Increasing circularity in organisations - A combination of modularity and the circular economy

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University of Twente
Business Administration
Entrepreneurship, Innovation & Strategy

Gijs Sturtz

Supervisors
dr. ir. E. Hofman
dr. D.M. Yazan

Abstract

Awareness for sustainable business practices is becoming increasingly important in today's societies. The circular economy (CE) proposes solution on how to include economic, societal, and environmental values at the core of businesses. To successfully employ a circular strategy companies face several challenges. Modularity can provide a solution to these challenges. This research creates a framework on how modularity can complement the CE. By creating a design that facilitates circular strategies modularity in product design and supply chain could boost circularity in organisations. Case studies are used to determine if modular practices can already be identified at circular companies. This gives insight in the applicability of the theoretical framework. This study concludes that modular product designs increase effectivity of circular strategies. Supply chain modularity on the other hand does not affect the level of circularity in organisations positively.

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1. Introduction

In the past years awareness has been raised concerning the negative impact of growing economies. The way in which economic growth has been achieved in the past had, without a doubt, negative effects on the environment and caused societal problems. In addition, amount of resources available is limited. Current models do not account for this limitation and discard resources as waste when products reach their end of life (Ellen Macarthur Foundation, 2014). This implies that a "new way of conducting business" will be necessary to create value and avoid negative impacts by businesses.

A business concept that has a high potential of achieving this is the circular economy (CE). The CE is a restorative system. It aims to design out waste and close the loop for products and materials. It aims to reduce energy and materials consumption, reuse products and materials, and recycle raw materials and waste output (Ellen Macarthur Foundation, 2014). These practices are known as the 3R principle of the CE (Ghisellini et al, 2016; Kirchherr et al, 2017). The concept originates from sustainability thinking and incorporates the environment, society, and economy as its core values (Gibson, 2006; Ciegis, 2009). The goal of the CE is not only to create economic value, but to create value for society and minimize environmental impact as well.

To effectively implement the CE principles business models will have to adapt as well. Currently, business model frameworks are based on the linear economy and are not fully equipped to account for circularity. The linear economy is a take-make-waste system. This means virgin resources are used in production. These are used to create new products. After their lifetime the products become waste (Ellen Macarthur Foundation, 2014). If businesses want to create value in the CE the traditional business models need to be expanded. According to Lewandowski (2016) business model frameworks should include two additional components to create circular business models (CBM). These components are take-back systems and adoption factors. Take back systems will realize return flows of products, components and materials, adoption factors are internal capabilities and external factors that support the transition to the CE (Lewandowski, 2016)

The transition towards CBM may encounter challenges which can act as barriers for adoption of the CBM's. The nature of CBM and the goals that it aims to achieve lead to necessary changes in the rationale of organisations and their "old" ways of doing business. Realizing these changes will have the organisations deal with several challenges along the way.

Oghazi & Mostaghel (2018) give an overview of these challenges. First, these authors claim that the products in the CE will have a longer lifetime due to increasing durability, upgradability, and repairability. This might incur more costs than simply producing new products. It also means that products will have to account for changes in market demands or technological developments. In addition, this will cause a need for new types of customer relationships. Customers should no longer simply dispose of the product. Instead, companies need to work with their customers to take the old products back.
Secondly, higher intensity of collaboration with other organisations is needed when adopting a CBM. This causes a degree of dependency and thus requires higher levels of trust between

the partners for the collaboration to succeed.
Thirdly, the authors argue that adopting a CBM increases future uncertainty. This increased uncertainty makes it more difficult to plan a successful scenario for all stakeholders involved.

The CE goes beyond the linear economy in its goals. It includes the environment and society at its core in addition to economic value. This means that business processes will have to change to include all three goals. Businesses need to employ specific strategies to achieve circularity. Product take back, reducing input and output, reusing materials, and recycling are essential business practices for the CE. Products and processes should be designed to facilitate these practices. The question remains how business processes and products can be structured to facilitate the CE.

To be successful in the CE companies need to find ways to form their product an processes around the circular goals. Questions that need to be answered are, for example: How to increase the product lifetime? How to perform maintenance and repair most efficiently? How to efficiently refurbish taken back products? How to design a product to be reused as much as possible?
When products and processes are structured, at the base, to facilitate these demands of the CE the company will be more able to reach its circular goals. Therefore, an approach that enables a company to perform these circular strategies needs to be examined.

A concept that could prove valuable to more effectively employ circular practices is modularity. The concept of modularity revolves around the way in which the functional elements of products and processes are arranged. The product or supply chain is broken down based on specific functions and processes. Based on these, modules are formed. These modules have low interdependencies between them. This creates a loosely coupled design which gives flexibility and allows for changes of modules without affecting the overall configuration (Baldwin & Clark, 2003; Schilling, 2000; Ulrich, 1995; Elmasry & Größler, 2018). Modular architectures could provide the necessary means to effectively reach the additional goals of the CE.

Modular product design could help the CE to perform maintenance and repair more effectively. Since modules are independent, parts can be easily replaced. This can help refurbishment practices of old products as well. The modular design could potentially aid in extending product lifetime, effectively exploit a market of pre-used products, and create a strong design for reusing products and parts.
A modular supply chain configuration will create low interdependencies between different companies in the value chain. This means that the circular company will be able to switch to different chain partners more easily. They can pick partners based on whether the companies also adhere to circular principles. This way they could create a network of circular organisations that forms the value chain.

The goal of this research is to investigate if the CE can be matched with modularity. It seeks to find if companies can benefit from modularity principles to achieve their goals in the CE. This study aims to take a first step in examining the relationship between the concepts. It starts by doing so on a theoretical basis. Then, several case studies are conducted at

companies in the CE. The cases are evaluated on the circular practices they perform and how they do so. In addition the case companies are analyzed to judge if modularity principles are present in their product design or value chain. This provides insight in how modular practices could (consciously or unconsciously) already be utilized by the case companies to achieve their circular goals. This in turn could support the theoretical framework of complementing the CE with modularity.

2. Literature review

2.1 The circular economy

The CE finds its origin in the pillars of sustainability thinking. It combines societal, environmental, and economic value creation as its core values (Ciegis, 2009; Gibson, 2006; Alhaddi, 2015). The CE employs the so called "3R-principles" to achieve these goals. These principles are: reduce, reuse, and recycle (Ghisellini et al, 2016).

Reduce – focuses on the reduction of raw material input and waste output of the production process. By increasing efficiency in production and consumption raw material consumption will decrease (Ghisellini et al, 2016). In addition, the waste generated from production will decrease since materials are used more efficiently (Kircherr et al., 2017).

Reuse – revolves around using products and parts again after their lifetime. The product parts are used for the same function in new products (Ghisellini et al, 2016; Kircherr et al., 2017). By designing products in such a way that its parts can be used again easily high degrees of reuse can be achieved, i.e. design for disassembly (Ellen MacArthur Foundation, 2014).

Recycle – involves the reprocessing of old materials into new materials. The recycled materials do not need to maintain their old function. Recycling does not include energy recovery or the use of materials as fuel (fuel (Ghisellini et al., 2016; Kircherr et al., 2017).

By employing the 3R-principles the CE is able to design out waste and minimize input of energy and raw materials. It achieves this by closing the loop of the supply chain and applying a strong redesign focus (Geissdoerfer et al., 2018; Murray et al, 2015; Zhu et al, 2010). Therefore, the CE has the potential to achieve societal, environmental, and economic sustainability goals.

2.1.1 Levels of circularity

To achieve effective circular business practices Potting et al. (2017) have put forward a number of circularity strategies. These strategies can be utilized to achieve certain levels of circularity in the product chain. The authors make a distinction between 9 R-strategies that all have a different level of circularity. As a rule of thumb, the authors argue that the more circularity a product chain possesses, the lower the consumption of natural resources and production of new materials will be, thus reducing the organisation's negative environmental impact (Potting et al., 2017).

Figure 1 shows the different approaches to achieve circularity for each R-strategy. The lower the R number, the higher circularity at the particular level will be. It is possible for organisations to apply multiple R-strategies at the same time. A company can, for example, use the rethink strategy and launch a new product line of multifunctional products. At the same time this company can take back and refurbish old product lines to keep these in the market as well.

The levels of circularity as they were originally proposed by Vermeulen et al. (2014) were meant to be used in public procurement. The levels act as a guide to determine how well suppliers perform with regard to circular business practices. It helps buyers in making a more educated choice with regard to sustainable purchasing (Vermeulen et al., 2014).

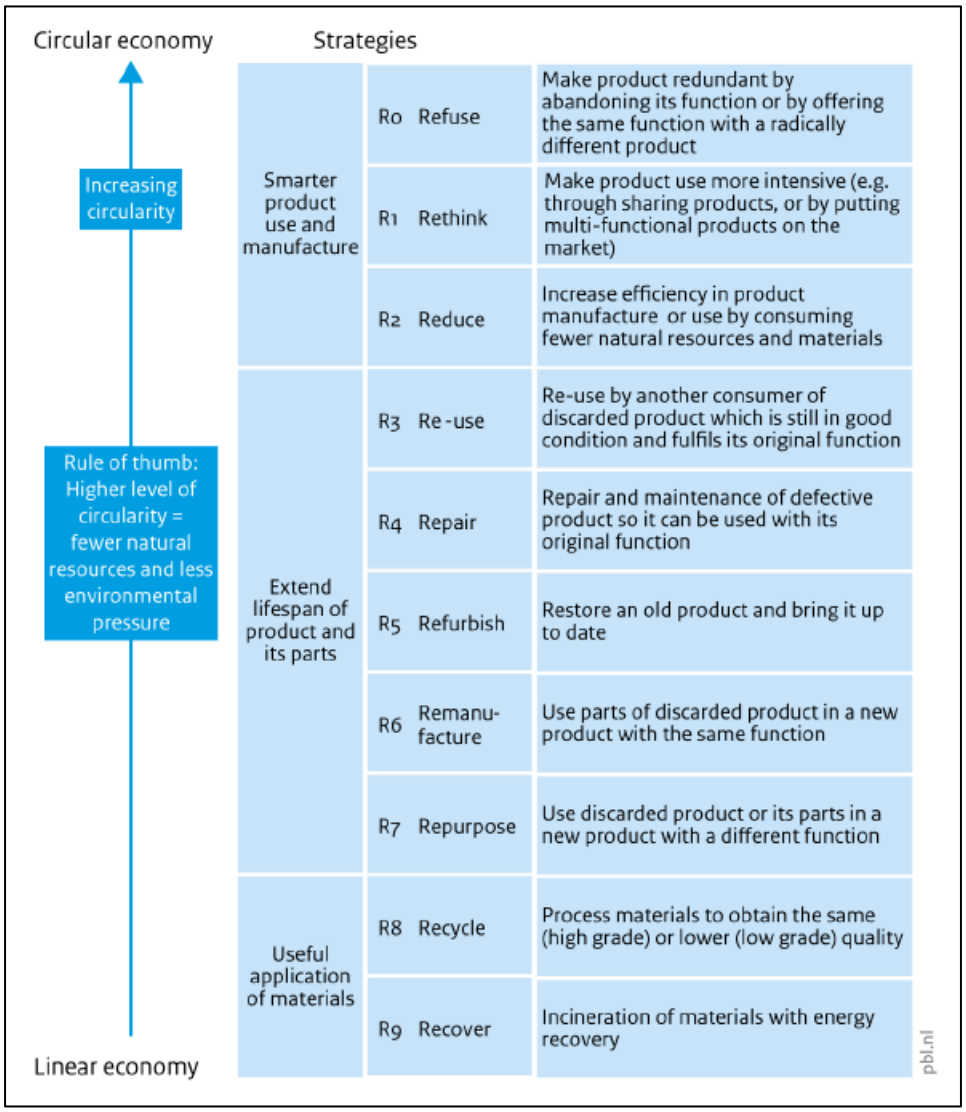

Figure 1 – "R-Strategies" *Adopted from: Potting et al. (2017)*

These ten strategies or levels of circularity can be employed by companies. Different strategies can be utilized in different parts of the company simultaneously. The higher the R-strategy, the more it helps the company to increase their circularity.

2.1.2 Circular business models

Traditionally business models have been developed for the linear economy. The models focused on the creation of products that, after sales, are no longer owned by the company. After their lifetime product are discarded as waste. This makes the linear economy a take-make-waste system. Scarcity of resources poses a serious problem for the linear way of thinking when economies keep growing. In addition, old products being discarded adds causes negative effects on the environment. It also means that the resources used in the products are lost forever when the products are destroyed (Ellen Macarthur Foundation, 2014).

The CE goes beyond the linear way of thinking by taking responsibility for products after sales. It aims to reduce waste to a minimum and to use old products and materials as input for production processes rather than discarding them (Murray et al., 2015; Kircherr et al, 2017; Ellen MacArthur Foundation, 2014).

To do so, business models need to be adjusted accordingly. In the work of Osterwalder & Pigneur (2010) the authors describe nine building blocks for creating business models. These building blocks form vital parts of business models in both the linear and circular economy. Still, business model frameworks need to implement additional building blocks to include circular practices at the core of the company.

Lewandowski (2016) proposes an additional two building blocks for circular business models (CBM) to be successfully employed. The additional building blocks are take-back systems and adoption factors.

Take-back systems - focuses on the realisation of material and product loops. It describes the way in which a company "manages take back, incentivizes return and reuse, and collection of used products" (Lewandowski, 2016).

Adoption factors - describes the internal capabilities a business needs to employ for the business model to be successful. In addition it describes the external factors that can provides issues for adoption. These can be "technological, political, sociocultural, and economic issues" (Lewandowski, 2016).

The CBM canvas is represented in figure 2.

Figure 2 - CBM canvas

Vermunt et al. (2019) have identified several barriers for CBM's to overcome in order to be successful. They make a distinction between internal and external barriers. Internal barriers

include lack of specific knowledge and technology for CE processes, legal and administrative issues, high investments and costs that come with the circular economy (Vermunt et al., 2019). External barriers include dependence on suppliers that do not adhere to CE principles, the needed for customers to change their mindset from disposable to reusable, and institutional barriers (Vermunt et al., 2019).

To summarize, there are three core aspects around which the circular economy revolves. These concepts, i.e. reduce, reuse, recycle, are vital to close the loop of products, materials and waste. They allow organisations to benefit from old products and reduce the need for virgin materials in manufacturing processes.
Ten strategies or levels of circularity can be utilized by companies. The higher the R-strategy, the higher the effect on the overall circularity in of the organisation.
To create business models for the CE two additional building blocks need to be added to the business model canvas. Companies need to include take-back systems and adoption factors as core aspects of their organisation.

2.2 Modularity

The concept of modularity revolves around the way functional elements of systems are arranged. In modular designs the goal is to have standardized interfaces and multiple different modules, based on the functions that need to be fulfilled within the overall system. The modules should have no, or minimal, interdependencies to make sure that if one module is changed no other modules are influenced.

2.2.1 Product modularity

The goal of a modular product design is to create a complex system out of independent subsystems, i.e. modules. The subsystems are subjected to design rules and are connected by standardized interfaces. This ensures the overall functionality of the system (Schilling, 2000; Baldwin & Clark, 2003; Langlois & Robertson, 1992).

Independent module nature

Modularity can be viewed as a division of a larger system into multiple building blocks. It is characterized by consisting of these building blocks, or modules, with each fulfilling a specific functional element of the larger system (Langlois, 1999; Ulrich, 1995). Because of this functional clustering modules have a high degree of internal connections (within modules) and a low level of external connections (between modules). Because of the low external connections modules can be created, innovated, or replaced without having any impact on the overall system functionality (Marshall et al., 1998; Gershenson et al., 2003; He & Kusiak, 1996; Sanchez & Mahoney, 1996; Sanchez, 1999).

A modular product design can stimulate radical innovation as well as the speed of product performance improvements. Furthermore, it becomes possible to significantly change products within their product lifetime (Pil & Cohen, 2006; Ulrich, 1995).

The independent module nature therefore allows for great innovative and creative freedom within each of the modules. As long as the modules adhere to the design rules they can be altered in any way without affecting the overall design.

Design rules

These rules set boundaries for the design so that modules fit together. By adhering to the design rules developers are allowed complete freedom for each module, as long as they stay within the boundaries of the design rules. These rules shape the boundaries for the system. By doing so, they ensure that the independent modules fit together in the product architecture (Baldwin & Clark, 2003; Langlois & Robertson, 1992; Baldwin & Clark, 2006; Gershenson & Prasad, 1997).

Design rules typically translate to standardized interfaces in the system design. These interfaces define the relationships among modules and allow for variations in the system composition without affecting the overall design. In contrast to the modules, the standardized interfaces are not allowed to change during the product lifetime (Sanchez & Mahoney, 1996; Sanchez, 1999).

Because of the loose coupling, enabled by the design rules, the mixing and matching of modules becomes possible. This way the most ideal composition of a product can be identified and employed. Furthermore, experimenting with new module configurations can result in new or improved products (Sanchez & Mahoney, 1996; Baldwin & Clark, 2006).

2.2.2 Supply chain modularity

A modular supply chain is divided into smaller parts based on the proximity of the elements in the chain (Fine, 1998). Mainly, the decomposition is based on the processes that take place in the supply chain. The modules are created based on the purposes of these processes. Since supply chains are constructed of similar elements across a broad variety of business fields, it stands to reason that supply chain can also be clustered into generic modules (Elmasry & Größler, 2018). These modules can provide handholds for determining a proper supply chain structure as well as insight in material flows and the effects of these flows on the overall supply chain and resource efficiency.
Elmasry & Größler (2018) have specified four design guidelines to which a modular supply chain design should adhere, namely:

- “Modules should depend on predefined design rules”;
- “Each module should have a defined purpose with no replication of purposes among modules”;
- “Interfaces between modules should be clearly defined”;
- “Modules should be hierarchical and build on each other”.

A modular design provides a clear way of understanding the design of complex systems. In addition, it makes it easier to select the best suited supplier for each process. Next to this, it allows for a dynamic supply chain. The configuration can be altered easily depending on market requirements. Innovative suppliers can replace non-innovative ones more efficiently which has a positive effect on development (Elmasry & Größler, 2018; Belkadi et al, 2018).

The more modularized a supply chain becomes, the more the loss of autonomy over processes poses a problem. Even so, this effect could be negated by the nature of the relationship between the partners in the chain. The tighter the relationship between partners, the higher the dependencies, and the larger the mutual benefits are, the higher the degree of collaboration and influence will become. The larger the part of the production of a company is for a specific buyer, the more influence this buyer has on the producing partner. The more these partners depend on each other with regard to the capital investment they made to generate this production, the tighter the relationship will become. In addition, by working closely with one others, companies can gain access to other parties (e.g. customers or suppliers) that are otherwise unavailable or unknown to the company. This creates certain mutual benefits for the partners (Dyer, 1996).

To summarize, a product can be called modular if its design is made out of independent modules that are connected through standardized interfaces. The structure of the product is not compromised by removing or changing a specific module.
Modular supply chains are characterized by being loosely coupled. The main company can change partners with relative ease. This allows them to quickly adapt to changes in the market and switch to more innovative supple chain partners.

3. Research questions and Research approach

This chapter introduces the main and sub research questions. In addition, it describes how the research is structured in order to answer these questions. The following research question is leading in this research:

Main research question

In what way and to what degree can product modularity and organisational modularity contribute to increasing the circularity of organisations in the circular economy?

The main research question is divided into three central questions, which in turn are divided into sub-questions. Together these questions provide a robust answer to the main research question. The sets of sub questions are provided below.

Central Questions

1. In what way do the modularity principles interact with the levels of circularity in organisations?

   1.1 How can product modularity contribute to achieving the different levels of circularity?

   1.2 How can supply chain modularity contribute to achieving the different levels of circularity?

2. How have the case companies structured their business, product, and supply chain to operate in the circular economy?

   2.1 What level of circularity do the case companies have?

   2.2 To what extent does each case company apply modularity principles?
      2.2.1 How is the product architecture structured?
      2.2.2 How is the supply chain structured?

   2.3 How do the modular principles relate to the level of circularity in the case companies?

3. How can modular design principles contribute to increasing the level of circularity in organisations?

Research Approach

To gather the information to answer the main research question several steps are taken. The outcomes of these steps lead to answers to the research questions.
This research will first discuss the literature on the CE and modularity. From this certain principles are derived and matched to see in what way the concepts can complement each other. Then, interviews are done at case companies that adhere to the CE. The interviews will be used to determine what the companies actually do with regard to the CE. Furthermore, the product and supply chain design are examined to see if they already employ modularity in any way and how this contributes to achieving the circular goals.
After this, the theoretical findings are compared to the findings at the case companies to see if the combination of modularity and the CE can be observed in practice. Finally, the combination of the concepts and case study findings can provide a bases on how modularity can contribute to realizing different levels of circularity. Figure 3 shows the research model and its steps.

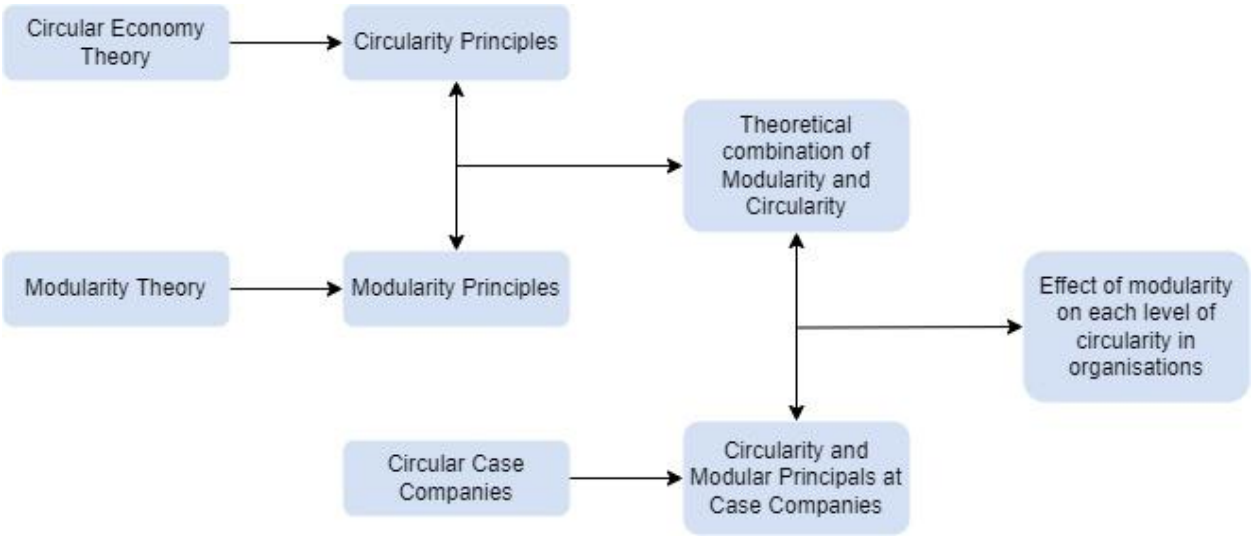

Figure 3 - Research Model

4. Theoretical model

The previous two chapters have provided a literature study of the CE and modularity. This research seeks to combine these concepts. By doings so answers can be found on whether modularity can help in achieving the goals of the CE.
Based on the examination of the literature the theoretical model in Figure 4 is proposed.

This model shows the different variables that influence the level of circularity in organisations. How businesses structure business aspects with regard to these variables will determine the degree of circularity. These variables also affect how the R-strategies are implemented in organisations.

Product design – if this is structured to enable the R-strategies it will have a positive effect on circularity. If not, the product design might impede these strategies which will have a negative effect on circularity.

Supply chain configuration – the way chain partners conduct their business will affect the level of circularity of the main company. The way partners develop parts or use materials will have an effect on the possibility of the R-strategies. Furthermore, partners will play a part in establishing take-back loops. The way companies collaborate will influence the circularity in both companies.

Production process – the way these process are structured and the efficiency that is achieved influences the raw material input. This in turn has an effect on the level of circularity.

Waste – the amount of waste and what the company does with this waste has a significant effect on the level of circularity of the organisation. What the company does to minimize waste will have an influence as well.

Environment – the degree of cradle to grave energy consumption is relevant for the level or circularity. The more effort a company makes to minimize this and use renewable resources the better for its level of circularity.

Economy – by creating value, making a profit, and employing people the company will contribute on an economic base. This can help increase its level of circularity.

In addition, Figure 4 shows the proposed modifying effect of modularity on the level of circularity. This effect is caused by the implementation of modular principles in the product design and supply chain. Modularity has the potential to facilitate the R-strategies. Therefore, implementing modularity in the product design and supply chain configuration could help to effectively apply R-strategies and increase the level of circularity in organisations.

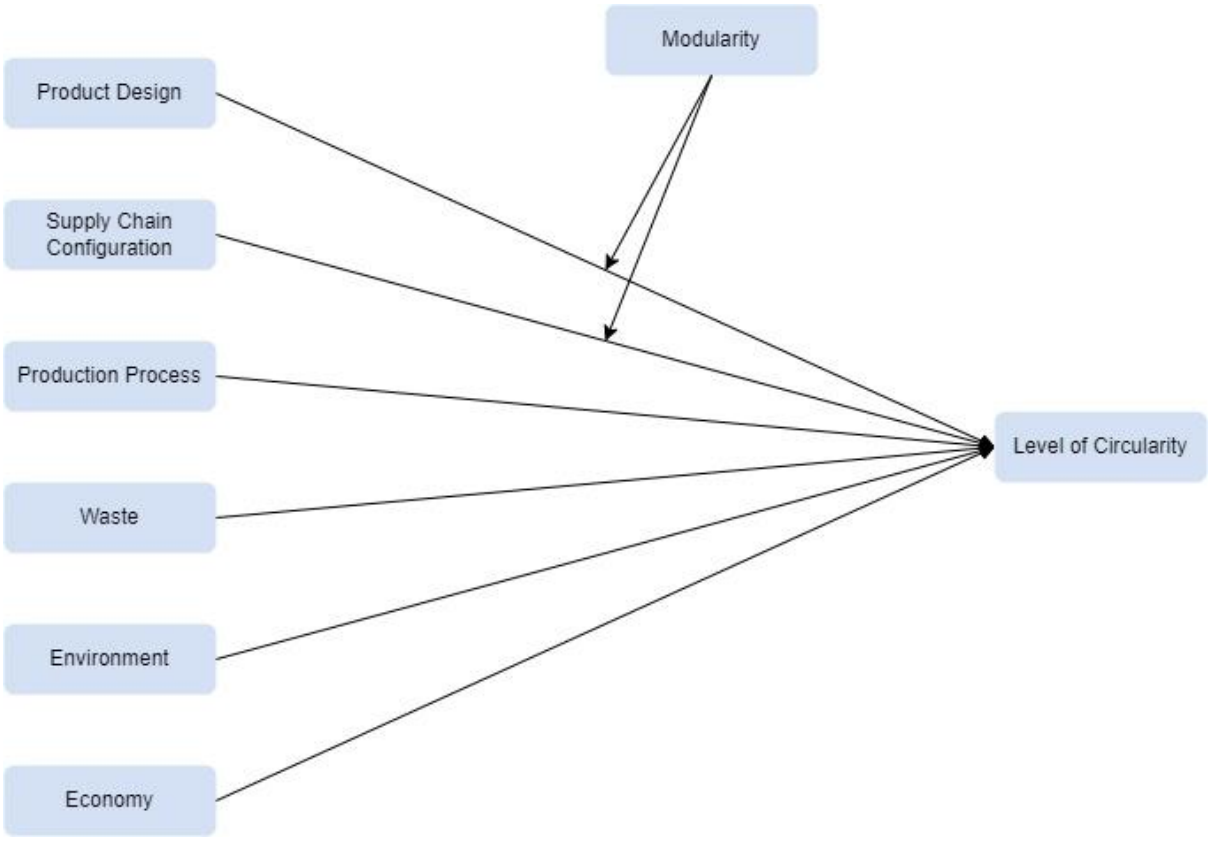

Figure 4 - Theoretical model

5. Levels of Circularity and Modularity

1.1 How can product modularity contribute to achieving the different levels of circularity?

1.2 How can supply chain modularity contribute to achieving the different levels of circularity?

This section will focus on the different levels of circularity that can be achieved in organisations and how a modular product and supply chain structure can contribute to successfully employing a circular strategy.
When looking at CE in a more general manner, two main aspects of the CE could benefit greatly from implementing modular design principles.

First, the CE proposes an alternative view on production and consumption to the neoclassical view. It mainly revolves around the circulation of used materials in the production process to reduce the necessary input for the production process and to minimize and recycle waste output (Zhu et al., 2010).
This implies that the takeback loops are a vital aspect for the CE to be effective since this will allow companies to use their sold products again. This reduces waste output and the need for virgin materials as production input. In order to create a supply chain structure that allows for the implementation of these takeback loops a modular supply chain can prove to be ideal. Since a modular design creates a number of blocks based on processes it becomes possible to more easily add blocks, such as takeback systems, to the overall supply chain. Next to this a modular structure will provide more insight in what the effect of adding takeback loops will have on the supply chain and will therefore make it possible to add them in the most optimal manner.

Second, the CE aims to have a high degree of reusing old products. The product architecture in the CE should be based on the premise that a product can be easily taken apart so that parts can be used again. The design should allow for disassembly, rearrangement, and re-design in order to utilize the materials to their full potential and extending the material lifetime (Zhu et al., 2010; Macarthur Foundation, 2014; Murray et al, 2015).
A modular product architecture seems to provide a good fit with these particular design requirements. Since modularity creates a product out of building blocks and connects them with standardized interfaces it becomes possible to remove and add parts of the product without affecting the overall design. This means that it will become easier to dismantle used products and take out the modules that are still functioning well, or replace the non-functioning parts. By doing so the reuse of old products and product parts can more easily be facilitated.

Next to this, when examining the list of R-strategies it again seems evident that modular design principles can play a valuable role in achieving these strategies. Most of the strategies include propositions could benefit from a modular product and network structure. By incorporating modular design principles along with the R-strategies the likelihood of successful adoption of the strategy can be increased.
The main purpose of product modularity will have a different orientation per level since, for

each level, it's application will shift slightly to facilitate the specific strategy. Supply chain modularity on the other hand will act as an umbrella concept across the levels since it is more applicable to effective incorporation of takeback systems which are vital to all strategies.
To illustrate the role of modularity with regard to the R-strategies the figure by Potting et al. (2017) has been extended to show the function of modularity for the different levels. This extended figure is represented below in Figure 5.

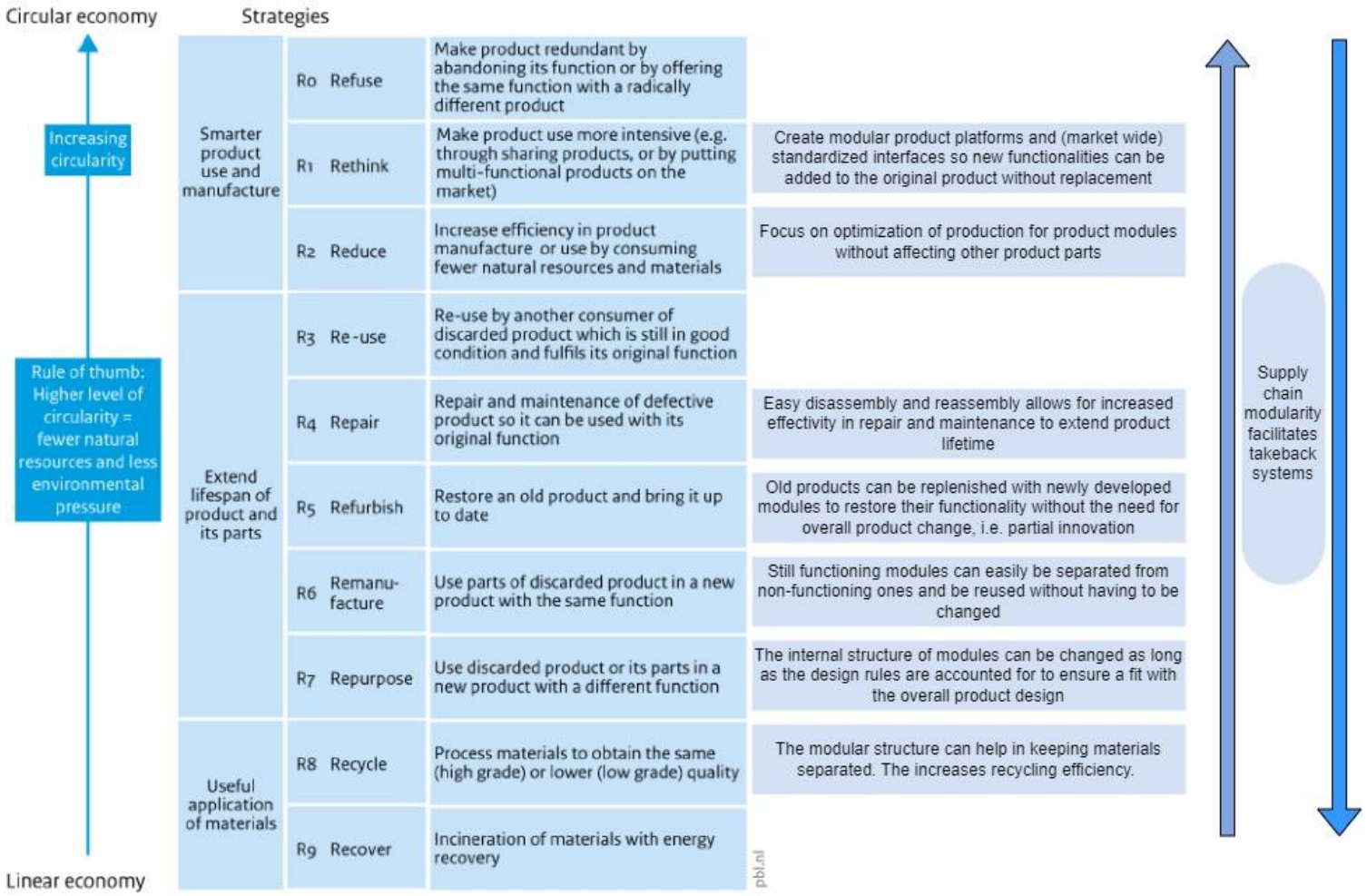

Figure 5 - R-Strategies & Modularity

The role of product modularity has been depicted for R1 to R8 (excluding R3 "Reuse) since this is where the modular design principles will have the most significant effects.
Energy recovery (R9) will be minimally influenced by dividing the product into modules since the recovery processes will remain similar whether or not the design is modular.
The "Refuse" strategy (R0) will not be affected by a modular design since this revolves around development of new products and abandoning product functions which goes beyond the modular design principles. Furthermore R3 "Reuse" builds on the concept of takeback systems in combination with second hand sales channels and therefore will be unaffected by a modular product architecture.

To conclude, the principles of product and supply chain modularity could prove to give a boost to the level of circularity. By employing modular principles the R-strategies could be implemented more effectively.

6. Interview Protocol

The interview protocol is partially based on the diagnostic questions used in the research by Potting et al (2017). Since one of the aims in the research of Potting et al. (2017) was the identification of the strategies used by case companies, a number of the diagnostic questions are applicable for this research as well.
Since this research utilizes a qualitative approach for gathering information the questions have been reformulated. In addition, several additional questions have been added to gain more information on the product architecture and supply chain. This is of importance because the interviews are not only focused on the levels of circularity but also aim to find information on whether or not the companies might employ modular design principles.
Also, several questions and topics that go beyond the scope of the main research question have been removed. This leads to the following interview protocol:

Interview protocol	
Direction	What are your vision, goal, and strategy towards your Circular Solution?
Supply chain	Are the same or similar circular goals and vision shared throughout the supply chain?
	Do partners also employ circular strategies?
	How high is the level of availability and exchange of knowledge in the chain and how is this maintained?
	To what degree do chain partners collaborate to create new circular solutions and improvements?
	How are take back loops of used products realized?
	What are the specific relationships between company and its chain partners? (arm's length, close partner, alliance)
Product design	What is the average life span of the product(s) and how does this compare to the market?
	Is the product designed to include recycled inputs in its original design?
	In what way does the product design enable the R-practices after the product lifetime?
	What product variations are available?
Production processes	Which processes are performed internally, and which are outsourced?
	What are the most important core processes?
	Which and how many raw materials are used in production and how does this amount compare to the market?
	Has a reduction in input and waste been achieved through the CE production strategy?
Waste	What is the nature of the waste output from production, what can it be used for?
	What degree of waste output is unusable/incinerated?
	Has a reduction in waste output been achieved via CE practices?
	Are there partnerships to handle waste output, how is this done?

Environment	How high is the cradle to grave energy consumption of production compared to the market?
	How high is the cradle to grave energy consumption of R-practices compared to the market?
Economy	What is the added value of the product an accompanying services?
	How does this compare to the market?
	Are employment levels in the product chain increasing?

7. Case study results

2.1 What level of circularity do the case companies have?

2.2 To what extent does each of the case companies apply modularity principles?

2.2.1 How is the product architecture structured?

2.2.2 How is the supply chain structured?

7.1 Results per company

Company A

Company A is an organisation that has the ultimate vision of creating multiple regional networks of companies. These networks will allow them to create closed loops and, ultimately, become self-sufficient within the networks.
The company's core practices are the manufacturing and sales of trash bins. These trash bins consist of an outer bin, which is made of metal, an inner bin, which is made of plastic, and a lid, which is made of bamboo. To ensure the product contributes to the company goals the choice has been made to design the bins in a fully modular fashion.

When the company first started they utilized an integral product design. The bin was completely welded together and all interfaces between product parts were locked in. After employing this design for a while the company realized that this was not practical because they could not respond to changes in customer demands easily in with the existing product lines. So, a change had to be made. Now, the product is designed in a fully modular manner. So much so that a single product can be almost completely taken apart with a couple of screwdrivers. The choice for the modular design was made on the bases that a modular design allows for easy repairs, and changes to the product during its lifetime. This way there is no need to replace the product when it is broken or when it needs an update. Its interfaces are made in such a way that is even possible for customers to implement the changes themselves. The company merely has to provide the parts to the customers and they can attach them themselves.
By adopting this design it also allows the company to respond to differing demands from customers. If customers have specific wishes on, for example, how many different waste streams the trash bin should separate the changes can be made immediately and for each product individually. Similarly, if demands for the product specifications change during its lifetime the company can very quickly make these changes for each product. No changes in the production process are needed to do so.

The trash bins are designed to last long. By using metal much of the materials, even if damaged, can be used again when the product returns to the company. Because the inner bin and the lid are not attached to the outer bin with locked interfaces it can easily be removed, cleaned, replaced, or exchanged.

When the products are sold the customer will pay a standard deposit of €25 per product. The customer will get the deposit back if they return the product to the company after its lifetime,

regardless of the state of the product. This ensures that the company receives the products back from its customers after they are used and thus will generate return streams of products and with this raw materials.

The product lifetime spans from 7 to 10 years. When the products return to the company they are completely taken apart, cleaned, and repaired. After this the product will be fully refurbished and sold again. The company tells customers that it takes back products and uses these materials in production. All products have a mix of virgin and refurbished parts. The company therefore makes no difference between new or refurbished and sells all products as mixed. They do not have a new and refurbished product line next to each other.

Company A produces the outer bins in their own factory. For this they have the full production process in house. The factory is a metal working factory which can work with plate materials up to 4mm.
The product is designed in such a way that cutting of the materials is not (or barely) necessary. The size is the bins is decided on the size of the metal plates so they only need to be bended in order to create the bins and minimize waste of materials.
The input for the production process at the moment is 80/20 virgin to used materials. In the future the expectation is that this degree will flip to 80/20 when more products reach their end of lifecycle and are returned. Metal and bamboo are virgin materials, plastic is gathered in the waste of the supply chain and used as input for the inner bins. The inner bins and the bamboo lids are created by local partners.

These local partners are focused on the plastic parts of the product. One partner is a social workplace that produces the inner bins. The other is a company that gathers plastic waste and recycles it. This recycled plastic is then used to create the inner bins.
A third partner is in charge of the logistics surrounding the delivery and pick up of the products. Company A makes sure that this partner does not go out for every product. They aim to cluster the rides so they can make as many deliveries and picks ups as possible in one go. This tactic, and the fact that this might have an impact on delivery times, is communicated to the customers as well.

Because the product design is aligned to the measurements of the material input waste is minimized as much as possible. However, the company constantly looks for opportunities to repurpose waste that is generated in the production of the bins (e.g. metal from cutting holes, spray paint after painting). For example, left over spray paint is gathered from the floor and used to spray inside parts that do not have to be perfect, leftover small metal disks are sold to other companies is the furniture industry.
Currently the company produces their products in their old factory and therefore the energy consumption in the production process is high. In a couple of years they will however move to a new facility which will be energy neutral which will significantly reduce the energy footprint of the business.

R-strategy	Implementation at company A
R0: Refuse	N/A
R1: Rethink	Product design Switch from integral to modular design. This enhances the product lifetime and allows for product variations increasing the usage range of the product, e.g. the bins can switch from collecting one garbage stream to multiple garbage streams even during the product lifetime.
R2: Reduce	Product design Size of the bins is based on the size of the steel plates which are the input for the bin. This reduces the waste from cutting the plates to a minimum.
	Production process Left over from spray painting the lids and outer bins are used on the inside where the paint job does not have to be perfect to minimize leftover paint
	Supply chain Product delivery and pick up (especially for smaller orders) is not done for one customer or product only. The company aims to combine pick-ups and deliveries in one ride to reduce the number of times trucks have to go out.
R3: Re-use	N/A
R4: Repair	Product design Choice for a modular design allows for repairs of the bins or replacement of parts while it is still at the customer. This enhances the lifetime of the product.
	Production process Product parts are returned (and replaced) if damaged, e.g. lids, inner bins, side plates. These damaged parts are repaired and used again.
R5: Refurbish	Product take back Old bins are taken back (use of deposit of €25).
	Production process Returned products are cleaned and fixed and afterwards used as new for sales. No distinction is made between new and refurbished by the company since they argue that all refurbished products live up to the quality of new products.
R6: Remanufacture	Product take back Old bins are taken back (use of deposit of €25). The parts that still have good quality are use in new products directly.

	Production process Old parts that are still good are salvaged and used again in the production process. These parts are used like new parts.
R7: Repurpose	N/A
R8: Recycle	Supply chain A partnerships is used with a company that gathers plastic and recycles this. This plastic is used in the manufacturing process. The inner bins that are unsalvageable are also recycled by this partner.
R9: Recover	N/A

Conclusion – Company A

Company A has woven the circular strategies throughout their organisation. Nearly all CE strategies are implemented in the company successfully. The company has used these principles to their advantage to create value. By using deposits, they create large take back streams of products. Reusing products and materials is implemented as a base principle in the production process. By doing this the company also manages to create value on a sustainability and economic basis.

Company B

Company B is a startup company with a vision to attribute to bringing an end to the use of single use plastics around the world. For their part the company focuses on the ready to eat foods industry, i.e. they want to replace single use packaging for take-away and delivery foods with reusable packaging. The reason the choice for the take-away sector is made is that the company has identified this as a rapidly growing sector that will produce increasingly large amounts of plastic waste with its growth.

The company aims to create a network restaurants that use the reusable food containers combined with delivery companies that not only deliver the food, but also pick up the empty containers and return these to the restaurants. Furthermore, the company argues that one of their main aims is to take back as many of their products as possible at the end of the product lifetime. The products can then be used in the production process again as raw materials. This way they hope to close the loop with regard to their products.
In addition, company B offers a washing service for their products. This means they rent out the containers. The containers are then used/filled by the restaurant and after that delivered and used by customers. The delivery partner will then pick up the empty containers which are delivered to company B. The company will clean them and have them ready to be used again. An example of where this would be applicable could be catering events or for companies.

The products utilized by Company B to pursue their goals are reusable food containers. These containers are made out of polypropylene (EPP) or out of silicone and are therefore highly endurable and easy to clean.
The EPP containers consist of a lower part (i.e. the container) and an upper part (i.e. the lid) which are attached to one another with a hinge. The hinge is fixed to both parts permanently and is also made of polypropylene.
The silicone containers are made of food grade silicone. These containers also consist of a container and a lid but these are not attached together through a hinge. These food containers lids click onto the lower parts.
As for now the technical lifetime for the containers is estimated at around a thousand uses. After that the hinges on the containers start to fail and the containers become unusable.
In each of the containers the company aims to keep the materials down to one material as much as possible. If mixed materials are used in the overall product they make sure that these materials can be separated easily, e.g. a non-attached lid on a container. The choice to do this was made so that the materials in the product can easily be used again as input for production after the product lifetime. If materials would be mixed too much the company argues that it would become difficult, if not impossible, to use the materials again.
The main choice for the materials used is the fact that these materials work well with food. The containers, and the food in them, can be cooled, heated, and cleaned without a problem. Furthermore these materials can be molded into the right sizes and shapes with ease and with low costs. This means that these materials meet the company's functional requirements perfectly. Still, company B also recognizes that the materials could be improved upon on a sustainability bases. They argue that there likely are materials that are better suited for

recycling or that will extend the product lifetime. The search and development for new materials and how to use these is an ongoing process for the company.

The core processes in company B at the moment are the cleaning of the containers. The company takes back the rented out containers and makes sure they are washed properly and ready to be used again. In this process they are attempting to make the water they use for washing reusable. This way they can keep cleaning the containers with the same water over and over again without wasting any of it.
The production of the actual containers is not done by company B themselves. The company has partnered with a manufacturer and a supplier that can create these containers in large quantities. The containers are manufactured in China and then shipped to the reseller in Germany who sells them to company B. The containers are then stored and cleaned (after take back) at the warehouse of the company.
Neither of the supply chain partners adhere to the CE principles necessarily. The supplier-buyer relationship is a standard one in the sense that company B specifies what they need, which sizes and which material, and the supplier manufactured the products and ships them to the company. The partners are not selected on the fact that they employ circular principles. The use of materials in the products therefore are 100% virgin materials.
The amounts of waste produced by production are quite low of the choice of materials. The materials are melted and poured in a mold in order to create the containers. By doing there is little to no need for cutting materials and leftover materials are minimized.
On the other end of the chain the company works with another partner, a delivery company, to pick up the used containers. For recycling they are looking into another partner to do this for them and make sure it is done in a proper manner. In the end the company aims to get back all of their sold products at the end of their life cycle and make sure they are recycled into new materials to be used in production. This does at start not necessarily have to be their own production since this is located in China at the moment
The company wants to shift production to a manufacturing center of their own in the future. When they realize this they aim to use at least 50% of their recycled products' materials in their production process.

R-strategy	**Implementation at company B**
R0: Refuse	N/A
R1: Rethink	<u>Product design</u> For the EPP containers the company tries to create a network with and between restaurants to share the containers among them. This makes the use more intensive and decreases the need for large stockpiles of single use containers.
	<u>Product design</u> For the silicone containers the company stays in possession of the containers and delivers them to other businesses on demand. This also

	increases the number of times a single container will be used since they won't be replaced quickly.
R2: Reduce	N/A
R3: Re-use	Value proposition The re-use of the containers is at the core of company B. The company revolves around creating a network to move from single use plastic containers towards multi use food containers.
	Product design By making containers out of "better" materials they replace single use containers and ensure that they are used again and again for food delivery.
R4: Repair	Core processes The company provides the service of renting out containers, taking them back, and cleaning them so they are ready to be used again. While this is not technically repairing (or refurbishing) since it is a service it is highly similar to these practices.
R5: Refurbish	N/A
R6: Remanufacture	N/A
R7: Repurpose	N/A
R8: Recycle	Product take back The company creates take back loops to make sure they get back the old containers.
	Product take back Partnering with another business to ensure the old containers are recycled and the materials are used again as input in manufacturing (if not at company B).
R9: Recover	N/A

Conclusion – Company B

Company B applies several CE strategies very well, yet is still developing in other areas. Since they have only recently started not all aspects of production are circular. Still, the company takes responsibility for their products after sales and seeks out partners they can trust to recycle the products into new materials for production. Next to this, the company takes charge of making sure products are reused by keeping ownership of these products.

Company C

Company C is a large established manufacturer of office furniture. The company is a family business and has been operating in the furniture industry over 70 years. They started with products bases on a linear lifetime. When doing this, the first step toward moving to CE practices originated from the wishes of optimizing the use of input materials, and thus also reducing waste. These wishes sometimes collided with the lean processes the company applied at the time. Bit by bit the company's orientation shifted from process optimization toward optimization of the use of materials. After a while the company started to shift more towards a circular mindset in their company because they believe this is the most logical way to do their business. They like to view themselves as a company with a clear long term mindset and by applying circular principles they create a solid basis for the survival of their company. They still identify themselves as a regular business in the sense that the company exists to make money, yet they also argue that applying circular principles helps in this regard since it creates continuity for the business, employees, and also the world around them.

With regard to their products they company is changing rapidly towards a circular organisation. New product lines are developed according to circular principles. Low to no mixing of materials, design for easy repair, and aiming for long product lifetimes. In order to achieve this the company often uses modular design principles. By doing so it becomes easier not to mix materials and taking apart the product for repair of disassembly also becomes a lot more practical. This allows for customers to do small repairs themselves and increases efficiency in the workplace when disassembling products. Furthermore, the company often has maintenance agreements with their customers to maximize the lifetime of their products. Since the company has been operating for long time they also have old product lines in the market. These product lines are still based on the linear economy and do have mixed materials and a lot of fixed interfaces. Still, company B actively tries to retrieve these products after their lifetime in order to make use of the old parts in new products. They do try to update the existing product lines where possible to include circular practices in production and reuse old materials.
In general their products are made with pre used materials or parts. If customers however demand to get products from virgin materials only this is also possible. Still, the demand for products with reused materials is so high that company B has to actively search for old products which can be used again.

Production of all products offered by company C takes place in their own factory. The company keeps the whole production process internal. This way they keep tight control of quality and make sure they provide for their employees. The optimization of material usage in the production process is the most important focus in the production process. This often means the company will produce more than is necessary at the time in order to not throw away materials. Next to this, the company continuously searches for new purposes for their leftover materials from production, outside of the company as well as inside. This way the company has found partners which can recycle / upcycle the leftover materials so company C can use it as input for manufacturing. This in turn leads to a reduction in the need for virgin materials.

The company has multiple partners for the supply of materials. The company tries to communicate circular values and principles to their suppliers and tries to get them to at least start thinking about the benefits of this strategy. In general, they try to find suppliers with a similar attitude towards circular practices. Still, they also realize that a switch to circular practices cannot be made instantly and takes time. Company C tries to take a step by step approach to guide these companies to more circular practices. First, they take a look at the origin of the materials and if this can be more sustainable. After that they look at material take back by the supplier and if they can start recycling these materials. Next to this, the company also thinks about the materials they want to use, and which they do not want to use, in their products. They communicate these as wishes or sometimes demands to their suppliers. They also work with the suppliers to search for optimal materials and design with regard to their products and the materials used in them. Even so, if suppliers do not meet the wishes specified by the company they will search for other suppliers.

Product sales are most often done through dealerships that are partnered with the company. Company C has a sister business that is in charge of delivery and product pick up. This way, they also keep delivery within the organisation. Deliveries and picking up products is usually done in large quantities. Especially picking up products is less economically beneficial if it is only one or a few products. This means take back of single products is difficult to realize for the company.

R-strategy	**Implementation at company C**
R0: Refuse	N/A
R1: Rethink	N/A
R2: Reduce	Production Process A strong focus on optimizing material use in the manufacturing process. Making sure leftover materials are used again in production by finding partners to re- or upcycle the leftover materials.
R3: Re-use	N/A
R4: Repair	Core processes The company has maintenance deals with customers in which they regularly perform maintenance on the sold products.
	Product design Products are designed with modular interfaces to make small repairs by customers easier. Because of the loose interfaces the company can perform larger repairs more efficiently at their facility.
R5: Refurbish	Product design Products are designed in such a manner that the different parts are not put together permanently (e.g. no glue or welding). This way parts of the products can be replaced and products can be sold again after being returned.

R6: Remanufacture	Production process Old products are taken back by the company and are taken apart. All parts that can be immediately used in new products when applicable. The company has already created a large demand for products with used parts.
R7: Repurpose	N/A
R8: Recycle	Supply chain The company has created partnerships to recycle the leftovers from production into materials that can be used as input for manufacturing
R9: Recover	N/A

Conclusion – Company C

Especially for the newer product lines company C scores well when it comes to their circular business practices. The company actively searches for their old products and makes sure they take them back to be used again. In using them again the company applies multiple CE strategies. Furthermore, company C aims to minimize waste and leftover material and adapts their processes to achieve this.

Company D

Company D is a new company that focuses on the sale of circular trash bins. These trash bins can be modified to collect multiple streams of garbage based on the needs of the customer. The main vision of company D is twofold. On the one hand the company wants to contribute to the proper separation of waste in general. On the other hand they want to promote the CE by creating a product that is created based on circular principles.
The company acts as the central player in the supply chain. They have created partnerships and have outsourced most parts of the chain, except the sales and marketing of the end products.

In order to achieve these goals the company focuses on the manufacturing and sales of trash bins. The company has chosen for materials that do not have to be downcycled after the product lifetime but can be used again at the same level after recycling. Next to this, the company has adopted a modular design of the trash bins. The company argues that the modular product design helps to increase the lifetime of the products. The main reason for this is the fact that products can be changed during their lifetime. This allows the company to easily respond to changing demands in functionality during product the product lifetime. Next to this, multiple products can be combined using loosely coupled interfaces in order to personalize. This allows customers to change the set ups of the trash bins according to their personal preferences.
The bins are made out of steel. The reason for this material is the fact that it is sturdy, lasts long, and does not damage easily. The fact that steel lasts long is the main reason the materials was chosen. The company argues that this means the product will have a very long lifetime which is beneficial for circularity. They argue that the sturdy material will help them with refurbishment since it will reduce the effort involved to do so because it is not damaged easily. The material is also a good choice when it comes to recycling of old products. The lid of the bins is made out of bamboo. The lid of bamboo is glued to the bin which makes this a fixed interface.

For the manufacturing of the bins company D has a partnership with a steel working company. This company in turn has a partner that collects old steel and transforms it into plates. These plates are then used by the steel working factory to produce the bins. The company assumes that the manufacturing facility is quite circular since they work with steel as a material. Company D argues that the steel industry already is quite circular so this translates to circularity in production.
The manufacturing facility is also used to refurbish the bins if they are returned. However, the only bins that are refurbished are those that are bought back from customers because customers no longer satisfied of the bins are damaged. These bins are stored at the factory and cleaned and refurbished. Afterwards they are sold again for a diminished price.
Even though company D has designed the bins in a way, and with a material, that makes it well suited for reuse or recycling they do not plan to take back their products after their lifetime. The company argues that the Dutch government has already implanted legislation to properly recycle different garbage streams. Therefore the company believes that the products can, after their lifetime, be thrown away and will be disposed of in a proper manner.

The delivery of the products to the customers is performed by another partner in the chain. They pick up the products from the manufacturer and bring them to the customers. The products are produced by lean practices in order to avoid large stockpiles of products. The company does therefore not have a storage facility.

R-strategy	Implementation at company D
R0: Refuse	N/A
R1: Rethink	Product design By offering a product that can be modified during its lifetime upgrades and changes can be made after sales. This combined with the material creates a very long lifetime for the products.
R2: Reduce	N/A
R3: Re-use	N/A
R4: Repair	N/A
R5: Refurbish	Production process A small amount of products are returned by customers. These few products are refurbished by the manufacturing partner and sold again.
R6: Remanufacture	N/A
R7: Repurpose	N/A
R8: Recycle	Production process An unspecified degree of recycled materials are used in the production of the trash bins.
R9: Recover	N/A

Conclusion – Company D

Even though company D does apply some (parts of) circular principles they cannot be called a circular company. The company relies on existing systems of garbage disposal for their products after their lifetime. They do therefore not take responsibility for the products after sales and take no action to get the products back and close the loop, nor do they plan on doing so. Furthermore, they assume recycled materials are used in production and do not really reuse or refurbish products or parts.

7.2 Cross case examination

This chapter provides a cross case examination of the four case companies. The comparison is performed on the aspects of circularity principles and the aspects of modularity principles. For each of the cases the principles are scored on the degree to which they can be identified at the company. If an aspect is scored as dominant (10) it implies that the company puts strong emphasis on it. Present (6) means that the aspect is clearly present in the company, yet it is not emphasized specifically by the company. Remotely present (3) signifies that the aspect can be found in the company but that it is not something the company focuses on at all. Not present (0) implies that the aspect cannot be found in the company.
Table 1 gives and overview of these scores along the case companies. Furthermore, it shows the totals the companies score compared to the total score companies can achieve in each category. This shows to what degree circular and modular design principles are present in the different companies. After the table the aspects are discussed in more detail. The cases are then compared to the theoretical model.

Circularity principles	**Company A**	**Company B**	**Company C**	**Company D**
Reduce				
Reduce raw material input	10	0	10	0
Reduce virgin material input	10	0	10	3
Extend product lifetime	10	10	10	10
Increase product usage	6	10	0	6
Reuse				
Product take back	10	10	10	3
Using old parts	10	0	10	0
Products used again	10	10	10	6
Recycle				
Repurpose leftover materials	10	0	10	0
No mixed materials	10	10	6	10
Circularity score	**86/90**	**50/90**	**76/90**	**38/90**
Modularity principles				
Product design				
Uncoupled parts	10	6	10	6
Module replacement / repair	10	3	10	3
Product modularity score	**20/20**	**9/20**	**20/20**	**9/20**
Supply chain				
Core processes by partners	6	6	0	10
Loose relationship to partners	3	6	6	6
Supply chain modularity score	**9/20**	**12/20**	**6/20**	**16/20**

10-Dominant 6-Present 3-Remotely present 0-Not present

Table 1 – Cross case examination

7.2.1 Circularity principles at case companies

Reduce

Reduce raw material input
Raw material reduction is seen in two of the four cases. Company A and C companies have intentionally kept the largest part of the production process within their organisation. This gives them full control on how this process is structured. It also means they have the possibility to make a reduction in raw material use for production or look for other ways to more efficiently use the raw materials. Since the other two companies have outsourced the production they have little to no control over the production process.

Reduce virgin material input
Company A and C have a strong focus on the reduction of raw materials as well as ways of achieving this since they the largest part of the production process. By using old materials and products as input for production they can achieve a reduction in the need for virgin materials. Both companies actively pursue this on both sustainability as well as economic grounds. Company B and D can make requests from their suppliers to use certain pre used materials. However, if the partner is not willing to provide this they have no option to enforce it.

Extend product lifetime
All companies make conscious decisions on product design and the materials used in order to make the product lifetime as long as possible. Company A and D choose metal over plastic to create a more sturdy product. Company A and C offer maintenance and repair on their products after sales. Company B creates a transition from single use products to a product which can be used over and over.
All of the companies offer products that have a longer lifetime than alternatives in the market either through choice of materials and/or services offered alongside the product.

Increase product usage
Company B has built its value proposition around more intensive product usage. By offering a reusable alternative to the market they aim to create a shift in the market. Company A and D both offer different variations of their products so the trash bins can collect multiple garbage streams. This creates a broader use for the bins.

Reuse

Product take back
Company A, B, and C all take back as many of their sold products after their use or lifetime as possible, whereas company D only takes products back if customers have complaints. Company A uses a deposit system on the trash bins which is returned to the customers when the product is sent back to the company after its lifetime. Company B stays the owner of its

products and has partners which return it to the company for cleaning in certain areas. Company C actively searches the market to find their old products and have them returned to the company.

Using old parts

Both company A and C have a high degree of using old product parts in their new products. Company A goes as far as not even making a distinction between refurbished and new products. They have fully incorporated the reusing of old parts into their core processes. Company C also use old parts in new products. They experience a very high demand for refurbished products. Therefore they aim to reuse as many product parts as possible in their production.

Both company B and D mainly use virgin materials in production. It is difficult for them to switch to reusing martials in their primary production process since this is done by partners. However, Company B is actively searching for ways the materials of their old products can be recycled and used again in different areas.

Products used again

Company B makes sure that their product is used by different customers over and over by keeping ownership of the products. They clean them and have them ready to use again. Company A refurbishes the taken back products and sells them as new products. They guarantee the same quality they do when virgin materials are used. Company C has established large refurbished product lines. Company D also has a small refurbished product line but this only includes products which are returned by customers after complaints. These are repaired and refurbished by their production partner and sold as such.

Recycle

Repurpose leftover materials

Both company A and C are constantly looking for new purposes of leftover materials. Company A creates small new products in their own factory, e.g. iron bowls from leftover metals. Next to this, the company looks for other companies in the region that might have a use for their leftovers and sells this to them, e.g. small iron disks which after bending can be used by a small furniture manufacturer. Company C looks at materials used throughout their product lines and tries to design products in such a way that materials are optimally used. For example, a table might become slightly smaller than planned so the leftover materials can be used for a chair. Next to this, they look for partners which can recycle the leftover materials so the company can use them again in their production process.

No mixed materials

All of the case companies design their products in such a way that they do not mix materials. They all do so in order to make end of lifetime recycling as easy as possible.

7.2.2 Modularity principles at case companies

Product design

Uncoupled parts
Company A has created a fully modular design. The different parts of their product are connected through non fixed interfaces making it possible for anyone with some screwdrivers to take it apart. They have intentionally done so to make repair, maintenance, and disassembly as efficient as possible.
Company B has some food containers that have loose lids and dividers in the containers. These can therefore easily be replaced when necessary.
Company C has also designed their products with uncoupled product parts. They have made this choice to make disassembly and repair more efficient in their workplace. This also allows them to keep the materials that are used for different part separated.
Company D also created a product in which the parts are not fixed together. They do so to avoid mixing materials. The interface that is fixed however is the lid which is glued to the bin.

Module replacement / repair
Both company A and C offer services to repair the products and, because of the uncoupled parts, make replacement of parts possible. Company A has made disassembly so straightforward that they can send new parts to customers which they can assemble themselves. Company C takes products back for repair from customers and them brings them back. Both companies also refurbish products by replacing or repairing parts of the products. Company B can replace broken lids or containers since these are not fixed which makes the overall product usable again. Company D also performs repairs of broken products and has the option for partial replacements.

Supply chain

Core processes by partners
Company B and D both have outsourced their production processes and product delivery to other companies. These companies now form vital partners in the supply chain. Company D focuses on the sales of the bins as their core business, the other parts of the chain are outsourced. Company B also outsourced the production and delivery. On the other hand they do perform the cleaning of food containers which is one of their core processes next to the sales.
Company A has the largest part of production and all of the assembly in their own factory. One partner produces the inner bins. Other partners are suppliers of materials. They do pick partners critically on circularity and sustainability basis. They actively pressure and help their partners to become more circular as well.
Company C has the complete production process in their own company. Their partners are the suppliers of the materials and companies that recycle waste and leftovers for them.

Loose relationship to partner
All of the companies argue that they have a loose relationship to their partners. Even so, company B and D do have a high dependency on their partners since these companies are in charge of their production. Still, if they find suppliers that are more suited to their needs or demands they can easily switch.
Company A does rely heavily on one of their partners. On the other hand they also engage with partners to try and get them on board with their own values. However, if partners won't try to become more circular and the company does not feel like it is a good match they are able to switch.
Company C has partners for materials supply and recycling. If they want they can switch relatively easy.

7.3 Modularity and level of circularity - case companies

4.3 How do the modular principles relate to the level of circularity in the case companies?

This chapter will use the scores in table 1 – "cross case analysis" to examine how modularity influences circularity in the case companies. By looking at the scores for the different aspects of modularity and circularity conclusions can be drawn on how two concepts interact

<u>Company A</u>
Company A scores high for circularity, with a 3 on eight out of nine aspects.
For product modularity they score a 3 on both aspects. Company A clearly uses a modular product design to achieve their circular goals. The modular product design helps the company to keep materials separated which makes recycling and repurpose of materials more effective. Furthermore, the modular design makes dis- and reassembly more straightforward which helps repair and maintenance activities. This in turn increases the product lifetime. After the product lifetime the modular design enables the company to refurbish the products and salvage parts and materials more effectively. Product modularity therefore contributes significantly to the level of circularity in company A.
On the other hand, supply chain modularity does not play a large role in the level of circularity in company A. The company scores a 2 and a 1 on the aspects of supply chain modularity. From the interviews it is clear that production has been kept inside the company as much as possible. The company has close interactions with the partners they do have and aim to keep tight control over the supply chain. This reflects in the scores for supply chain modularity. Supply chain modularity cannot be said to influence the level of modularity for company A.

<u>Company B</u>
Company B scores a 3 on five out of nine aspects of circularity. However, they score a 0 on the other four aspects. This can be explained by the company's focus on providing an alternative for single use products. Even so, production is outsourced which means the

company is not in control over other aspects with regard to circularity.
The company does apply some modular design principles but does not put emphasis on this. The scores on product modularity reflect this with a 2 and a 1 for product modularity. For company B product modularity does not seem to affect their level of circularity.
Company B has outsourced most of their supply chain. They score a 2 for both aspects of supply chain modularity. Since they have partners for specific processes, such as production and logistics, which are arm's length relationships the supply chain is modularized. Still the company does have a large dependency on these partners. This means it is not easy for them to switch to another partner. On the other hand the arm's length relationship does not give them much influence to promote circular practices. The supply chain modularity therefore does not help in increasing the level of modularity in the company.

Company C

Company C also scores high on circularity with a 3 in eight out of nine aspects. For product modularity the company scores a 3 in both aspects.
Company C has implemented modular product designs to reduce the mixing of materials. Different parts consist of certain materials but the materials are not combined. This has benefits for reusing materials and recycling of product parts. Furthermore the modular product design allows the company to be more effective in refurbishment of old products. Next to this repair and maintenance can be done with greater ease. Product modularity plays a large role in increasing the level of circularity of the company.
On the other hand, company C scores low on supply chain modularity with a 2 and a 0. They have made the choice to keep the production process within their company completely. The only partners they have are material suppliers. They can switch these with relative ease. Supply chain modularity therefore does not play a role in the level of circularity for this company.

Company D

Company D scores for circularity are quite spread out. Overall, the company does not score very high for their level of circularity. The main focus lies on extending the product lifetime and increasing its use intensity. However, the other aspects of circularity are not, or barely, implemented.
Product modularity is applied to a certain degree within the product, and also between products. The company only refurbishes small amounts of products and does not provide repair or maintenance activities. The benefits of a modular design are not exploited fully by the company. Company D does not use the modular product design principles to increase their level of circularity.
The company does have modularity in their supply chain. They score a 3 and a 2 on the aspects of supply chain modularity. They have outsourced all their core processes and are in charge of sales and managing the supply chain. Even though the company does not have close relationships with their partners they have high dependencies on them. They have little

power to increase the circularity in the chain. Therefore, supply chain modularity does not increase the level of circularity for company D.

To conclude, company A and C apply a modular product design. By doing so they are able to increase their level of circularity. Mainly, a modular product design enables these companies to more effectively apply circular strategies. It allows these companies to easily dis- and reassemble the products. This in turn increases the effectivity of circular practices.
On the other hand, supply chain modularity does not increase the level of circularity. Company B and D have a modular supply chain. Because of this, they lose autonomy over the processes in the supply chain. Since they do not have power over the partners they cannot ensure that everyone in the supply chain adheres to CE principles.

8. Discussion

3. How can modular design principles contribute to increasing the level of circularity in organisations?

8.1 Contribution to literature

The goal of this research was to explore the possibility of increasing circularity in organisations by employing modular design principles in products or supply chains. The CE provides a possible solution to resources scarcity, increasing waste output, and the take-make-dispose attitude of many industries. By employing reduce, reduce, and recycle principles and closing the loop of products throughout businesses the CE provides an alternative to linear ways of thinking. To successfully do so, products and supply chains need to be structured to support the CE. Therefore, this research has focused on answering the following research question: In what way and to what degree can product modularity and organisational modularity contribute to increasing the circularity of organisations in the CE? By addressing the research question this research contributes to theory by searching for a fit between these two theoretical concepts. Furthermore, it provides a way of more effectively achieving circular practices and thus making the CE a more viable option for businesses.

The research finds that modular principles in product design does help to increase the level of circularity in organisations. On the other hand, the research does not find that supply chain modularity increases the level of circularity in organisations.
The way in which the concepts of modularity and circularity interact are described in more detail in the next section. Since a different effect is found for product and supply chain modularity both are discussed in two separate sections.

Product modularity & circularity

This study has shown that product modularity has a positive effect on the application of the CE. By applying a modular product design, and thus, having loosely coupled product parts, companies can more effectively apply the 3R principle of the CE.

First of all, this study finds that applying a modular product design has a positive effect on the reuse aspect of the CE. By using a modular product design it becomes easier to dis- and reassemble which allows the companies to reuse and replace parts, perform maintenance and repair, and refurbish old products more effectively. These benefits stem from the loose coupling in modular architectures. By applying loose coupling between modules the architecture allows for high freedom toward changes in the product without compromising the overall structure (Pil & Cohen, 2006; Ulrich, 1995). This means product lifetimes can be extended by replacing parts instead of replacing the product. Additionally, modular products can easily be disassembled since they are designed to enable this from the start (Gershenson et al., 2003). This implies that discarded products can be taken apart effectively and parts can be used again in production of other products.
Since a modular product design allows product parts to be removed and replaced with greater ease. This creates more opportunities to increase product lifetime, refurbish old products, and reuse old product parts. Therefore, product modularity will have a positive effect on the reuse practices in the CE.

Second of all, the results show that applying a modular product design can help companies to reduce the virgin material input in production. By establishing design rules in product lines, or even between different product lines, it becomes possible to reuse product parts from other products. This in turn will reduce the need to produce new product parts and thus the need for virgin materials will be lower. As long as the "old" parts fit in other products they can be used again, i.e. the parts need to adhere to the design rules of the product architecture. By creating standardized interfaces and establishing the boundaries for product modules the design rules ensure that the product parts fit together (Baldwin & Clark, 2003; Langlois & Robertson, 1992). This allows companies to effectively use old parts again in their products and thus reduce the need for virgin materials in production.

Lastly, this study finds that product modularity can help companies in their recycling activities. Product modularity helps companies in keeping materials separated by not mixing materials within modules. Companies can go as far as modularizing a product based on the materials used in the modules to increase recycling efficiency. Since the modules are not fixed to one another and materials are mapped one to one with the modules, the effort to separate materials for recycling will be reduced significantly (Gershenson et al., 2003). This means that companies can take apart the product they take back and recycle the parts more effectively. Since they do not have to put effort into separating the materials in the parts before recycling a modular product architecture will boost circularity.

Supply chain modularity & circularity

This study does not find a positive relationship between supply chain modularity and circularity in organisations. The companies that apply a modular supply chain score lower on their overall circularity than the ones that own (most) of their supply chain. The main reason for this is the loss of autonomy that comes with outsourcing supply chain processes. The more loosely coupled the relationships in the chain become, the less influence the different companies have on each other's processes (Dyer, 1996). This means that the main company might adhere to the CE, yet, its partners may not. This decreases the overall circularity in the supply chain.
On the other hand, supply chain modularity also allows for easy switching partners (Belkadi et al., 2018). If the current partners do not fit the requirements (in this case circular practices), companies can switch to other parties that have a better fit. However, CE companies do need to find these suitable partners. If no alternatives exist or they cannot be found switching is not an option. If this is the case the switching advantage of supply chain modularity is negated. By keeping processes internalized the company has more control over how the processes are structured. It gives them full control over prioritizing CE principles. When these processes are outsourced the companies lose control over the processes. Therefore, outsourcing supply chain processes can lead to lower overall circularity in the supply chain.

8.2 Managerial implications

This research shows that modularity can support companies in achieving their circular goals. To gain the benefits of combining a modular product architecture with the CE two recommendations for practice are proposed.

Create awareness – Companies need to be made aware that applying a modular product structure can act as an enabler for CE practices. Information on how modularity allows companies to become more able to reuse, reduce, and recycle needs to be presented to companies. Furthermore, they need to be aware on how to properly create a modular product design. Different methodologies already exist in modularity literature. Even so, the question remains if these methodologies are known to people outside the field. The methodologies need to be accessible and understandable to people operating outside of this field of research.

Guidance for CE – The CE is proposed as a solution to the current linear economy and its inherent issues. Certain strategies for reaching levels of circularity have been developed. Still, guidance on how to apply these practices properly and how to take responsibility for an entire product chain is still lacking. Currently, for example, companies that merely recycle waste are calling themselves circular companies and are allowed to do so. This blurs the market and makes it more difficult for customers and practitioners to find companies that truly adhere to the CE. Helping companies become more circular and, on the other hand, sifting out those that actually aren't will help practitioners find the right partners. In addition, increasing collaboration and openness among CE companies will underpin the viability of the CE and can help new and existing companies to effectively employ circular practices.

9. Limitations

First, it is not yet possible to quantify the level of circularity in a standardized way. No clear and standard measures for the different aspects of circularity have yet been developed. Next to this, the information necessary to perform such an analysis includes sensitive information which many companies are hesitant to provide. In addition, when the needed information is gathered determining whether it is high of low will be arbitrary. A framework to score the findings does not yet exist. This means the only way to judge the level of circularity is to determine if certain aspect are present or not. Then, implications of this presence can be discussed in the context of the specific cases. This approach is what was conducted in this research.
To provide a standard framework for analysing companies in the CE is beyond the scope of this research. However, it is a very interesting direction for further research. Not only will it provide researchers with a tool for analysis, it could also be a valuable tool for the market. It can help companies to identify points for improvement to become more circular, it can weed out companies that only use the CE for marketing instead of employing it, and it can help companies find likeminded organisations for their network.

Second, the findings in this research cannot be broadly generalized. Since only four cases have been examined the results could be significantly influenced by chance. Still, the goal of this research was examining the theoretical combination of the CE and modularity and evaluating if the combination could be identified at circular companies. Even though this cannot be generalized based on four cases, the results do underline that the combination is viable. This provides a bases for future research.

10. Conclusion

Based on the theoretical findings complemented with the case study findings it can be concluded that modularity is able to support the CE. Even so, the findings only support the proposed the theoretical model partially.

The results show that modularity in product design can act as a strong facilitator for many of the strategies in de CE. By its nature product modularity allows for loosely coupled designs. Because these designs enable efficient dis- and reassembly many of the CE strategies can be employed more effectively. In addition a modular product design will help companies to lengthen product lifetimes and recycle or reuse product parts more easily for input in production processes.

On the other hand, supply chain modularity does not appear to positively influence the level of circularity in organisations. If companies implement supply chain modularity they outsource parts of their business processes. This means they lose control over how these processes are conducted as well. The CE includes societal and environmental goals in addition to economic goals. If an organisation wants to achieve these goals, its business processes need to be modelled along these values as well. If control over the processes is lost, it becomes significantly more difficult to achieve the circular goals. It depends on the partner whether or not circularity plays a role in the business processes. If CE partners cannot be found as alternatives the overall circularity of the value chain will decrease.

To conclude, the theoretical model presented in this study can be partially supported. Product modularity will, because of its nature, enable the CE. Supply chain modularity does not enable the CE unless partners can be found that also adhere to the CE principles.

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