started producing results, the aim of the work became clearer and with that more literature was reviewed. Prior to this, the focus of the literature study was on overlying concepts such as CEs, but after the point in which the simulation started to produce results, the focus of the literature study shifted to finding suitable utility metrics. The metrics that were relevant either to the simulation or subject area as a whole where chosen to be included in the thesis.

Nearly all literature regarding the Onto-DESIDE project was found on their website. In one of the papers, an early add-on to the Solid interface was mentioned. This add-on was then found on a public Github repository which then could be described in the results section.

3.2 Findings from Literature Study

In this section, the findings from the literature study are presented. The study focused on two areas: the current Onto-DESIDE progress and various example metrics.

Onto-DESIDE graphical interface

The Onto-DESIDE project has implemented a first version of a framework that can be applied on a Solid pod[41]. This project, currently called the "open circularity platform" is linked to each Solid pod and makes it possible to set access rules for that specific pod. The interface enables users to specify what database they are trying to access to then perform queries on that database. Users are only allowed to perform these queries if they have the right access rules which is determined when logging in through the Solid account in the interface.

In the demonstrated case there are four specified roles: manufacturer, user, building owner and admin. A manufacturer can read user data and generate their own data regarding their products. A user can only read the products from the manufacturer. The building owner can read about product data. Lastly, the admin can read the entire database. All roles are only able to query the database and not write to it. The querying works through SPARQL, a query language used for querying and manipulating RDF (short for Resource Description Framework, a framework for representing information on the web) data, allowing for advanced search and retrieval of specific information from the data.

The demonstration shows a clear use case scenario of fine grained access control on the Solid interface. All data was generated and loaded into the Solid pod using RDF, which means that its appliance is interoperable and made available for different actors coming from various sectors.

Example Metrics

This passage will present several metrics that are used for measuring information sharing and circularity of a CE.

- **New Product-Level Circularity:** This metric compares the economic value of recirculated parts with the economic value of all parts [42]. To get a centralized method for measuring the value of said parts, some other calculations needs to be done where the cost of the raw material is taken account for. The result, c_0, is given in a percentage, and calculated as

$$c_0 = \frac{Economic\ value\ of\ recirculated\ parts}{Economic\ value\ of\ all\ parts}. \tag{3.1}$$

- **Global Circularity Metric:** This metric compares the amount of circulated products in tonnes to the weight of the input material. Similarly to the New Product-Level Circularity metric, this result, c_1, is also given in a percentage [43]. The equation is given by

$$c_1 = \frac{Amount\ of\ circulated\ products}{Amount\ of\ input\ material}. \tag{3.2}$$

- **Circularity Index:** The paper that presents this metric compares the vision of a perfect CE to a perpetual motion machine [44]. To indefinitely recycle material with no new inputs is not possible, the metrics which accounts for this will therefore never reach a perfect score. This metric compares recovered end-of-life (EOL) materials to total material demand, where a 1 is a perfect score. By including materials which cannot be reused you eliminate the "perpetual motion" problem. The index, c_2, is given by

$$c_2 = \frac{Recovered\ EOL\ material}{Total\ material\ demand}. \tag{3.3}$$

- **Global Open Data Index (GOBI):** This metric covers data openness in governments and includes all types of data from government budget to land ownership. The metric is measured by taking the data which is available for everyone and dividing it by the entire data set [45],

$$g = \frac{Openly\ available\ data}{Total\ amount\ of\ data}. \tag{3.4}$$

Applicable Metrics for Simulation

Most of the metrics that were presented in the previous subsection are created for a complex world with a lot of variables to consider and could therefore be difficult to implement in a simulation that tries to simplify it into a few key variables. One metric that encompasses the variables that are included in the simulation is the "Global Circularity metric" (GCM) which accounts for the total amount of input material and compares it to the amount of material that has been created through waste. Therefore, it suitable to use the GCM in the simulation. In reality, other metrics might be more applicable, like the "Circularity index" or "New product-level circularity" that accounts for more factors then just weight. For example, the New product-level circularity actively works towards centralized calculations by also presenting ways to calculate the economic value of the parts.

In contrast to the many ways of measuring CEs, it was more difficult to find a relevant metric for information sharing. Therefore, instead of using an already defined metric, a new one was created which could be tailored to the simulation, called "Sharing index". The metric takes the number of factories all other factories share their waste with and divides it with the total number of factories in the network. The result, s, is displayed in a percentage and is calculated as

$$s = \frac{Number\ of\ factories\ sharing\ with\ each\ other}{Total\ number\ of\ factories}. \tag{3.5}$$

This metric is used on the x-axis in diagrams generated by the simulation program, to measure how many factories any other factory need to share their resources with.

With the intention of gaining further understanding of how circularity and sharing index compare, a new index has been created: the Sharing for Stable Circularity Index (SSCI). This index is meant to display how much sharing is needed to reach a stable level of circularity,

$$SSCI = Minimum\ sharing\ index\ needed\ for\ stable\ level\ of\ circularity. \tag{3.6}$$

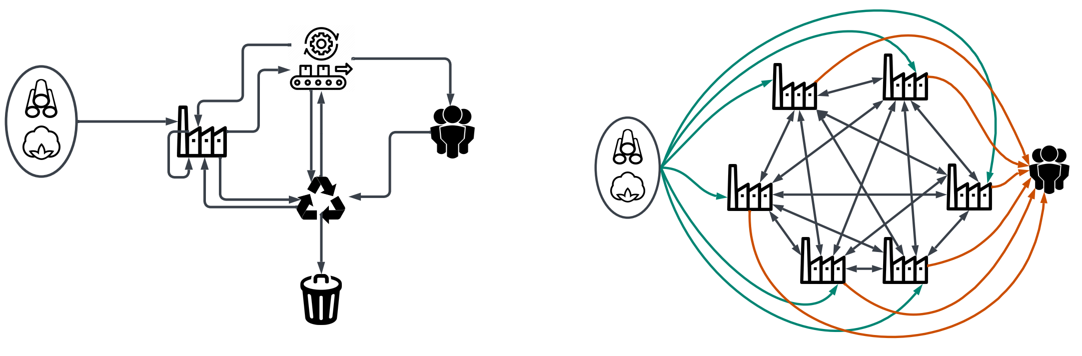
This metric is useful for understanding how a third variable might impact circularity and sharing.

4 Simulation Framework

This chapter presents the initial thought process behind the creation of the simulation and provides an explanation of the underlying framework utilized. During the initial stages of creating the simulation, a choice had to be made regarding what part of the economical system that should be simulated. This choice is explained in the first part of the chapter, followed by a section on the simulation architecture. Finally, the limitations of the simulation are presented.

4.1 Choice of system

In order to evaluate metrics and flow in a CE, a simulation was created. The program was made as a means to try out and experiment with different levels of information sharing in a supply chain, and its effect on circularity. Two different scenarios were considered for the



(a) Option 1 **(b)** Option 2

Figure 4.1: Figure 4.1(a) illustrates the first explored scenario. Here, all parts of the product lifespan is included in a value flow network with nodes representing feedstock, refining, production, consumer, recycling depot, and landfill. Figure 4.1(b) illustrates the second explored scenario, where the the process between raw materials and consumer is in focus. In this scenario, circularity is implemented by minimizing waste, using information sharing between agents. The number of factories or arrows representing connections in the figures are not final. Option 2 was chosen as the structure for the simulation program.

simulation, see Figure 4.1. The two alternatives were developed after researching current simulations of economies, and discussing and refining the scope of the simulation. The first option, Figure 4.1(a), is a system where the whole lifespan of the product is included. This is to encompass all aspects of circularity, such as reuse and recycling after consumers are done with the product. After discussions and analysis of the implementation of such a simulation, an idea for a new scenario was brought up, Figure 4.1(b). This time, the simulation would be limited to the "production process" of products. Discussions and initial tests proved the concept viable and possible to complete within the given time frame. Here, circularity is implemented by sharing resources and produced waste between agents in the production process. It is dictated by how much information is shared between agents. Therefore the decision to move forward with the second option was made. The two options roughly correspond to the two waste scenarios discussed in Section 2.1.

4.2 Simulation Architecture

As soon as the scenario had been chosen, planning of the simulation program began. Following the structure of the initial idea, it was decided that separate classes would be created for material, product, factory, and arrow (representing connections between factories). The program was designed to be flexible and scalable. Most attributes are based on lists to allow for multiple materials in a product, multiple products in a factory, etc. Ultimately, only a limited portion of this flexibility ended up being utilized. The structure of the program is as follows:

1. The program is initiated with a set amount of materials, products and factories. Important data such as number of rounds, number of simulations, change in sharing index between rounds, etc. are used as inputs to the program at this point.

2. The program starts, and loops over each round.

3. For every round, the program adds predetermined inputs to factories. It also sets arrows, connections, between the factories based on the current level of information sharing.

4. For every factory, the program checks the incoming connections to see if it can produce an output. If it can, it produces its set outputs as well as its waste, while removing the inputs from the system. Waste is calculated as a percentage of produced materials, based on real-world data [20]. Outputs and waste are put in relevant connections to become inputs for other factories in following rounds.

5. After the program has iterated over all factories, the round is over and it starts a new round.

6. After all rounds are completed, results are saved, sharing index is incremented and a new set of rounds are then simulated.

7. When all sharing indices have been simulated, the program starts over, resetting everything. This is done as many times as has been inputted as number of simulations. Multiple simulations help increase credibility.

8. When all simulations have been run, all results are saved in a text file. This includes number of rounds, number of factories and number of simulations, circularity and sharing for every simulated round, as well as saved averages and other statistical data.

9. A different program reads the data in the saved file and outputs a figure, based on what is relevant in the current context.

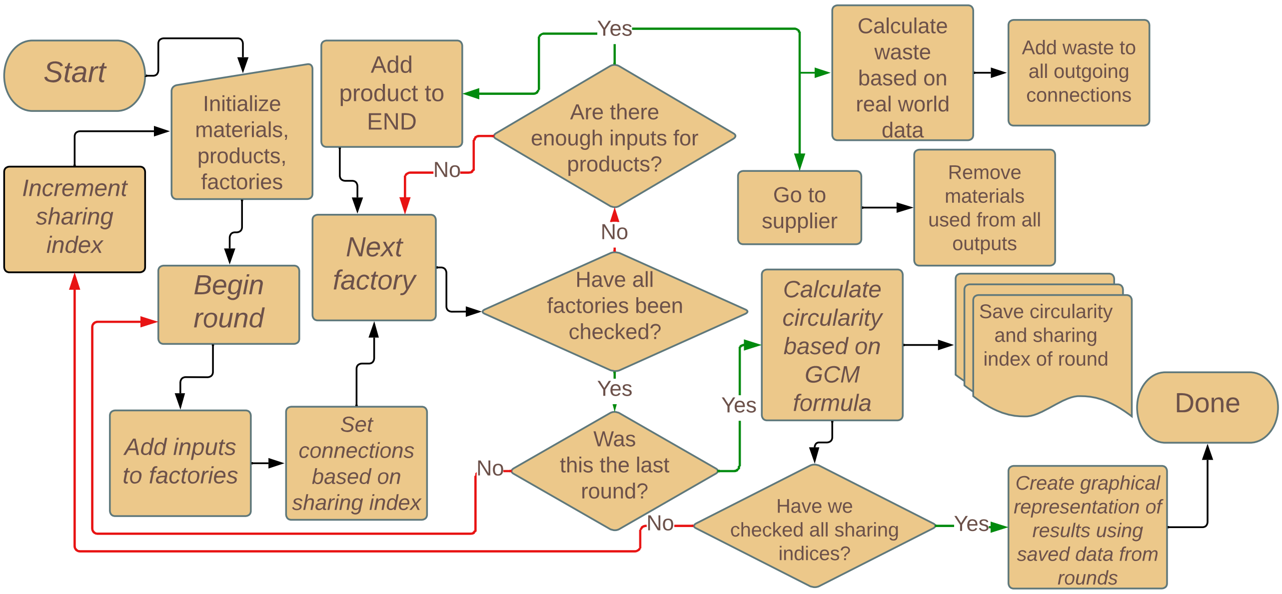


Figure 4.2: A flowchart showing a simplified version of the simulation program.

A simplified flowchart showing the basic loop for the simulation program can be seen in Figure 4.2. In an effort to improve readability of the chart, some parts of the program, such as implementing randomness and repetitions for more accurate results, were left out.

In order to enable the possibility of changing the amount of factories or inputs between simulations, multiple materials and products were defined in the program. Four materials and eight products consisting of different amount of materials were used. Factories could be defined to produce either identical or different products. Additionally, the number of factories receiving inputs could be changed between simulations in the code. To guarantee that all materials were available in the system, the factories chosen to go without inputs were often the ones using fewer materials for their products. Values determining production and waste were set to reflect the textile industry.

To present the results of the simulation, it was concluded that a scatter plot showing all simulated scenarios should be created. Since the large amount of scenarios made the plot difficult to analyze, it was decided that the mean value would be calculated for every sharing index and plotted on top of the scatter plot. There was also an idea to add a plot of the median, but after some experimentation it was excluded from the code since it was very similar to the mean.

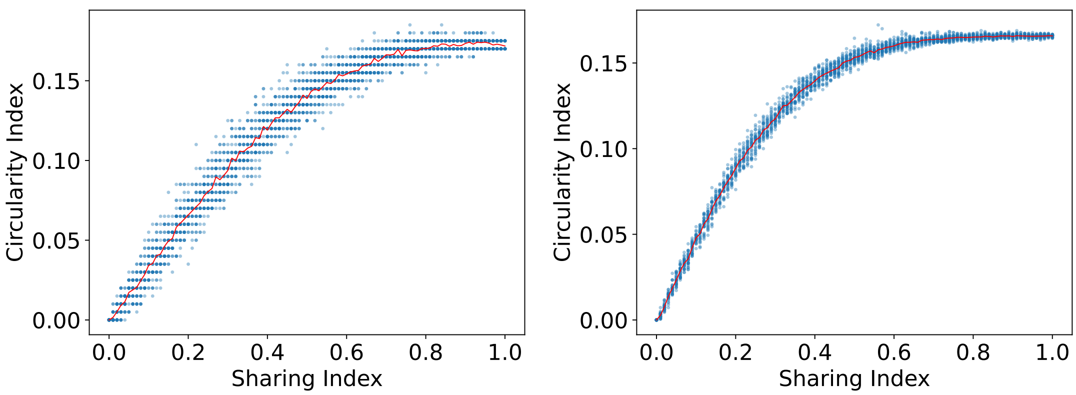
The program was made in an iterative manner, meaning the first versions were trivial in nature, only containing a few factories and materials. This way, results could be analyzed quickly and new iterations of the program can be made accordingly. In later iterations, new metrics and additional goals made certain newer versions differ slightly, but the core components of the simulation remained the same. The program was written in Python, but it is the impression of the authors that the choice of programming language is relatively inconsequential.

5 Simulation Results

This chapter presents the results from the simulation. The simulation has a variety of initial parameters that can be set. Therefore, the chapter is divided into three cases, where each case changes one of these parameters.

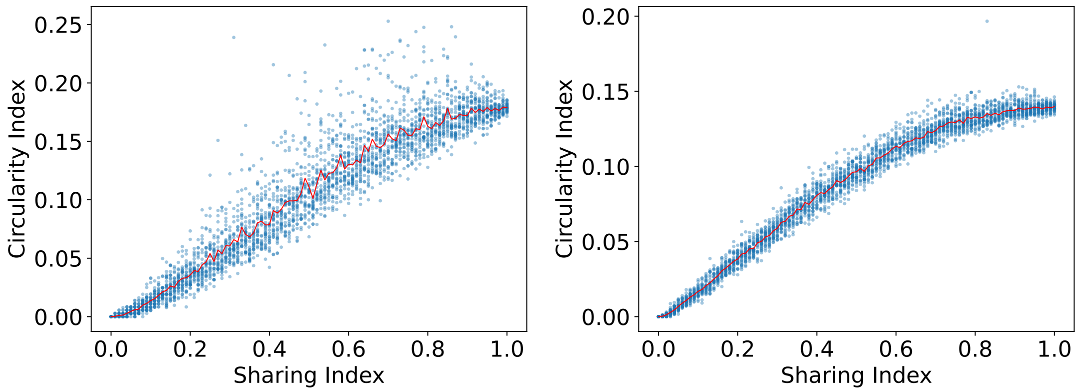
5.1 Case I: Varying Number of Inputs

At first, it was decided that only one product is produced. This does not imply that only one factory can exist, but all existing factories will be identical and produce the same product. Only one type of material is in circulation in the system. The first simulation, seen in Figure 5.1(a), ran with nine identical factories, out of which only one was supplied with inputs every round of each scenario. The resulting graph clearly shows how circularity increases as the sharing index increases. The rate of change decreases, and seems to approach 0. Since only one factory receives inputs, in fixed increments, the resulting circularity index is spread along fixed points. By calculating and graphing the mean of multiple results for every sharing



(a) 9 factories, 1 input **(b)** 9 factories, 9 inputs

Figure 5.1: (**Case I**) Simulation results considering the tradeoff between circularity and sharing. Each blue dot represents the results after ten rounds of continued simulation. Every 1/100th step of the x-axis incorporates 100 of these dots. The red line shows the average value of each dot.



(a) 9 factories, 2 inputs **(b)** 9 factories, 9 inputs

Figure 5.2: (**Case I**) In this test, 9 different factories producing 8 products are implemented.

index, a smooth and consistent line is apparent. The graph suggests that changes in sharing index become less and less significant as it approaches 1.

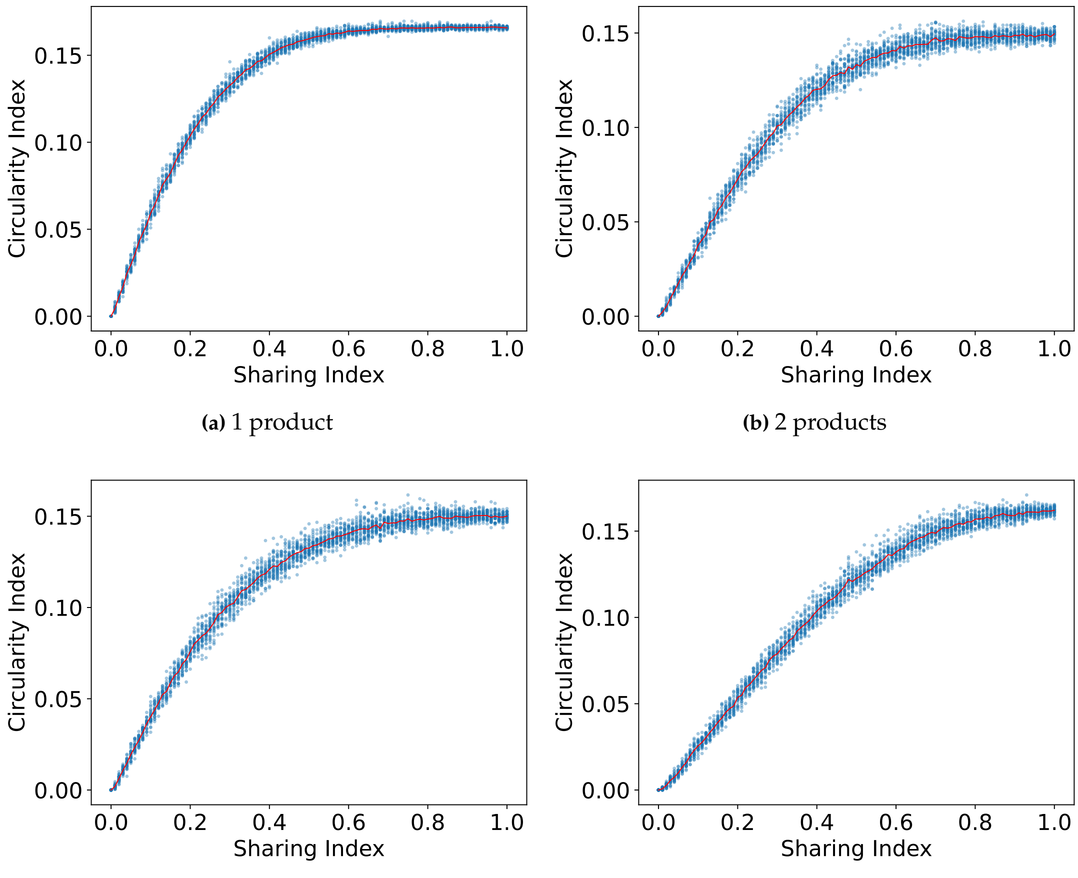
After implementing supply for every factory, the simulation was carried out once more. This time, the resulting graph showing circularity against sharing, Figure 5.1(b), looks similar to the previous test, Figure 5.1(a). In both cases, the results indicate, that for a network of nine factories with identical inputs, there exists a point where increasing sharing index has a minimal effect on circularity. However, that sharing index seems to be lower for a higher amount of inputs. Looking at the graph for multiple inputs, that point seems to be around 0.6. Increasing the sharing index more than that has less impact on circularity.

Next, implementation of multiple products were added. Here, there are still nine factories, but they produce eight different products. These products are made from 4 available raw materials which can be traded between factories. For the first test, it was decided that as few inputs as possible would be implemented. Since no factory requires all types of materials, two were required to guarantee that all materials are available in the CE. The result of this simulation with two inputs are shown in Figure 5.2(a). Looking at the graph, the increase in spread is noticeable. This is excpected, as circularity will vary depending on which factories can attain its required resources. Moreover, the mean appears more linear than previous tests without multiple products.

Next, all nine factories were allowed inputs and the simulation was carried out once more. Compared to the previous test, this setup seems to decrease the maximum circularity slightly, seen in Figure 5.2(b). Furthermore, spread is reduced greatly, as factories no longer have to compete for inputs.

5.2 Case II: Varying Number of Products

To further investigate the effects of producing multiple products, four tests were conducted, incrementing the number of products between each one. In these tests, every factory is supplied with inputs every round. The resulting graphs are shown in Figure 5.3. The four produced graphs are all similar. A significant result of these simulations is that linearity of the mean seems to increase with number of products. However, this increase is quite small and the most linear result still displays a decreasing rate of change for higher sharing indices. The values of circularity remains the same throughout the simulations.



(a) 1 product

(b) 2 products

(c) 3 products

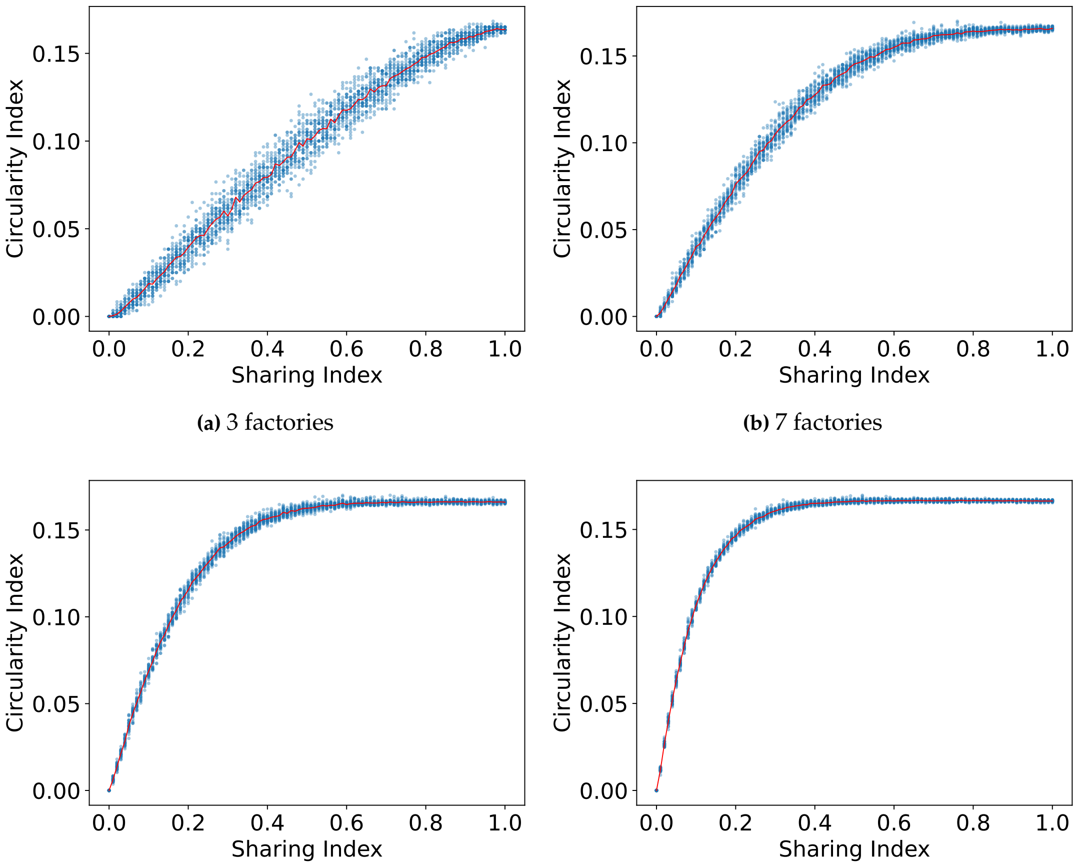
(d) 4 products

Figure 5.3: (**Case II**) Difference in results when running simulation with varying number of products. All tests are carried out with 12 factories, all receiving inputs.

5.3 Case III: Varying Number of Factories

Another factor which could affect the results are the number of factories involved in the network. To identify any impacts this quantity may have, a number of tests were conducted, were factories could be added between them. Since the intention was to isolate the significance of the amount of factories, all factories were set to be identical, only producing one product, using a single material. Four of these results are presented in Figure 5.4, ranging from 3 to 30 factories. Looking at the graphs, it is clear that the amount of factories included in the CE has an impact on circularity. With fewer factories, circularity practically increases linearly with the sharing index. Adding more factories, a curve is formed on the graph, indicating that increasing sharing index has less significance for the circularity when it has reached a certain point. As even more factories are added, this effect is even more distinguishable. With a higher number of factories in a CE, circularity reaches a stable point with notably less amount of sharing between them.

In an effort to gain additional insight into this effect, the required sharing index for stable circularity can be tracked and plotted. For this visualization, the SSCI described in Equation 3.6 is used. This index describes the level of information sharing required to achieve and maintain stable circularity in the system. It is calculated by running the simulation and extracting the sharing index where circularity reaches a stable point, in this case after passing 0.15. In this way, the metric is an indication of how efficient a CE is. A lower index value indicates a higher level of sharing efficiency.



(a) 3 factories

(b) 7 factories

(c) 15 factories

(d) 30 factories

Figure 5.4: (**Case III**) Difference in results when running simulation with varying number of factories. All tests are carried out with identical factories, all receiving inputs.

The SSCI was measured for cases up to 30 factories, plotted in Figure 5.5. The correlation to the results in Figure 5.4 is evident, as the values where the results stabilize in the simulated instances correspond to the SSCI values plotted in Figure 5.5. A noteworthy element of the graph is its lack of linearity, which indicates that the inclusion of an additional factory into a CE becomes increasingly insignificant for circularity as the CE grows.

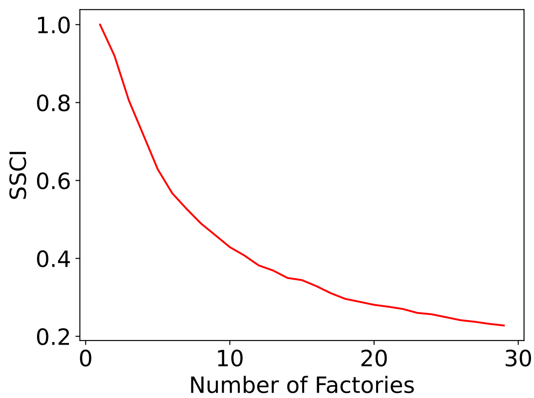


Figure 5.5: Sharing for Stable Circularity Index (SSCI) vs number of factories.

6 Discussion

In this chapter, the results of the simulation and literature study is examined and their implications for the broader field of research are explored. Firstly, the key findings are analyzed, highlighting any trends, patterns, or unexpected results we observed. The methodology used to collect and analyze the data is also discussed, including any limitations or challenges encountered. Lastly, the work is placed in a wider context, drawing on previous research in the field to situate our findings within the current state of knowledge.

6.1 Results

This part of the discussion reflects and justifies the produced results. Here the reason for why the simulated results look the way they do are presented. Apart from that the choice of metric and some reflection over the Onto-DESIDE implementation is brought forward.

Literature Study

Two main findings are presented in the results section. Firstly, different metrics regarding CEs and information sharing in addition to what metric is applicable on the simulation. Secondly, some preliminary work from the Onto-DESIDE project. This section discusses and analyzes both of these results and puts them in the context of the thesis' aim.

Metric

This thesis decided to use the GCM as a metric to measure circularity in the simulation. This was mainly due to the fact that its parameters already existed in the simulation, which means it was trivial to incorporate. The GCM provides a simple indicator of circularity which may not be sufficient for a real world economy. If work on the simulation had not been prioritized, a more complex metric could have been incorporated which would create a more realistic reflection of the world. By trying to include a more intricate metric, goals are automatically created to work towards that will enhance the simulated environments realism. If, for instance, the "New Product-Level Circularity" metric from Equation 3.6 were to be used a lot of other components would need to be included, such as price of raw material and value of components which consequently will add more realism to the simulations.

Onto-DESIDE

The preliminary Onto-DESIDE proposal gives a good picture of what their vision is: to be able to utilize the Solid pod system as a distributed database and then apply their own implementation to employ fine grained access control. This kind of implementation makes the interface easy and available for new actors entering CEs due to the accessibility of the Solid interface and also due to the usage of RDF. The Solid pods also make for scalable databases that does not require a massive centralized database because of the private hosting aspect.

The Onto-DESIDE project puts a lot of focus on access control, which is an aspect that was not included in the simulation. This makes it difficult to apply the metric, and with that the results, that was created from the simulation on the Onto-DESIDE paper.

One key obstacle with CEs that the Onto-DESIDE proposal does address is the security aspect. It is unwise to count on total collaboration between participating members of the economy. The same goes for data security, it is not possible to have an open database. By utilizing fine grained access control on the shared database, this issue is taken care of.

Simulation

The three examined cases from the simulation brought many points of discussion.

Case I

In the first case, number of inputs were isolated. The results indicate that the number of inputs does not have a significant impact on the mean circularity. However, circularity spread between simulations was affected considerably. This may indicate inaccuracies in the simulations, which dissipates as inputs are added. Another noteable aspect is the effect of number of inputs on circularity when implementing multiple products. Comparing Figure 5.2(a) and Figure 5.2(b), a small, yet noteworthy, difference in maximum circularity can be observed. The reason for this is not trivial, but it could be affected by the fact that more factories have to rely sole on circularity in the system in the first instance, since they are not receiving any input of their own. In reality, all factories would receive inputs by default, rendering these results less significant than other cases.

Case II

In the second case, no meaningful effects on the circularity could be observed. Basing an idea in reality, it is to be expected that no major differences are seen when introducing multiple products. Since all factories will have 100% overlap in used materials when only producing one product in the CE, one could suppose that circularity would not suffer from it. On the contrary, it could be assumed that circularity might decrease with multiple products in the system, since some factories will require materials that are not produced as waste from others. When taking a closer look at the graphs in Figure 5.3, this small decrease in maximum circularity is evident. Furthermore, tests were only conducted for the relatively small span of 1-4 products. This small interval displays that more products might contribute towards a linear result. The implementation of products in the simulation program made it difficult to add more products dynamically for more extensive tests. A more prominent effect might become evident if simulating on a larger scale.

Case III

In the third case, different amounts of factories were implemented. The results clearly show that circularity increases at a faster rate when more factories are added. This might suggest that the sharing index is not the most suitable index in this context. The sharing index is simply the share of available factories that information and waste is shared with. The number of

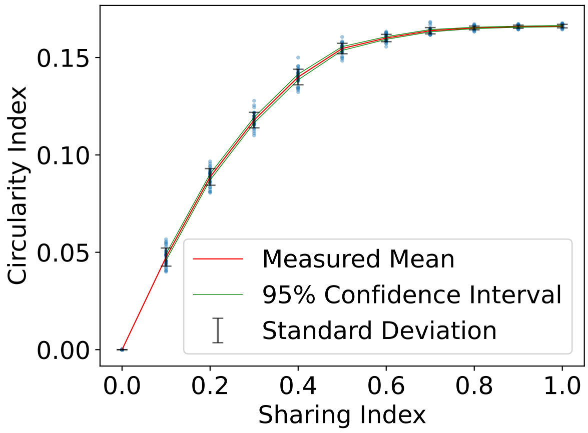


Figure 6.1: Standard deviation and 95% confidence interval.

factories in the system will affect the results, but it is not taken into account when calculating the sharing index. The maximum circularity value does not increase with more factories, as it is taken into account when calculating the index. Perhaps a different index could be created with this in mind.

Credibility

While analysing the outcome of the simulation, it is important to consider the credibility of the results. While the simulation is partially based on real-world data, most elements were approximated with lower resemblance to reality. These abstractions certainly separates the results from reality, but conclusions drawn from them can still be significant and meaningful. As long as the abstractions are taken into account before implementing changes in real-world use cases, benefits can be gained.

To further assess credibility, standard deviation and confidence intervals were calculated, which can be seen in Figure 6.1. Standard deviation, which describes spread, differs depending on initial values in the simulation. However, in the commonly used case of 9 identical factories, a small standard deviation ranging from 0 to about 2.3% can be observed. To better understand the accuracy of the results, a 95% confidence interval was calculated. As seen in green in Figure 6.1, the interval is quite narrow. This indicates that the results are precise and accurate, which adds to the credibility of the simulation.

Effects of delimitations

Because the simulation could not be implemented to a state where material costs were of importance, the delimitation of only using the textile industry could not be noticed. If negative aspects of CEs had been included such as transport costs, the results of the simulation would probably have been different. However, this is hard to discuss because the structure and goal of the simulation would also be different from the current case. The same goes for blockchain, it is hard to know what a literature study on the appliance of blockchain on CEs would have resulted in if it has not been done.

6.2 Method

The purpose of this sections is to discuss the methodology of the project. The discussion reflects over how the work was done and what could have been improved for better results.

As with previous sections, this section is divided between the literature study and the simulation.

Literature Study

The literature study quickly became a time consuming part of the project. There are many reasons for this. Firstly, the subject area of the project introduced a lot of new theories and terms which in many cases where quite difficult to grasp. This meant that a large portion of the research and source gathering process was allocated to understanding the concepts which where introduced in the papers.

Secondly, the large amount of papers on the subject of CEs meant that a lot of time was spent on discarding irrelevant sources. The positive thing about this factor was that at times when a good source was found it was closely related to the research area.

Lastly, the original research questions did not create goals that where easy to work towards. This was mostly due to the aforementioned limited knowledge on the subject which led to confusion regarding what the goal of the thesis was. If a clear aim had been introduced earlier it would have been possible to work towards the aim and then build upon it in an iterative fashion. Instead, during the initial stages, the research was conducted with a large and undefined scope, which was narrowed during the course of the project.

The negative consequence of putting a lot of time on the literature study was that not as much time could be put on the simulation. While the literature study could provide some key insights into metrics regarding CEs and information sharing, the simulation ended up giving the most interesting and analyzable results. Therefore, if the project is to be repeated, more focus should be put on the simulation to be able to create results.

Simulation

The workflow encountered some limitations. Firstly, the simulation has a large time complexity, running it thousands of times to be able to plot out reliable results can take a substantial amount of time. This introduces the need for a compromise, where either the number of simulations, iterations or the magnitude of variable changes must be prioritized. The fact that the simulation has a variety of factors which can change the results makes this problem even more apparent.

Due to the iterative workflow, the initial version of the simulation applied simple metrics for measuring circularity. This could unfortunately not be updated in later versions, which meant that the simple metrics were used in the final results.

Another limiting factor of the reliability of the simulation is the difficulty of implementing real-world data. Although the simulation was created on top of a comprehensive literature study of the field, it was difficult to locate areas where specific values could be implemented. The calculation of waste production was the only instance where this was achievable, the remainder of the program is only loosely based on real-world conditions, rendering the results less reliable.

The initial work on the simulation was slow, much time was put into researching how other simulations worked and what the approach would be toward implementing it in code. The slow start which did not produce any meaningful results led to the simulation being put on hold for a while. When a clearer understanding of the simulation's objective was achieved, the simulation began to yield results.

If this work is to be replicated or built upon, it is important to establish an initial question that specifies what is to be investigated. The question needs to be thought through and analyzed in a way which makes its underlying purpose clear throughout the development of the simulation. In our case, we knew that we wanted to emulate a simulation, but the object of the simulation was unclear during a large part of its creation. This led to the progress of the simulation reaching a stand still when the basic framework of the it was built because it became unclear what the next steps were. If instead, the underlying question had been clear from the start, the completion of the framework would just be the first stage of the testing of the simulation.

Transient Period Analysis

To take the transient period mentioned in Section 2.5 into account in the simulation, tests were conducted plotting circularity against rounds. The simulation ran for 100 rounds and the results were graphed, see Figure 6.2. The graph clearly illustrates that a transient period is present in the simulation, as it takes approximately 40 rounds before circularity results are consistent. This meant that the values from the first 40 rounds of any simulation should not be included in the results. In the final structure of the program, results from each simulation is recorded only after all rounds are simulated, rendering this issue resolved. However, this analysis prompted a decrease in number of rounds simulated from 100 to 40, significantly optimizing the program.

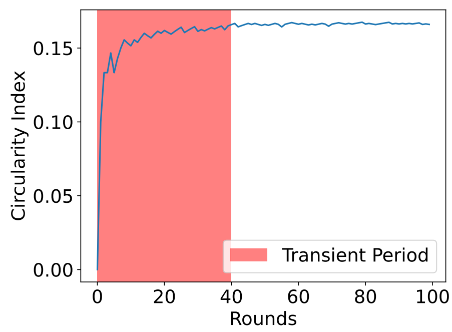


Figure 6.2: Transient period.

One factor at a time

Towards later iterations of the simulation, time complexity became a growing issue as ambitions rose and new ideas were explored. Due to this limitation, different simulation methods, such as OFAT, were explored. When implemeting OFAT in a simulation, all but one of the variables are set to a standard value, which can be computed ahead of time. This was thought to be a relevant addition to the simulation, but was only partially implemented. The program was built in a way where changes are inherently dependent on other changes, which effectively means OFAT cannot be implemented efficiently without rewriting large parts of the program. In this project, the three examined cases each focused on one variable. However, this was not implementing OFAT. In the current implementation, all values still had to be calculated on each simulation, as implementation states that variables are non-orthogonal. If this project was redone at a later time, it would be wise to implement OFAT originally.

Reproducibility

For any scientific work, reproducibility is essential. In this project, reproducibility warrants consideration as some parameters were left out in the chapter explaining how the simulation works. However, these parameters were arbitrary, affecting elements such as values on the y-axis and simulation spread along both axes. It is the opinion of the authors that the description of the simulation architecture presented in Section 4.2 is described in enough detail for a new simulation to produce similar results.

Source Criticism

All sources were thoroughly reviewed before being used in the thesis. This was to ensure a factually correct project that could reach reasonable results and conclusions. Primary sources were found by tracing referenced material in academic papers until the origin of the referenced statement was reached. Most sources where found using Google Scholar, which only displays academic papers. In the case of a private actor contributing to a paper, such as the Ellen MacArthur foundation, research was done into these backers to ensure objectivity.

6.3 The Work in a Wider Context

The research and results that this thesis has presented is merely a small slice of a much larger project that will span over many years and affect the economy (and hopefully the climate) on a global scale [1]. The long term goal of the EU is to reach climate net neutrality by 2050 [7]. Although the time frame for the goal is large, the objective of it is just as big which further emphasizes the importance of innovation and research on the subject.

This project has treated the concept of CEs as an "absolute good", the concept has not been questioned nor has its negative effects been examined. Instead it has been treated as something to strive for at all costs. The thesis has presented some proofs of concepts to support CEs but due to the fact that it never has been adapted on a global scale, its profitability and actual impacts on the environment can be questioned. It would be beneficial to look at a CE from a critical standpoint, not necessarily to debunk or discard it but to find points of improvement.

There have been some difficulties with connecting the simulation to the Onto-DESIDE project, which was one of the underlying goals of the project. This was mainly due to the fact that the simulation was created in an iterative work fashion which meant that each new component was added successively. If more time had been allocated towards working on the simulation, some additions to make it more relevant to the Onto-DESIDE project could have been included. For example, real data from the companies working with Onto-DESIDE or incorporation of access control .

7 Conclusion

This chapter provides a comprehensive summary of the research findings and conclusive thoughts on CEs and information sharing. It also presents the answers to the research questions and estimates to what extent the aim of the thesis was achieved. Finally, it provides recommendations for future research.

7.1 Summary of Work

This project was divided into two distinct but interconnected areas: the literature study and the simulation. The literature study put a lot of focus on CEs and information sharing in addition to metrics to measure its effectiveness. The result of the literature study was a presentation of the current Onto-DESIDE progress and a list of metrics that are used for measuring the circularity of a CE and for measuring information sharing.

The simulation provided insights into how open producers need to be with their resource to benefit the economy. This was done by making factories, resources and products where waste is created as a byproduct when producing products. By changing variables, such as number of factories, number of products and number of inputs the results can be plotted with the sharing index on the x-axis and the GCM on the y-axis. This resulted in insights regarding the best tradeoff between sharing index and GCM.

7.2 Research Questions and Aim

- **What should be included in a utility metric for a circular economy?** This thesis concludes that the optimal utility metric for measuring a CE in regards to data sharing is a combination of two other metrics. One regarding CEs called GCM which compares the total amount of products in an economy to the amount of recycled products. The other metric was created during the course of the project and is called "sharing index". This index compares the total amount of factories to the number of factories that are sharing resources with each other. By comparing these two metrics one can get a good picture of how much information each factory need to share with the other to benefit the GCM.
- **What should be the trade off between data sharing and privacy to ensure a well functioning circular economy?** The simulation shows that, at a certain point, an increase in

the sharing index does not create the respective increase in GCM. From this, the conclusion that a factory does not need to share with more factories after that specific point to contribute to the GCM can be drawn. This point is dependent on multiple variables, particularly the number of factories in the CE. However, this point does not increase with added factories in a linear fashion, indicating that it may not always be worth including another producer in the interest of promoting circularity, depending on the cost of incorporation.

7.3 Future Work

This project has a lot of prospect for further research and investigation. The current version of the simulation is still at a primitive stage, there are several additions that can be implemented to create more realistic results. The simulation could, for example, have greater relevance to the Onto-DESIDE project if it incorporated fine-grained access control. With this function it could be possible to test how access control affect circularity and how much access producers should give each other.

Another add-on that could benefit the analysis of the simulation is a function that could enable OFAT. With multiple changing variables it is time consuming to run the simulation numerous times, even with minor changes. By locking two variables and keeping one changeable, the required computation time can be reduced substantially for each simulation.

As discussed briefly in Section 6.1, it would be beneficial to further consider the effect of amount of products in a CE. The program used for this project created difficulties implementing multiple products dynamically. If a similar simulation program was to be created in the future with this in mind, it might be interesting to investigate the effect of multiple products on a larger scale.

An additional suggestion to enhance the simulation would be to incorporate a more challenging metric that gives a better representation of a CE. If, for example, the "New Product-Level Circularity" metric was implemented, a lot of other factors needs to be taken into account. This would require more detailed information about products and the supply chain, and may require the integration of data from multiple sources. However, incorporating such a metric would provide a more comprehensive assessment of the circularity of a product and could help to drive improvements in product design and supply chain management towards a more circular model.

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