MASTER THESIS INDUSTRIAL DESIGN ENGINEERING

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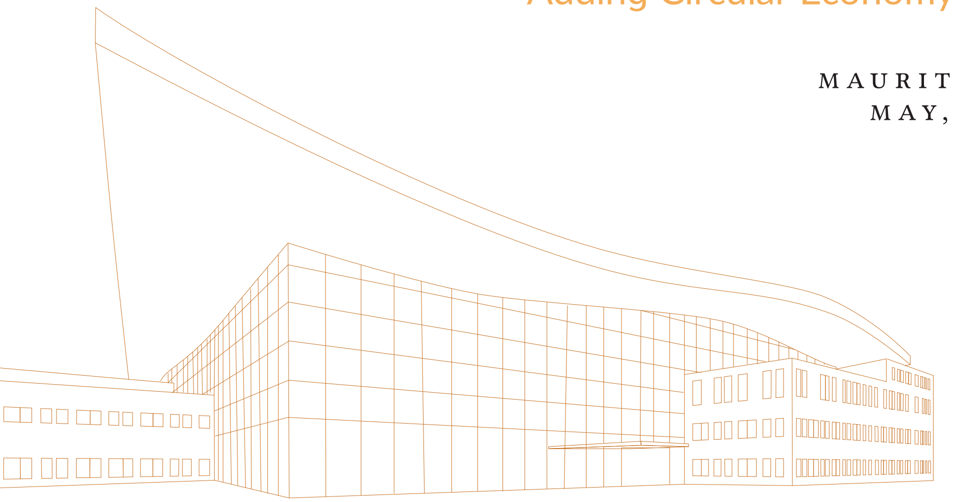
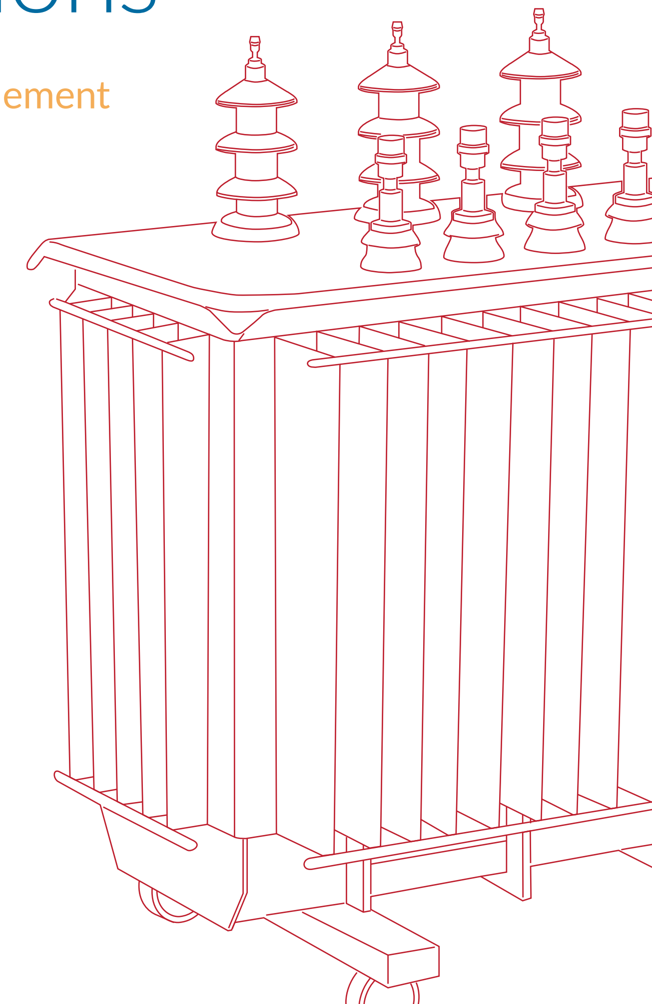
A Business Case Model to Make Sustainable Investment Decisions

Adding Circular Economy to Asset Management

MAURITS KORSE

MAY, 2015





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Adding Circular Economy to Asset Management: *A Business Case Model to Make Sustainable Investment Decisions*

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Preface

The scientifically illogical, and as we shall see, often meaningless questions "Where do you live?", "What are you?", "What religion?", "What race?", "What nationality?" are all thought of today as logical questions.
By the twenty-first century it either will have become evident to humanity that these questions are absurd and anti-evolutionary or men will no longer be living on Earth.

Buckminster Fuller Operating Manual for Spaceship Earth, 1969 [1].

During my time at high school, I biked every single day fifteen kilometres from my home to school. Many fellow students from my town couldn't wait to get a scooter to speed up the travel along the long straight boring roads through the meadows and along the wide and windy fens. To me, these vast open spaces gave me inspiration to contemplate about life and the world. Over time, these fens became a symbol of how the effect of historic economic activity now became nature and a place for leisure. These fens were created from the cutting of peat. At the time, it was an easy to retrieve fuel for heating the workers houses. Now the fens are used for swimming, sailing and ice-skating.

That man has changed its land throughout history to provide for the essential needs to its life. Next to that, technological developments, new fuels and materials became available to many people around the world. And so our welfare has grown. The consequence of this increased hunger in materials and energy is now causing our economy to run into limitations.

Even though the people that extracted the peat did not think about the consequences of their actions, the result turned out pretty well. With the increasing global population, it becomes more crucial that whatever we do benefits all aspects of our life on Earth. Systems theorist Buckminster Fuller thought that our lives would drastically change by the 21st century if our way of exploiting the Earth would continue. He suggested to operate our "spaceship" in a responsible way. Especially if we would like our trivial daily problems to still lead our lives.

Luckily, Buckminster Fuller's expectation did not come true. Yet. Instead, it would be great if we could transpose our limitations and environmental problems into opportunities and solutions. Such that all those problems have a similar effect as the traditional extraction of peat: a more beautiful world.

This is something I have learned to aim for, and I hope that part of this thesis and my future work may support this ideal. That would be my way of giving back to the world as gratitude for what I was able to take during the past years.

And of course, don't start extracting peat now, because there is a lot of CO_2 that gets released while doing that...

This master thesis is a result of an intensive process of research, days of sifting and many discussions. It is a thesis that I am proud of as it is an attempt to make sustainability become a more natural and inherent element of businesses and thus our economic. If this will lead to some new thoughts, ideas or even changes on how companies look at their impact and the responsibility they bear, it would not just be thanks to this thesis, it would be a result of all that has preceded and those that have supported the process. For this reason there are many that I would like to recognize to have a part in this. And I want to name a few explicitly.

Acknowledgements

First of all a thanks to those that have been close to the actual research and writing. Richard, even though I sometimes have demanded quite a lot of your time, I am amazed by how thorough and patient you have been in guiding this process. The extensive criticisms you have given on my writing as well as the ideas and suggestions for improvement lead to a lot of rethinking, recycling and refurbishing of the chapters and paragraphs. Even though this tedious process has frustrated me more than once, I am grateful for your guidance and help. Jan, your guidance on a higher level helped to get the focus of my research and keep the direction clear. It was necessary to stay critical and reduce my thesis as much as possible to its core. Yet, it did not prevent this thesis from turning out as a weighty tome. Next to the guidance, I would like to thank as well for the possibility to join the World Class Maintenance Summer School, and let me present my work there. It has been a great experience! Marten, thanks for bringing me in contact with Jan and Richard and for the other support during my master course.

In addition, I want to thank Liander, and especially the department of Policy and Standardisation. Co, Camiel, Ihsan and Kees, thanks for providing the opportunity for this research, to participate in the organisation and sharing the knowledge. Ihsan especially, thanks for the moral and personal support! Dominique and Hendrik, it was great to join the meetings, and thanks for all the insights you have given me.

Then to a more personal note: Hanke, I am very happy and grateful to have had your support for during the tough times of my graduation. It was great to have you as a good friend during the first eight years of our study, and it has been better ever since. Last but far from least, mom and dad, I want to thank you from the bottom of my heart for your support throughout my education. Even though it took a little long, I am grateful for all the experiences and opportunities that I have had. That could not have been possible without your support.

To all others who have given me advice, reviewed my thesis or were involved in any other way: thank you. I hope you enjoy the end result!

Table of Contents

Nomenclature

Constituent (Investment Decision)

A main category of the investment decision analysis such as the financial appraisal, stakeholder appraisal or the risks.

A circular economy

Referring to the notion of a complete systemic change of our economic system in which all resources will be reused and become cyclic.

The Circular Economy (paradigm)

The conceptual idea of, and its paradigmatic characteristics and requirements that are expected to be necessary to finally achieve 'a circular economy'.

Ecosphere

Generic term for all Earth's major elements; atmosphere, hydrosphere, lithosphere and biosphere and the interactions between them.

Ecological value

The abstract value a material, gas, liquid or living thing has to sustain the ecosphere.

Indicator (Investment Decision)

The indicator describes part of a specific constituent of the investment decision analysis. For example the environmental impact being part of the sustainability constituent or return on investment of the financial appraisal.

Level of recycling

Used as a term to indicate the various end-of-life feedback loops for material. From reuse, reconditioning to the physical process of recycling.

Levels of scoping

The implementation of the Circular Economy can be done at various levels throughout the economy. Three levels have been defined for this:

MICRO *At a material, component, product or company level*

MESO *At an inter-company, industrial park, city or regional level*

MACRO *At the level of the country, continent or world*

Metric (Investment Decision)

The actual value of an indicator. For example the total tonnage of carbon dioxide emissions as part of the environmental impact indicator.

Recycling

The actual recycling of material through separation and liquefaction to return it to a pure a solid state again.

Sustainability

A term for the general concept of sustainability that aims for development that meets the needs of the present without compromising the ability of future generations to meet their own needs [2].

Sustainable Investment Decision Aiding Model (SIDA)

The model developed during this research. This model aims to aid a sustainable investment decision process.

Transformer

A distribution transformer as found in the distribution grid that has a rated power between 100kVA and 2500kVA.

xR

Referring to the waste hierarchy as a general form of the 3R and 6R principle.

Abbreviations

3R	*Reduce, reuse and recycle*
6R	*Reuse, repair, refurbish, remanufacture, retrieve, recycle*
ACM	*Authority for Consumer and Markets in the Netherlands*
BCS	*Business Case for Sustainability*
C2C	*Cradle to cradle*
CRGO	*Cold Rolled, Grain Oriented steel*
CSR	*Corporate Social Responsibility*
DNO	*Distribution Network Operator for the energy grid as defined by EU regulations*
DSRM	*Design Science Research Methodology*
EMA	*Ellen MacArthur Foundation*
ELECTRE	*Elimination and Choice Expressing Reality, a multicriteria decision method*
EV	*Electric Vehicle (electric cars)*
EVA	*Economic Value Added*
FSSD	*Framework for Strategic Sustainable Development*
GHG	*Greenhouse gas*
IT	*Information Technology*
IRR	*Internal Rate of Return*
KPI	*Key Performance Indicator*
LCA	*Life Cycle Assessment*
MCDA	*Multi-criteria decision analysis*
MFA	*Material Flow Analysis*
NCA	*Natural Capital Approach*
NCC	*Natural Capital Coalition*
NPV	*Net Present Value*
PV	*Photovoltaic Cell (solar panel)*
RAMS	*Reliability, Availability, Maintainability, Safety*
ROI	*Return on Investment*
ROV	*Real Option Valuation*
SAIDI	*System average interruption duration index*
SBC	*Sustainable Business Case*
SIDA	*Sustainable Investment Decision Aiding model*
SWARD	*Sustainable Water industry Asset Resource Decision*
TBL	*Triple Bottom Line, or People, Planet, Profit.*
TCO	*Total Cost of Ownership*
TECK	*Technology, Economic, Commercial, Compliance*
TMI	*Thermal Maximum Inspection*
TNS	*The Natural Step*
UNCECE	*United Nations Economic Commission for Europe*
UNEP	*United Nations Environment Programme*
WCM	*World Class Maintenance*
WWF	*World Wildlife Fund*

Abstract

Resource scarcity has been a topic within literature since the mid of the 20th century. In recent years, this topic has regained attention due to environmental, social and financial problems that our society has to deal with. Now the focus is found in both literature and practice. The Circular Economy is a new paradigm within sustainability that focusses on resource efficiency in support of the environment, social cohesiveness and enables new business opportunities. Research on implementing the Circular Economy concentrates on product design and procurement of consumer goods, clothing and furniture.

Liander, a distribution network operator (DNO) based in the Netherlands, has set the aim to become the first circular grid operator. To achieve this they set out several questions. First, how to further develop the concept of Circular Economy, especially in relation to their asset base. And secondly, how to incorporate the Circular Economy and thus sustainability in their business case. The aim is to enable a bottom-up approach for securing sustainability in their business. To implement this, the complexity of this subject is structured into a practical and comprehensible method.

Implementing the Circular Economy for assets with long life spans, like those of Liander, has not yet received much attention. To embed the environmental sustainability into the business, tools are required that help to oversee the complexity and to support decision-making. Investment decision methodologies are a tool to gain this required insight and help to choose between the trade-offs. However, investment decision methods that contain sustainability are still scarce within the business case literature. Several scholars have addressed the need for this but also pointed out the problem of the subject's complexity. Hence, this study addresses this problem by structuring environmental sustainability from a Circular Economy perspective.

A conceptual model for a sustainable business case has been developed which answers the need to embed environmental sustainability. This model has been translated into a sustainable investment decision aiding (SIDA) model that aims to make asset investment processes more transparent and comprehensible. This model has been established through the Design Science Methodology based upon literature and a case study at Liander. Distribution transformers were the subject of this case study and acted as a test case to evaluate the model and its application.

The case study concerns two investment decision problems: (1) whether a current age limit to replace transformers is defendable, and (2) whether to invest in a technology different from the current standard. Additionally, three other scenarios were tested that influence the life cycle or efficiency of the distribution transformer.

The research concludes that environmental sustainability should be included as a separate constituent in the investment decision methodology. This constituent is defined using three indicators: (1) material usage, (2) ecological footprint and (3) environmental impact. Considering the case study, some preliminary conclusions about the sustainability of distribution transformers are drawn. The use of bio-oil to replace mineral oils is expected to have a large impact. As follow up of this study it is recommended to validate the developed model in different sectors with different product characteristics. In addition, various recommendation are given towards for further research, towards Liander and to the government.

Samenvatting

Vanaf het midden van 20e eeuw is materiaal schaarste is een belangrijk onderwerp geweest in de literatuur. In de laatste jaren heeft dit onderwerp hernieuwde aandacht gekregen vanwege opkomende milieu, sociale en financiële vraagstukken waar onze maatschappij mee te maken krijgt. De focus ligt nu dan ook op literatuur en praktijk. De Circulaire Economie is een nieuw duurzaamheidsconcept dat zich richt op materiaal efficiëntie ter ondersteuning van het milieu, sociale cohesie en zakelijke kansen. Onderzoek naar het implementeren van de Circulaire Economie richt zich met name op product ontwikkeling, consumenten producten, kleding en meubels.

Liander, een Nederlandse netbeheerder, heeft als doel gesteld om de eerste circulaire netbeheerder te worden. Om dit te bereiken hebben ze verschillende vragen gesteld. Ten eerste, om de Circulaire Economie met betrekking tot hun bedrijfsmiddelen verder te ontwikkelen. Ten tweede, hoe de Circulaire Economie, en dus duurzaamheid, in de business case meegenomen kan worden. Het doel is het bevorderen van een bottom-up aanpak voor het waarborgen van duurzaamheid in de bedrijfsvoering. Om dit te implementeren is de complexiteit van het onderwerp gestructureerd in een praktische en begrijpelijke methode.

Er is nog maar weinig aandacht geweest voor het toepassen van de Circulaire Economie voor bedrijfsmiddelen met lange levensduur, zoal die van Liander. Om de Circulaire Economie in de bedrijfsvoering mee te nemen, zijn instrumenten nodig die helpen om de complexiteit te overzien en om de besluitvorming te ondersteunen. Investeringbeslissingsmethodieken zijn dergelijke instrumenten om inzicht te verkrijgen in de keuzes en afwegingen in de besluitvorming omtrent investeringen. Deze methodieken zijn echter nog schaars, met name degene die duurzaamheid meenemen worden amper besproken in de literatuur. Wel hebben verschillende onderzoekers de noodzaak hiervan besproken en aangetoond. Om die reden richt dit onderzoek zich op het structureren van duurzaameheid vanuit het perspectief van de Circulaire Economie.

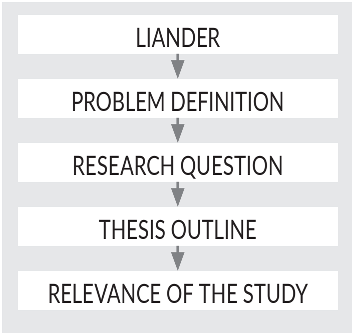
Een conceptueel investeringbeslissingsmodel is ontwikkeld om de voorgaande vragen te beantwoorden en duurzaamheid te waarborgen in de business case. Dit model is vertaald in een ondersteunende methodiek voor duurzame investeringsbeslissingen (SIDA) en is er op gericht om investeringen transparanter en inzichtelijker te maken. Het is tot stand gekomen middels de Design Science methodologie op basis van literatuur en een casus bij Liander. Deze casus, over distributietransformatoren, fungeerde als een toets om het model en de toepassing hiervan te evalueren.

De casus betreft twee investeringsproblemen: (1) of de huidige leeftijdsgrens van veertig jaar voor distributietransformatoren verdedigbaar is, en (2) of er geïnvesteerd moet worden in een technologie anders dan de huidige standaard. Naast deze twee vragen zijn nog drie andere scenario's getest die de levenscyclus of efficiëntie van de distributietransformator beïnvloeden.

Het onderzoek concludeert dat de duurzaamheid van het milieu moet worden opgenomen als een afzonderlijk onderdeel in de investeringsbeslissing methodologie. Dit onderdeel wordt gedefinieerd met behulp van drie indicatoren: (1) materiaalgebruik, (2) de ecologische voetafdruk, en (3) de milieueffecten. Vanuit de casus kunnen een aantal voorlopige conclusie worden getrokken over de duurzaamheid van distributie transformatoren. Zo zal gebruik van bio-olie in plaats van minerale olie naar verwachting een grote impact hebben. Daarnaast wordt er geadviseerd om vervolg onderzoek uit te voeren en worden er aanbeveling gedaan richting Liander en de overheid.

1. Introduction

Resource scarcity, technological innovations and the economic crisis: these are all big challenges for companies as they bring about a greater focus on the social and environmental responsibilities of companies.



Outline Introduction Chapter

Common examples are the public outrages about companies disrespecting working conditions in the clothing industry in Bangladesh [2], movements that try to counter the use of minerals from conflict areas like FairPhone [3] or the forgotten social responsibilities of financial institutions and housing corporations [4,5]. Also from an environmental perspective, each year there seem to be more disturbing signs that call for change of direction. For example, 2014 is on track to be the hottest year since climate measurements started [6], and Earth Overshoot Day[1] has never been as early as in 2014 either [7]. Moreover, this happens within a context of growing global population and quick industrialisation of economically fast growing countries.

However, these challenges can be turned into opportunities for a more profitable and sustainable business case if companies allow themselves to act ahead of the change. To achieve that, the business may need to account for these issues in an early stage within their business processes. For example, at the design stage of products, in their business model or in the business case. A common approach is the Triple Bottom Line (TBL) that aims towards a balance between people, planet and profit[2] [8]. However, criticism towards this method is increasing and improvements are welcomed [9–12].

In line with the increasing awareness on environmental issues, the Dutch distribution network operator (DNO) Liander strives for sustainability in the regions where they are active [13]. To do this on environmental level, Liander currently uses carbon footprints as

1. Earth Overshoot Day is the day at which the World Global Footprint (the cumulative amount of resources used) exceeds the World's biocapacity (the amount of resources the Earth is capable of regenerating) for that year.
2. The Triple Bottom Line is commonly known as "People Planet Profit" or 3P.

a tool to measure their impact. Next to that, Liander decided to adopt the Circular Economy paradigm as approach to address the resource scarcity issues that are expected to arise. For example, Liander heavily relies on the use of copper in their network, however at the current global production and the estimated reserves, copper ore is expected to be finished in 40 years[3] [14]. By adapting the company's actions, such as new investments, the impact and dependency of the company on resource reserves can be limited. To secure this practice within the company, the underlying processes such as investment decisions and the actual business cases should be adjusted. These can be seen as a tool to adjust the direction of the company towards the aim of a sustainable business.

The question is however, what sustainable investments are and how the right decision can be made. It would therefore be useful to support this decision making process for investments through a methodology that incorporates sustainability besides other business values.

This thesis will study the Circular Economy paradigm as a sustainability approach and how it can be incorporated in the business case and investment decisions. This will be done with Liander as case study company. The investment decisions will consider Liander's assets; the main components that make up the energy distribution grid such as transformers, cables and switches. The focus will be especially on the distribution transformers. These will act as a case study to guide the development of a sustainable investment decision model. Most of the research is executed during an internship at Liander's Asset Management, Policy and Standardisation department.

Within this chapter, the background of the study will be described. It will start with a short introduction on Liander, then the problem definition, research question, thesis outline, and finally the relevance of the study will be introduced and discussed.

3. This is the estimated reserve to production ratio (R/P) based on the current known reserves. It is expected that much more copper resources are available but these are not of the required physical or chemical properties that make it economically feasible for mining and production [14].

1.1. Liander

Liander N.V. operates about a third of the distribution network for gas and electricity in the Netherlands. With a turnover of over €1.7 billion in 2013, approximately 6,000 full time employees, and serving over three million homes, Liander is the largest utility operator in the Netherlands [15]. It takes care for about a third of the Dutch market. Besides having a public function the company is also in public hands as shares are owned by province and local governments. This has been the case since 2009, when legislative changes split the energy suppliers from the infrastructure operators [16,17]. Grid operators and distributors like Liander are, in contrast to the energy suppliers, not influenced by direct competition and profit based incentives. This is because the utilities market for gas and electricity distribution is regulated by the by the Authority for Consumer and Markets (ACM), an independent regulator. It determines the exploitation of each of the grids to a single dedicated DNO per region. Liander is responsible for the regions illustrated in figure 1–1. In the other regions, one of the other eight DNOs that the Netherlands counts is responsible. Enexis, Stedin and Delta are besides Liander the largest [18].

Even though the DNOs do not compete commercially, they do compete based on their performance. The ACM decides every two years the fee that DNOs may charge. This is based upon their efficiency and the system average interruption duration index (SAIDI). This is the average power outage per household that a DNO had within its grid.

Since customers cannot choose between different grid operators Liander regards itself highly responsible for customer satisfaction by providing a safe and reliable grid that is sustainable for people and planet [15]. This has been one of the driving forces for Liander to co-author with other Dutch companies a manifest on circular entrepreneurship, *Ondernemen in de Circulaire Economie (Entrepreneurship within the Circular Economy)*. This manifest illustrates the principles and advantages of the Circular Economy for businesses [19]. Some of these advantages are reduced costs, increase in jobs, material and energy reduction and the evasion of toxic materials.

To embed the Circular Economy into its business, Liander has initiated several projects. For example refurbishing an old company building into a highly energy and resource efficient building, the development of the FairMeter that should be produced in a socially and environmentally sustainable way, and procurement of office furniture in which circularity was taken into account. However, Liander wants to embed the Circular Economy in their core business: the operations of the distribution grid. To do this, the Asset Management department, responsible for the deployment, maintenance and operation of the network assets, will need to adopt this paradigm.

Nevertheless, embedding the Circular Economy within this field is relatively new and so far, only little research has been done on the topic. To do this, the full asset life cycle should be considered (investment, maintenance and disposal). The Policy & Standardisation department within business unit the Asset Management is responsible for the life cycle planning of the assets. It is therefore taking a leading role in embedding circularity into their business.

1.2. Problem Definition

Liander has committed itself to the Circular Economic principles by signing a Green Deal[4] on Circular Procurement [20]. Next to that Liander's Board of Directors approved a goal that 40% of the purchased components should be circular in 2020. Unfortunately, there is currently little knowledge about applying the Circular Economy on long lasting assets within the utilities sector, neither in practice nor in science. Next to that, there is a trade-off between energy reduction and material preservation. For example, replacing older assets for new ones will lead to the positive benefit that the total population would become more energy efficient. However, disposing of the old assets before the end of their actual technical life causes a loss of high quality materials as result of the disposal process. Next to that, energy is also necessary to manufacture the replacement assets.

Besides this conflict of material versus energy, there are also other trade-offs that complicate decision-making. For example, the trade-off between increasing environmental sustainability and the total investment costs, as well as the compromise between a technological optimal solution and the strategy of the company. The question generally comes down to how every aspect is valued and thus what the opportunity cost of the trade-off is. To be able to answer these questions, one could assume that all information necessary to make the decision is available. And that it is available in a format in which it can be compared to one another. Unfortunately, that is often not the case due to complexity of the problems, missing coherence of definitions, fuzzy information and uncertainties in forecasting.

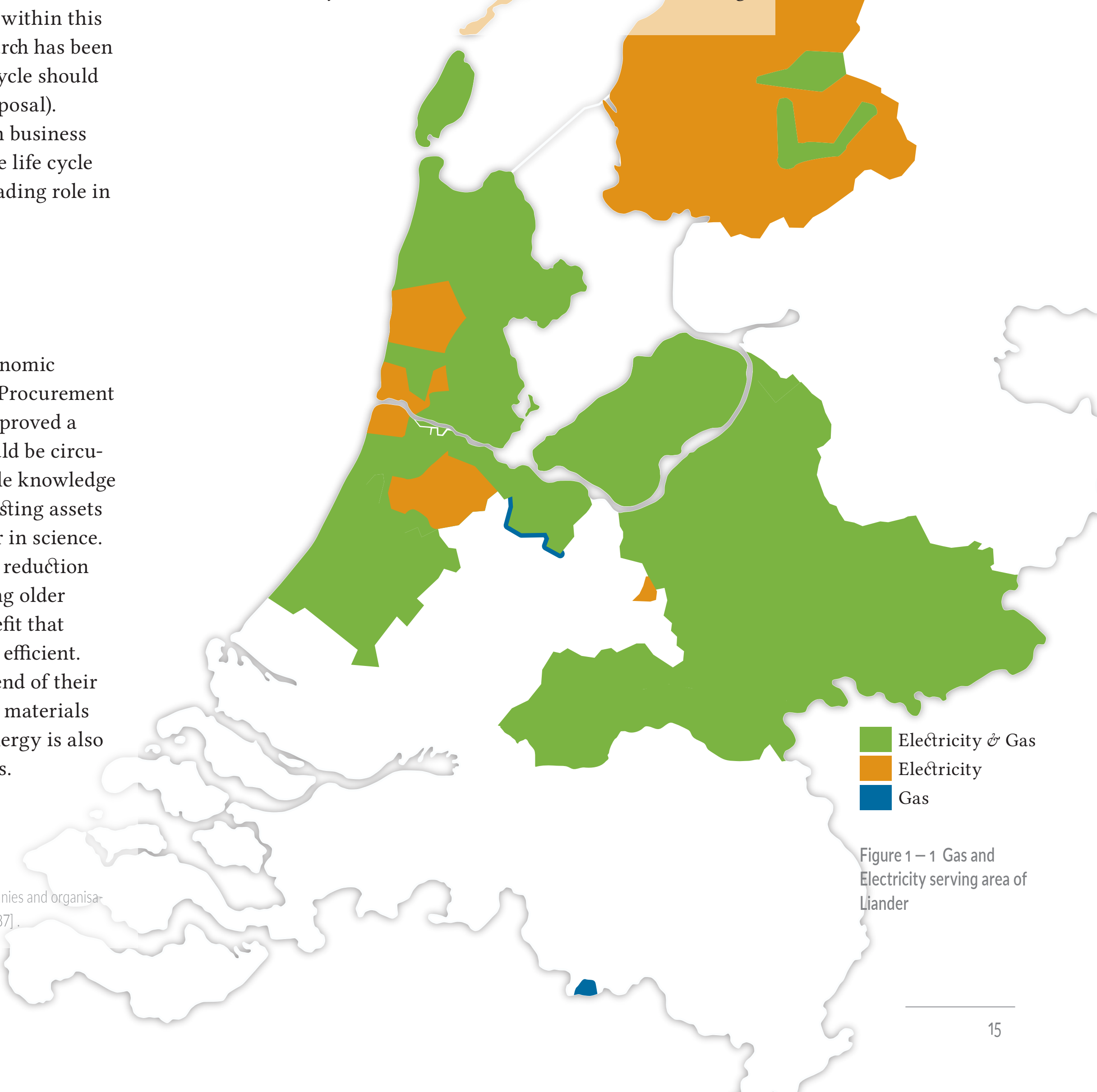


Figure 1 – 1 Gas and Electricity serving area of Liander

4. Green Deals are agreements between the Dutch government and companies and organisations to commit themselves to sustainable projects and collaborations [187] .

The main aim of the research is therefore to develop a method that aids in the investment decision-making process with a focus on sustainability. This is done by incorporating sustainability into existing business case methodology. The Circular Economy is used as paradigm to address the sustainability aspect. The Circular Economy is a paradigm that mainly addresses resource scarcity resulting in economic and social benefits. A theoretical focus on how to value the Circular Economy within the business case is therefore required. Practically, Liander would like to know what they have to do with their older population of assets. Hence, the developed method should fit within the framework and scope of business cases in Liander's asset management.

Scope

Summarising the problem definition, the scope of this study considers the sustainability and the Circular Economy concerning assets within the energy distribution infrastructure sector. These assets are characterised by their long life span, inherent energy losses and indispensability to secure the reliability of the energy supply. Next to that, the methodological scope includes business case- and asset investment decision methodologies.

1.3. Research Question

The goal of this research is rephrased to the following research question:

"How can environmental sustainability be incorporated in the business case tools used by Liander by means of the Circular Economy paradigm?"

The research question can be split into several elements: the Circular Economy paradigm, business cases for sustainability and the asset management of Liander as application area. These elements require further elaboration to fully understand the topic and enable the development of a thorough model. To clearly scope and frame these elements the main research question is elaborated through sub research questions.

The first two questions address the relation between the Circular Economy being used as paradigm for sustainable business cases and hence what the current developments and methods within this field are; (Q1) *What are the principles of the Circular Economy, what is its current state of art and how can it be measured?* and; (Q2) *How does the Circular Economy relate to sustainability?*

To be able to embed sustainability into the business case and eventually into the investment decision methodology, the context and current methodologies of business cases and investment decisions need to be investigated. That results in the third sub research question: (Q3) *What are investment decision methods, how do they link to the business case, and how are the decisions established?* The common theoretical methods and assessment criteria of the investment decisions within Liander and the utilities sector are the main focus within this question.

The fourth sub question focuses on the incorporation of sustainability within the business case and investment decisions. (Q4) *In what way can sustainability be accounted for in investment decisions?* This fourth question will lead to the development of a conceptual investment decision model. To be able to evaluate this model a case study on an actual investment decision problem of distribution transformers will be executed: (Q5) *How does the conceptual model perform on an investment decision problem considering distribution transformers?* The specific research questions of the case study will be introduced in chapter 6. These are practical questions put forward by Liander.

These five sub research questions were a guideline throughout the research and so they will be throughout the thesis. Paragraph 1.4 will further elaborate on this.

1.4. Thesis Outline

The process, background and results of the study as reported in this thesis will be discussed over a total of nine chapters. After this introduction chapter, the second chapter will address the research methodology of design science and the supporting literature framework and case study introduction. Chapter 3 will address the background information on the main topics of this study: circular economy, investment decisions and sustainable business cases. Chapter 4 will discuss the developed framework for addressing sustainability from a perspective of the Circular Economy paradigm. Next to that, the questions on measuring the Circular Economy will be addressed, resulting in three indicators. These will be used in chapter 6 that addresses the conceptual model for the Sustainable Investment Decision Aiding (SIDA) methodology. The three indicators of the theoretical framework will account for the environmental sustainability constituent of this model. Chapter 6 will then

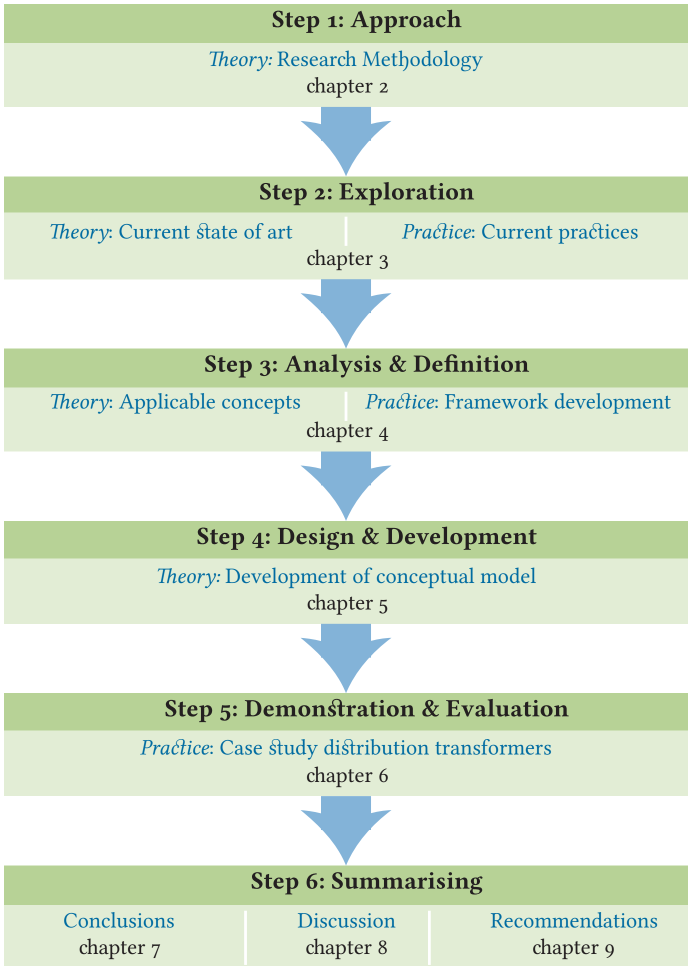


Figure 1 – 2 Thesis outline.

discuss the usage and evaluation of the model presented in chapter 5. This is done through a case study on distribution transformers. After chapter 6, three chapters on the overall conclusions, discussion and recommendations remain.

Throughout the thesis there will be several sub conclusions and discussions for the topic addressed in that specific section. Next to that, assumptions and design criteria that are used for the development of the conceptual model in chapter 5, will be listed at the end of each chapter.

1.5. Relevance of the Study

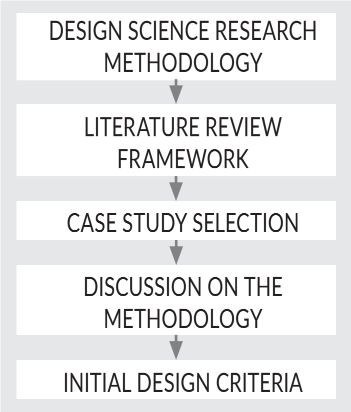
The relevance of this study can be found in four major elements. The first considers the fundamental principles of the Circular Economy, which, as will be discussed later in chapter 3, are not coherently defined in literature [21, 22]. In current literature there are many indicators mentioned that could help to value or to measure the Circular Economy. But what is often missing, is that there is no clearly defined basis on why these indicators were chosen, and whether they are directly or indirectly related to the Circular Economy paradigm. Within this research a structure and hierarchy has been developed to put the elements in their right context in relation to the Circular Economy.

The second relevant contribution can be found in how the Circular Economy relates to long lasting products. The current implementation of the Circular Economy in Europe has its main focus in two industries: the fast moving consumer goods and the building and office sector. There is however not much research done or business models developed for products and assets with long life cycles. Especially for the infrastructure and utilities sector, which account for a large part of the material and energy usage[5], it can be very beneficial to improve its material and energy management.

The third element that will show the relevance of this study is in the field of business cases and investment decisions. Theories and methodologies developed for business cases often include economic, risk and technical or functionality appraisals. Even though the topic of sustainability is becoming very popular over the last decade, the question on how to embed it in business cases has not yet been widely discussed [23]. Especially the problem of complexity should be accounted for. Addressing this topic may yield new insights on how to develop business cases that consider sustainability in a pragmatic way.

The pragmatic approach of the Circular Economy, and environmental sustainability as a whole, is the fourth relevant element of this research. Several organisations such as the Ellen MacArthur Foundation, Utrecht Sustainability Institute, Circle Economy and others are trying to develop tools and guiding the discussion for practical implementation of the Circular Economy into the business. However, a sound theoretical background is often missing in these discussions as well as a more holistic view of the Circular Economy within the sustainability paradigm.

5. According to CBS (Dutch statistics institute), over 3.5% of the total energy supply is lost in the form of energy losses in the electricity grid alone [188].



Outline Methodology Chapter

This chapter will introduce the research methodology and techniques used during the study. The Design Science Research Methodology will be introduced, as well as the literature framework and the case study selection. Finally, the limitations of these methods will be discussed. The chapter will finish with the initial design criteria as introduced in section 2.1.

2. Methodology

2.1. Design Science Research Methodology

The aim of this study is to develop a method that helps to give a more comprehensive overview of how different factors of sustainability influence an investment decision problem. Especially with a focus on including sustainability into the business case. This decision problem, as posed by Liander consists, mainly of two elements: the trade-off between comprehensive but practical asset investment design making; and secondly, how to include and value environmental sustainability in the decision-making process. These two problems, further discussed in chapter 3, are a precedent for the choice of research methodology. Specifically, they indicate the need for a model that combines various disciplines such as business case methodologies, decision-making theory and sustainability. Design Science Research Methodology is a research method that fits these needs.

Design Science Research (DSR) Methodology is a method that can be applied to research within design or applied sciences such as engineering and medical sciences [24]. These sciences try to match theoretical knowledge to real world problems by creating things that serve a purpose [25]. Because of their practical characteristic, the research methodologies within these sciences are often carried out in close cooperation with customers, professionals, businesses and governments. So is the DSR methodology, as it includes the development of knowledge on the design problem and apply or translate that into a practical application or other form of *artefact* [24, 26]. According to Hevner, the knowledge and understanding of the problem is acquired during the development and application of that artefact [26]. To achieve this, various process steps need to be taken during the research. Peffers *et al.* summarised the various process steps within Design Science as defined by different scholars [25]. These steps, represented in figure 2–1, will guide this study.

The DSR methodology process, as defined by Peffers *et al.*, may start at any stage in the process and move back and forth through the process steps during the research. This allows for process iteration and better understanding of the problem and the knowledge that has to be developed. The process can be started at any stage depending upon the motive for initiating the research. The entry points as depicted in figure 2–1 indicate these starting points.

Applying the DSR methodology process steps to this study shows that the first step has already been accounted for in chapter 1. The research problem and its relevance have been discussed. To understand the problem and the research context, additional knowledge on the background of the disciplines will be discussed in chapter 3, *Contextual Background*. This information has been gathered by means of literature research of which its framework will be introduced in section 2.2. Next to the theoretical sources, practical sources have also been used. This practical knowledge has been mainly developed through partaking in meetings and discussions while being an intern at the Policy & Standardisation department of Liander. Next to that, meetings with other relevant organisational bodies within and outside Liander, such as the departments of Corporate Social Responsibility, Procurement, and external organisations like Circle Economy, have been held. A complete list of all meetings and people inquired that contributed to the understanding of the researched topic is presented in Appendix M.

The understanding of the design problem leads to the second step on the *Definition of objectives for a solution*. Within this step the objectives, of the to-be-developed artefact, will be identified through transforming the problem definition and the contextual knowledge into design criteria. Within this study these criteria were identified throughout all process steps caused by the iterative nature of the study and development of the artefact. Even though this thesis is not a chronological report of the study, the various criteria are mentioned at the end of each chapter linking them with the topic discussed within that section. The initial design criteria based on the first two chapters will be discussed at the end of this chapter in section 2.5.

The third process step, *Design & Development*, focusses on the actual design and development of the artefact, a conceptual business case model. This can be done by focussing on various disciplines as well as through an iterative design process. To support the design of the conceptual model, development of knowledge on Circular Economy and sustainability is required. This is discussed in chapter 4, *Theoretical Framework* and leads to additional design criteria. Based on these aforementioned design criteria, chapter 5 will then discuss the development and design of the model, the product of this study.

The micro level considers material, product and company scope; the meso level is on the inter-company, industrial park, city or regional level; and macro scope is at the level of the country, continent or world.

After development of the artefact, the research methodology mentions to use a *Demonstration* and or *Evaluation* to prove that the idea works. Within this study, both demonstration and evaluation will be addressed. Chapter 5 ends with an initial theoretical evaluation of the developed model based on the design criteria. Chapter 6 will demonstrate, through a case study on distribution transformers, how the model can be used. The case study therefore acts as practical evaluation of the artefact. The case study selection will be further discussed in paragraph 2.3. The rest of the case study design and results are presented in chapter 6. In addition, its evaluation and the complementary evaluation on the conceptual model will be within that chapter. The final evaluation is based, just like the identification of many of the design criteria, on involvement of professionals from Liander.

The final step of the DSR methodology process considers the communication of the results. This has been done through presentations, collaboration, discussions and, as final embodiment of this step, this thesis.

2.2. Literature Review Framework

The theoretical part of the research is guided by a literature review framework (figure 2–2). The framework encompasses a keyword search in Scopus, ScienceDirect and Google Scholar for the main topics of this thesis: *asset investment decision methodology, business cases for sustainability* and *circular economy*. The search queries (Appendix A) yielded 1596 unique articles. After evaluating the articles by accessibility, title, abstract and keywords, 85 articles remained. After cross-checking the references and authors as well as inclusion of additional sources such as consultancy and governmental reports and methods, a final number of 68 articles were the basis for the literature research. Out of these articles, 45 considered Circular Economy and 14 Investment decision methodology.

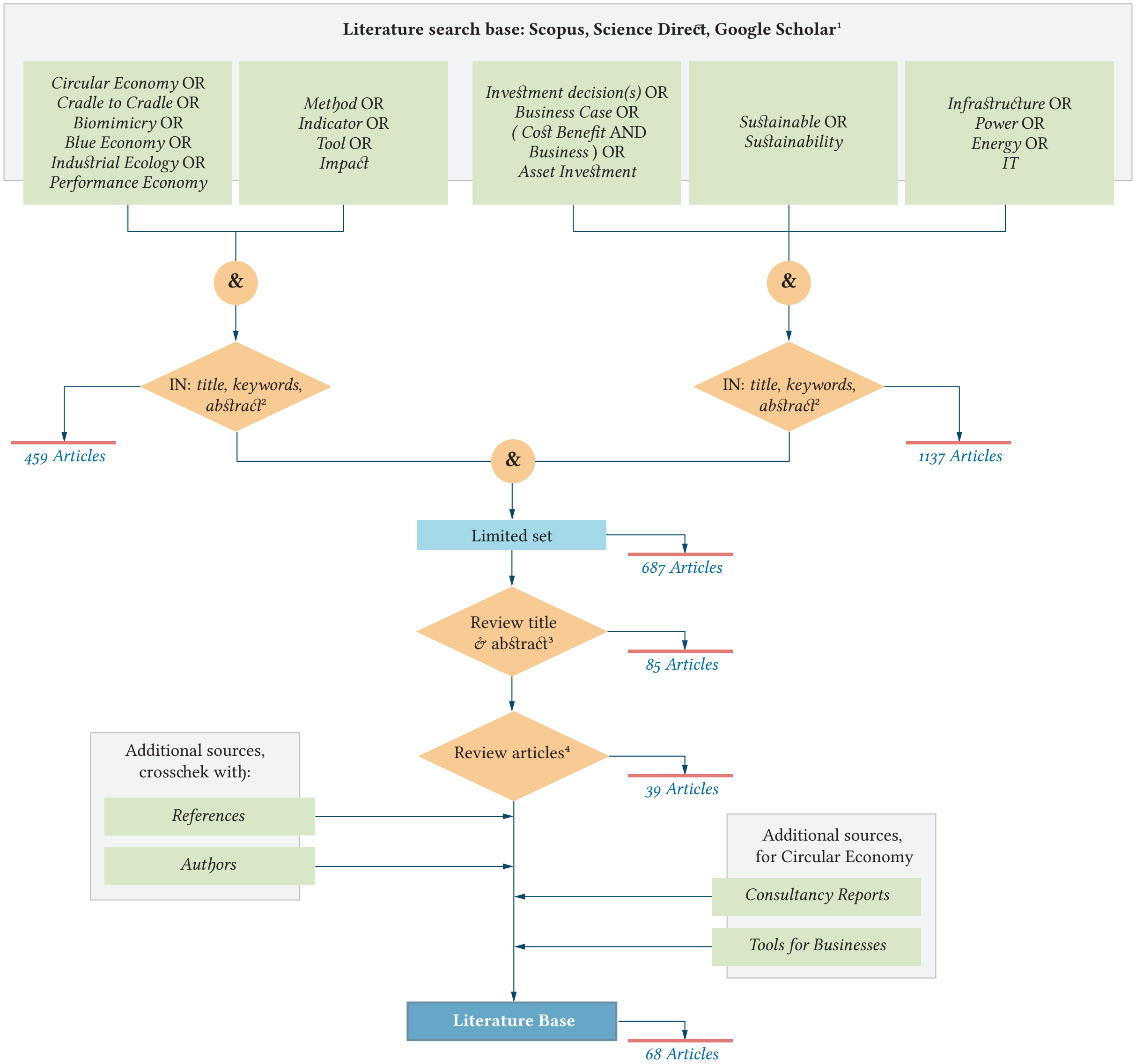


Figure 2 – 2 Literature review framework on Circular Economy for Business Cases. [1]Within Google Scholar the search query only considered the title. [2]Unique articles. [3]Title and abstract considers micro/meso, Dutch/European/general scope. [4]Article should be accessible. [5]Additional sources

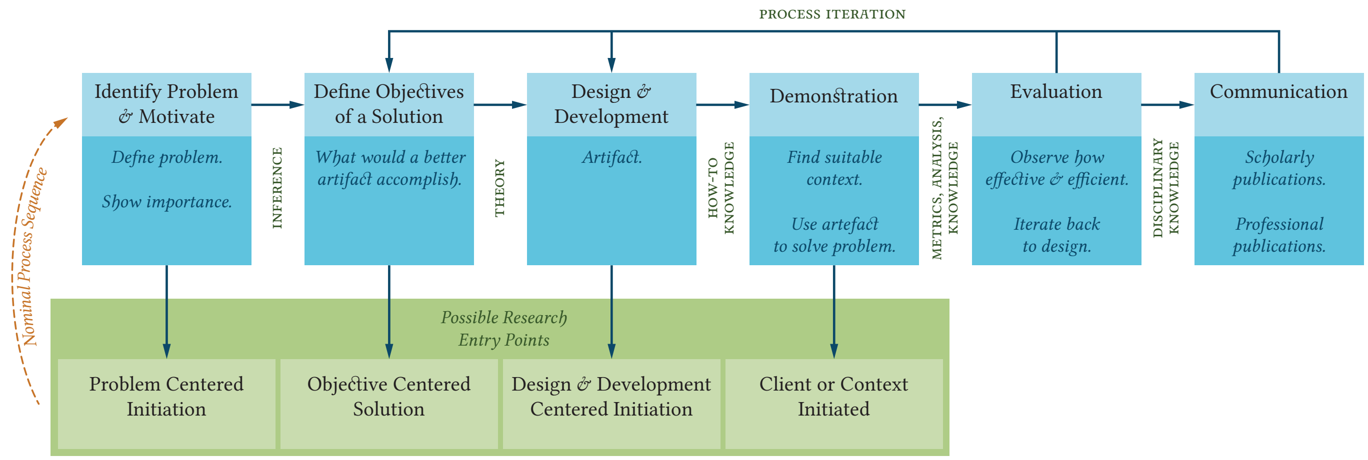
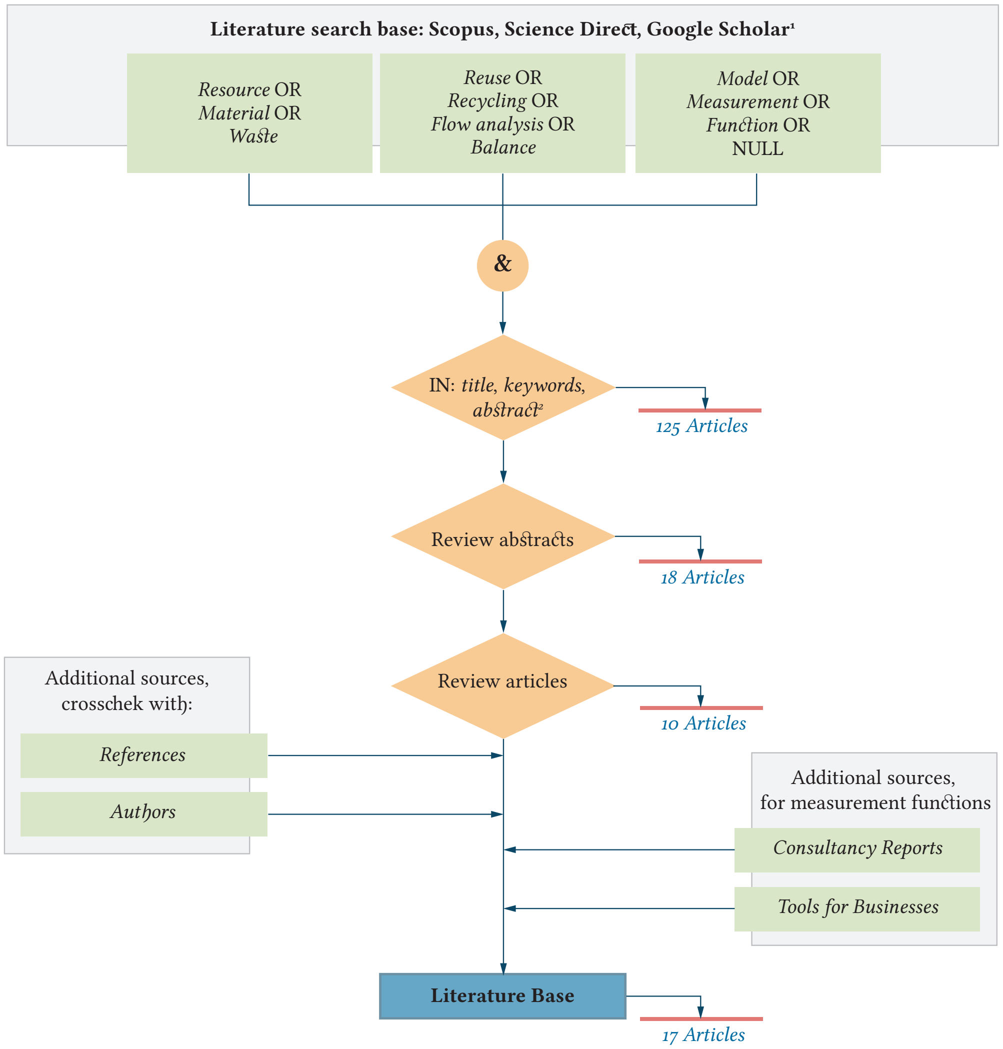


Figure 2 – 1 DSR methodology process model by Peffers *et al.* [25]. The entry point of this study was the problem centred initiation.

Figure 2 – 3 Literature review framework on resource methods and models.



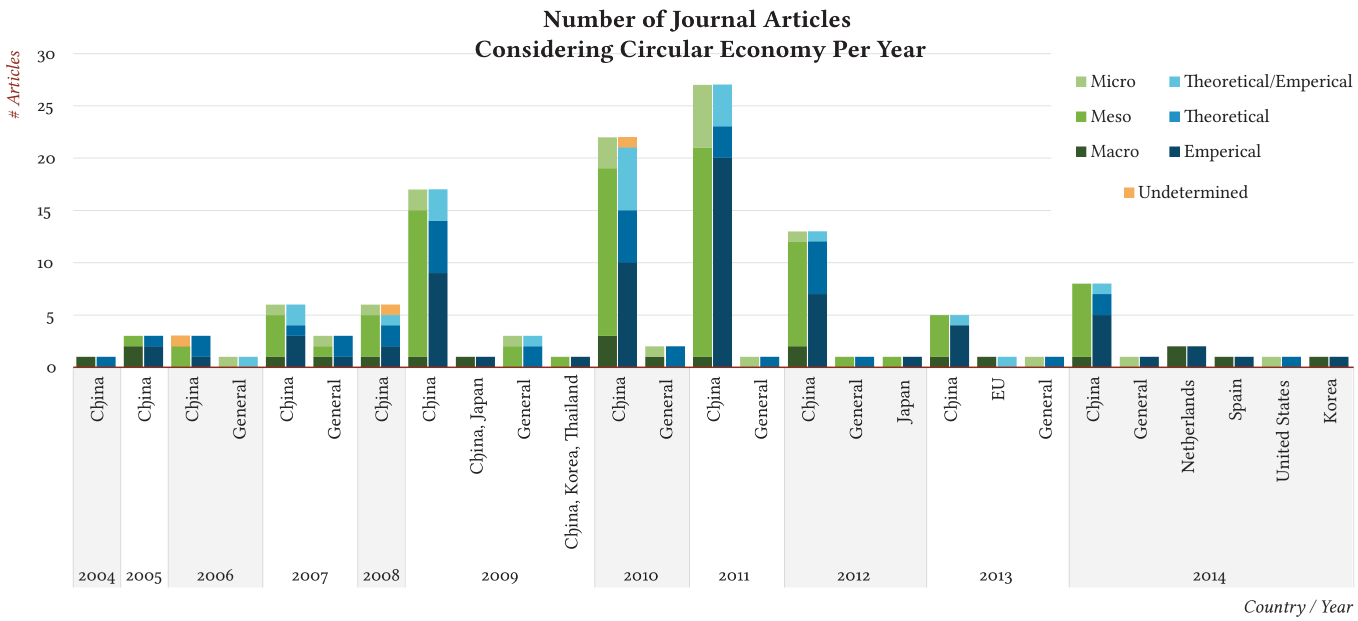


Figure 2 – 4 Published journal articles on Circular Economy per year and country categorised by type (September 2014).

During the literature research and development of the theoretical framework, the need for a secondary literature research raised. For this reason a second literature review framework was set-up considering resource flow and analysis methodologies (figure 2–3). The relating search queries can be found in Appendix A. The initial search yielded 264 unique articles. Using a similar review technique as in the primary literature review, this research resulted at the end in a total of 17 articles and additional sources.

The general research results will be used and discussed in chapters 3 and 4. However, an interesting observation can be made from the meta-literature review about the focus and scoping of the literature on Circular Economy[1]. Of the 134 unique and reviewed articles, around 83% focused on Circular Economy in China. Most of these articles were scoped on a meso and macro level based on empirical research. Figure 2–4 gives a more detailed account of the literature review results. Relatively few articles had a general (10%) or European (3%) focus.

This research focusses at giving better insight in asset investment decisions that include sustainability. This makes this research have a primary focus at the micro level (product and company). Therefore, the Chinese focussed literature is only partially applicable.

2.3. Case Study Selection

The case study within this research has as main role to support the development of the investment decision model through demonstration and evaluation of its application. To do this an appropriate asset should be selected to act as case study.

Currently the purchasing contract for distribution transformers (see Chapter 6 and Appendix I) has ended and Liander is in the process whether they should extend the current contract an extra year or initiate a new tender. The aim is to include Circular Economy in the new tender and be able to determine whether old transformers should be replaced for new ones when taking economical and sustainability factors into account. Distribution transformers also account for part of the energy losses that Liander has to compensate. Besides these losses causing substantive costs they also result in additional carbon emissions. Liander therefore seeks for effective and efficient options that reduce this financial and environmental expense. Liander does not have a definite answer on how to tackles these questions yet. Taking this possible tender for distribution transformers as an investment decision problem creates the opportunity to address these questions while evaluating the conceptual model.

The advantage of using distribution transformers as case study is that these are a type of asset, which from material perspective, is a good representative for the asset base. Especially for the electricity grid, materials such as iron, copper, aluminium, oil, plastics and ceramics are common materials that can be found in most assets. Also, the relative simplicity, the long life span and maintenance demand is similar. In case the developed model is successfully applied during the case study, the model and findings may be easily translated and applied to other assets.

More information on the case study such as the distribution transformers, the problem definition and case-study set-up will be discussed in chapter 6.

2.4. Discussion on the Methodology

As discussed in the first section of this chapter, the DSR methodology is chosen as it matches the research problem. This method brings about various advantages such as a clear research process that can be followed, however, the research methodology also knows certain limitations. Understanding these limitations is important to draw conclusions from the final results.

1. As resulting from the search criteria shown in Appendix A for Circular Economy.

The limitations of the methodology itself will be discussed below, while the limitations of the results will be discussed in section 8.1.

The DSR methodology is mostly discussed from an Information Systems perspective. Most examples describing the use of DRS methodology, such as Peffer [25] and Hevner [26] do, are within this field. Cases of using DSR within asset or operations management are rare in literature and thus best practices of DSR within these fields are not available. However, the execution of the methodology is not expected to be much different for these fields of application other than the tools used for demonstrating the artefact. Within Information Systems, this is often a prototype and the implementation of the IT solution within the organisation. In this study a case study, expert sessions, and application of the artefact are the main tools used. All as part of an internship at Liander. Therefore, the limitations mainly result from these tools. They are related to their scope, the position of the researcher and the qualitative form of the research results.

The scope is restricted to the Asset management of Liander. Liander, being a Dutch DNO without commercial motives, may therefore have different implementation on the decision-making process, time-frame of asset investments and necessity of sustainability than other companies. Secondly, the position of the researcher during this study is from within Liander. This means that observations may have become biased towards that position. On the other hand, it allowed for a more thorough understanding of that environment and the research problem through informal information gathering. This can be seen as both a strength and weakness of the case study. The form of the research is mainly qualitative. Only little is quantitative, such as the meta-literature research as presented in section 2.2, and is therefore of little importance to the limitation of the entire study. The qualitative research has limits considering its rigour and objectivity; conclusions cannot be simply based on deterministic rules but are subject to the interpretations of the researcher. This form of subjectivity is countered by using additional information sources to base the findings on. For example the literature research as described in section 2.2 as well as taking part in external sessions, workshops and excursions organised by independent parties. A list of participation in these sessions can be found in Appendix M.

2.5. Initial design criteria

Since the research methodology of this thesis is built upon design science to develop the final model, prescriptive design criteria are collected throughout the research. These define how the final model should be. From the first two chapters the following design criteria can be identified:

CREATE TRANSPARENCY: Create transparency in decision-making process.

SHOW TRADE-OFFS: The applicable tool needs to make trade-offs in the decision visible.

SOUND BACKGROUND: The theoretical background on which the model is based should be comprehensive.

FLEXIBILITY IN APPLICATION: The model should be adaptable to other asset types.

MICRO PERSPECTIVE: The research should be asset related, and hence be scoped to a micro level.

DUTCH/EUROPEAN SCOPE: The research is mainly executed within Liander, a Dutch DNO, and therefore the research result should be applicable to this Dutch/European scope.

INFRASTRUCTURE SECTOR: The research should be applicable to electricity distribution infrastructure sector.

USE CIRCULAR ECONOMY: The principles and ideas of the Circular Economy should be used as basis for the sustainability element of the model.

REDUCE ENERGY USAGE: One of the reports leading to this research refers to energy reduction as benefit of Circular Economy [19]. In line with this, Liander wants to reduce its energy losses. The model should support this incentive.

REDUCE MATERIAL USAGE: Just like energy reduction, material reduction is expected to be a benefit of the Circular Economy. The model should support this incentive. Liander sees its dependency on valuable and scarce materials such as copper and seeks a proper approach to this problem.

RESOURCE SECURITY The model is expected to make the availability of resources more secure.

EFFICIENT MATERIAL USAGE: The model should incentivise efficient usage of material.

PROMOTE LIFESPAN EXTENSION The lifespan extension of resources and assets supports the implementation of the Circular Economy.

POSITIVE ECONOMIC BENEFIT: The model should lead to positive economic benefits in line whit what the expectations of the Circular Economy are.

ACCOUNT FOR CO_2: The model should appreciate the CO_2 emission accounting as is done within Liander. These are generally indirect carbon emission due to energy loss within the grid.

ACCOUNT FOR STAKEHOLDERS: Stakeholders should be accounted for within the model because in a market with limited suppliers each business within the supply chain is dependent on each other.

RISK ASSESSMENT Take risk assessment into account as governing and mitigating risks are one of the most important values within the energy distribution infrastructure in the Netherlands

FUNCTIONAL VERSUS PHYSICAL REQUIREMENTS: Differentiate between functional and physical requirements within the model. Assets like distribution transformers have their main priority at functionality, while the physical requirement should be subordinate to the functionality.

PRACTICALITY: The model should be practical for decision makers by making it easy to understand and easy to use without high time demands

3. Contextual Background

Outline Background Chapter

The focus of this research is about embedding sustainability into the business case and hence in investment decision methodology. The contextual background of this study is therefore built upon the two main elements; (1) sustainability from a Circular Economy perspective and (2) investment decision methodology in business case theories. This chapter will introduce the background of these two elements, introduce their limitations and link them to current practices of Liander. After the separate introduction of the Circular Economy and investment decisions, the current state of art of sustainable business cases will be discussed.

Scope

For the theoretical part on sustainability and the Circular Economy the defined scope considers, after discussing the various perspectives, mainly the European approach towards the Circular Economy as this is the environment in which Liander operates. Likewise, the theoretical background on the investment decisions will focus on the utilities sector. These decisions are generally characterised by high demands on asset reliability, safety and lifespan.

3.1. Contextual Background on the Circular Economy

The Circular Economy is an emerging paradigm for an economy that does not consume its resources, but instead uses materials without destroying them or making them useless for future use. Due to the many different perspectives on the circular economy and the possible different origins, a thorough research has been conducted. This section will give a brief introduction on the definition and the various approaches within the circular economy. An historic overview of the Circular Economy can be found in Appendix B.

3.1.1. Definition of, and Perspectives on the Circular Economy

The term Circular Economy was first mentioned [27–29] in 1990 by Pearce and Turner. They argue in their book "Economics of natural resources and the environment" that the classic view on the economic system is too much focussed on growth, and that the interactions with the limited ecological system are neglected [30]. Instead they say that the economic system is characterised by a circular relationship with the environment; a circular economy. They develop a model that focusses on material management within the economy and how it is affected by the ecological system and affects social welfare (figure 3–1). Since then the ongoing research on the Circular Economy has caused the emergence of various definitions of the paradigm. Differences in definition can be found amongst scholars, but also between businesses and governments. Each of their perspectives on the Circular Economy is different.

In China, governmental policies have greatly influenced the Chinese scholars. The Chinese government adopted the Circular Economy around the turn of the millennium. It focusses on resource reutilisation using the 3R method[1] to achieve economic development. For example Ma *et al.* states that "a *Circular Economy is a mode of economic development that aims to protect the environment and prevent pollution, thereby facilitating sustainable economic development.*" [27]. The European Commission only adopted the Circular Economy in 2014 following the market, and defined it as a *"development strategy that entails economic growth without increasing consumption of resources"* [31]. Both governments see economic development as incentive to promote the Circular Economy, but the way of implementation is different. In China, it is a government-push that focusses on Circular Economy on large scales such as industrial parks and entire regions, while the European Union focusses more on a broader implementation through a market-push on products and within supply chains.

The definition of the European Commission has a slight different perspective than the various organisations in Europe that promoted the Circular Economy already before the Commission introduced the directive. These companies

1. Chinese often refer to the 3R principles (reduce, reuse and recycle) [21, 22, 29, 36, 84, 91, 161, 175, 189–191].

2. The Commission postponed the relevant directive [192] the same year [193] in favour of aiming for a more ambitious proposal, for example by addressing product design and secondary raw materials.

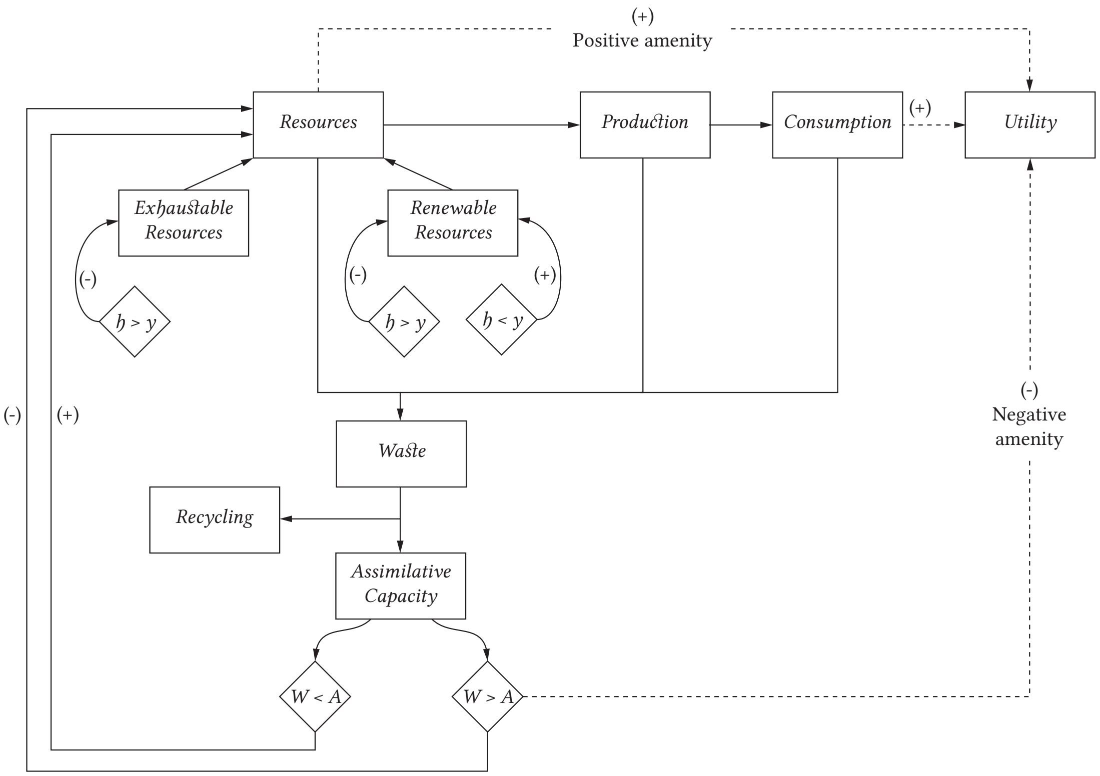


Figure 3 — 1 The Circular Economy model as described by Pearce and Turner. Nature has an "assimilative capacity that converts waste into harmless ecologically useful products" [30].

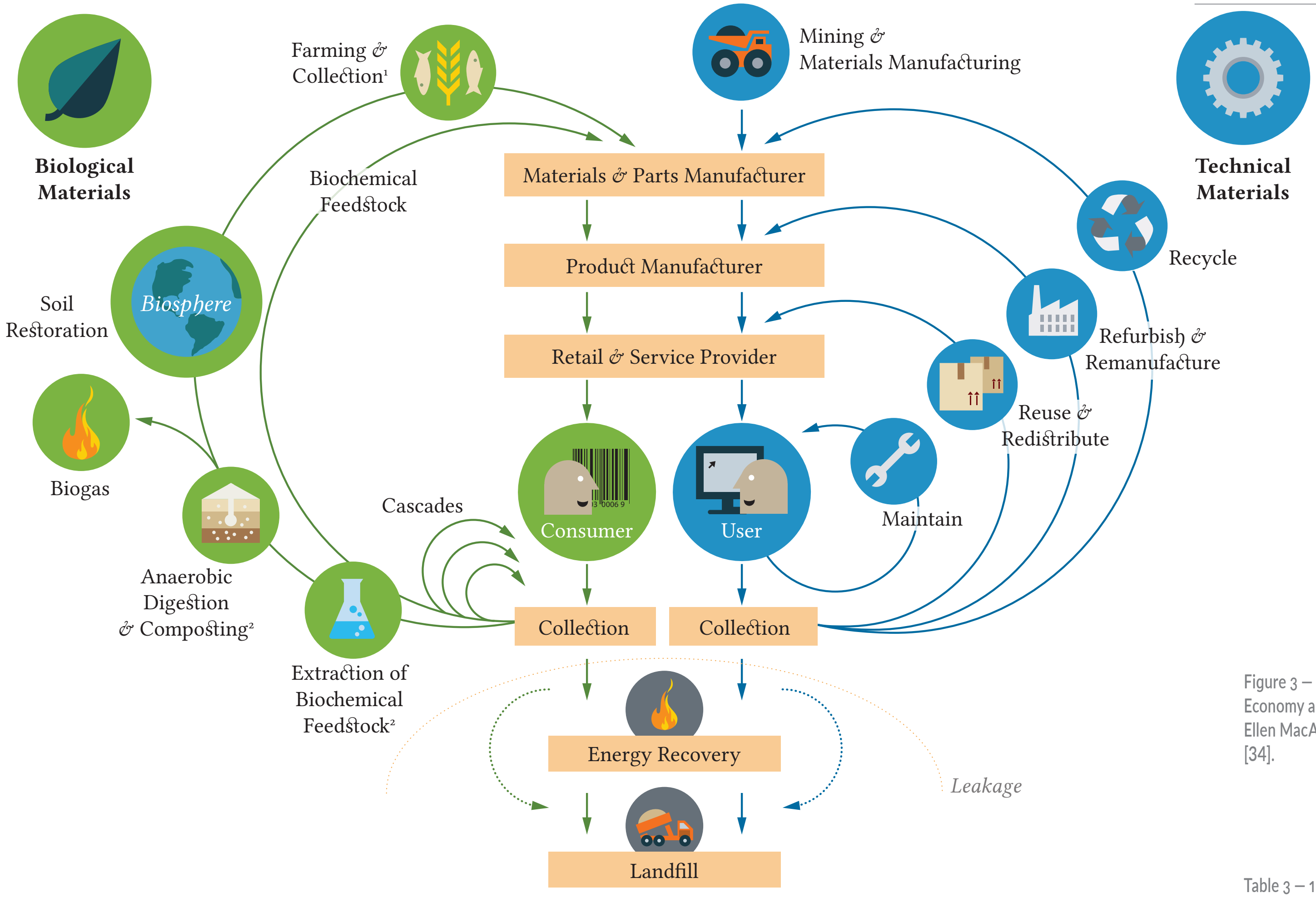
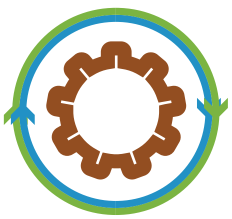
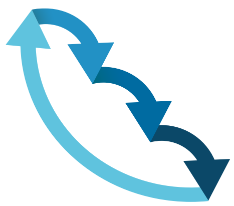
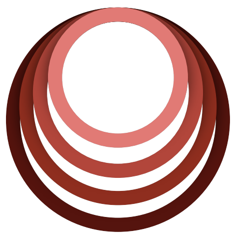
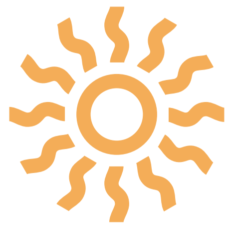


Figure 3 – 2 The Circular Economy as depicted by the Ellen MacArthur Foundation [34].

Table 3 – 1 Overview of the various approaches related to the Circular Economy [34, 38–43].

					
Industrial Ecology	**Cradle to Cradle**	**Blue Economy**	**Waste Hierarchy**	**Biomimicry**	**Performance Economy**
What is the impact of the technical resource loop?	What is the best resource loop?	Can more parties use the resource subsequently?	How to reduce resource losses?	How should the design of the resource loop be?	What is the required performance?
Footprint of technical material	Material health of the used resources	Increase resource effectiveness	Increase resource efficiency	New routes and solutions to achieve one's goal	New business model on providing performance instead of giving ownership

generally reason from the challenges that material scarcity bring about. The awareness of material scarcity is brought about by the notion that the Earth is a closed loop system for materials; hence, all our businesses are dependent on this limited amount of materials. The definitions of these organisations on the Circular Economy are therefore more resource focussed. But to promote the idea they suggest the implementation of new business models which are assumed to save businesses millions of Euro's while creating thousands of new jobs [19, 32–34]. Next to that they are supposed to provide the business with other economic advantages such as securing the supply chain, price stability and advantage over competitors [19, 34, 35]. Accenture and the British Ellen MacArthur Foundation (EMA) are two of those organisations. Accenture uses the following

> *Circular operational management comprises:*
>
> *Throughout the entire value chain of all*
> *raw materials and products we purchase:*
> *lifespan, value and reusability will be maximised,*
> *Waste and energy use will be minimised.*
>
> *With respect to ecological, economic and social values.*

Quote 3 — 1 Liander's definition for circular operational management of the business, translated from the document Aanpak Circulair Aanbesteden (Approach to Circular Tendering) [44].

definition "*an alternative model decoupling growth from scarce resource use*" [33], while the EMA states that "a *Circular Economy is an industrial system that is restorative or regenerative by intention and design*" [34].

Finally, scholars also vary in their definition. As Dajian notes, the Chinese focus is on an economic development [36, 37] while others focus more on environmental management [22]. For example Zhao *et al.* tries to summarise the Circular Economy as "*an ecological economy*", "*by closing the material cycle economy*" [21] and Andersen writes that it "*envisions a form of material symbioses*" [28].

The perspective of the authors and their incentive to write about the Circular Economy seem to play a big role in the definition that they use. This results in a different approach on how to embed the paradigm in the business, in the city or on a larger scale.

3.1.2. Approaches to the Circular Economy

Currently several actors propagate the Circular Economy. Especially in Western Europe, there are several foundations, platforms and network organisations. Next to Accenture and EMA, there is Circle Economy in the Netherlands. They take a leading role in this movement and generally refer to a couple of other paradigms as basis for the Circular Economy. The most common are Industrial Ecology, Cradle to Cradle, Biomimicry, the Performance Economy and the Blue Economy, which are paradigms that try to anticipate on environmental issues or economic limitation. A common depiction of the Circular Economy is developed by EMA (figure 3–2) and is clearly influenced by Cradle to Cradle's techno- and biosphere and Lansink's Ladder waste hierarchy [35].

Comparing the various paradigms one can conclude that there is a general aim throughout these paradigms that focusses on resources and how they should be managed to sustain them for the future (table 3–1). The differences between the approaches relate to the various life cycle stages of a product, the resource loops as well as a possible business model.

3.1.3. Circular Economy within Liander

From a sustainability point of view, Liander has been reporting on their carbon emissions for some time. To incentivise CO_2 reduction, Liander has included these emissions within their risk model. Next to that, Liander has recently started to embed the Circular Economy throughout the company[3]. For a new office building in Duiven and its furniture, principles of the Circular Economy have already been taken into account during the tendering phase. Furthermore, there is a focus on embedding the Circular Economy into the procurement methodology as well as the core business. Liander drafted a definition what the Circular Economy means for their operational management. This definition includes the various elements that are considered important in this respect:

The bigger challenges for Liander considering the Circular Economy are mainly within their core business: operating and maintaining the grid. An important aspect in this regard is

3. This was one of the observations during the internship at Liander of which this thesis is the end result.

that the assets that make up the grid are of different characteristics than the goods and services that are commonly focused on in the Circular Economy. Common goods in the Circular Economy are often sensitive to fashion such as (fast moving) consumer goods, flooring and furniture. The assets of Liander last generally for 30 to 40 years, contain scarce materials such as copper and oil, may differ in maintenance intensity but require a very high reliability and safety standard. Due to these different requirements, different volumes, size of the market, level of innovation, supply chain and its recycling process, the assets of Liander are of a very different nature.

A common issue that arises is the trade-off between extending the lifetime and replacing an asset in favour of increasing energy efficiency. A second problem is forecasting the value of the asset at its end of life due to the large variation in raw material prices over 40 years (figure 6–12). These issues can be directly related to material scarcity. Other relevant, but indirect issues over the asset's lifetime are the uncertainty whether the manufacturer of the asset is still existent, whether there is still a potential need for parts or materials, or a more general issue, whether the functionality that is offered is still required in the same form and capacity. These issues also influence asset investment decision-making and thus material usage.

Liander is now investigation its supply chain to see what opportunities and changes on product level are possible as well as looking for new collaborations that may help to improve the 'circular value' of Liander and its assets. One of the issues that have arisen in this process is how to determine this circular value. This issue involves the question which aspects, like recycling level, life extension or material reduction, are important to consider in properly assessing one's circular performance.

3.1.4. Discussion on the Circular Economy

As indicated in the previous paragraph, there are some practical issues considering the Circular Economy for Liander. In general, there are various aspects that should be taken into account to value the actions and decisions that may result from implementing the Circular Economy. As a start, a clear definition and scope are necessary.

The most common denominator found throughout the definitions on the Circular Economy is that of a paradigm that explicitly looks at closing resource loops. It is in contrast to its name not by definition a financial or monetary paradigm but can be seen as a more environmental sustainability paradigm with economic benefits. From etymological point of view, the term economy actually fits very well with the historical perspective of the paradigm. Economy is derived from the Greek *οἰκονόμος* meaning household management [45] in which household is a metaphor for the Earth on which resources should be managed properly to enable future usage.

The different financial benefits, which are often given as argument to promote the Circular Economy, can be disputed. Some reports suggest that implementing the circular economy will result in millions of Euros of economic growth as well as thousands of new jobs [19, 32]. The question is whether it is actual growth or whether it is mere a matter of savings. In general the business models on which these estimates are based consider resource efficiency through design changes and shifting from product consumption to services. This means that saving on manufacturing costs would lead to less money trickling down the supply chain and rather stay at the final supplier or the company providing the service.

3.2. Contextual Background on Investment Decisions

The second pillar on which this study is built is investment decision methodologies within business cases, especially methodologies in utilities such as the energy, IT and water sector. Assets in these sectors have similar characteristics and requirements such as high reliability and long life cycles. First some theory on the decision making process will be introduced after which the relation with the business case and examples of methods will be discussed.

3.2.1. The Decision Making Process

The decision making process is a process in which the decision maker and the subject (decision problem) have a central position. Irrespective of the approach, the decision maker has to interpret, evaluate and judge upon the various aspects that influence the decision problem. Besides these aspects there are also other factors influencing the decision. Bannister and Remenyi developed a model that shows these external factors of the decision process (figure 3–3).

These factors are forms of information that are presented to the decision maker through others, such as salespeople, consultants, colleagues or technological systems. These proxies pass this information partially, in a certain form or adjusted in any other way and therefore form the exterior filter. The decision maker further filters that information aided by personal skills, experience and the decision maker's perception of value. They are the interior filter.

By understanding this process, one can then also understand that the results of decision problems are not static but may change. That change may naturally be caused when a new person gets involved, but also through present factors such as the interactions that decision-makers have with the process. Even though the process is not static, it is important that the decision can be explained and understood. Within businesses, this can be very important to enable fair and justifiable decisions towards stakeholders and to avoid legal action against the decision maker. To be able to explain the decision the decision maker should be able to make its evaluation method explicit and therefore know the various factors that have influenced the final result. Even though this rationality is important, Bannister and Remenyi also conclude that successful decision making requires a good instinct of the decision-maker [46].

An example of the complete decision process is given by the SWARD method, a decision methodology for assets within the UK water industry. It proposes a process consisting of the following seven phases [47]:

1. Review of current performance and definition of decision objectives
2. Generation of options
3. Selection of appropriate qualitative and quantitative criteria and indicators for the specific decision problem
4. Collection of data, generation of information and risk evaluation
5. Analysis of options through a decision methodology
6. Selection of preferred option
7. Implementation of option

As first three phases show, the type of decision and its aim may influence which criteria and indicators may be used. These are not completely fixed and various lower level indicators can be used to substitute each other to give the right focus to the decision objective. Even though this allows for flexibility, it would be important to clearly identify whether a decision process made use of different indicators to avoid possible bias.

Investment Decision Approaches

To guide the decision process, a decision maker can choose to use a certain methodology. Within this methodology space there are various approaches distinguishable that are either more outcome oriented or more process oriented. According to Banister and Remenyi these approaches may be applied in either a positivist or hermeneutic way [46]. The positivist application externalises the decision to the methodology. This may cause the perception of an independent entity, the methodology, that decides on the result of the decision problem. For example a predetermined computation of a final score. The Hermeneutic application, on the other hand, is much vaguer. In this process, metrics are generally used. However, the decision maker does not use a specific methodology to determine the score but decides on a result by interpreting and combining the metrics in his or her mind. In contrast to the positivist application the hermeneutic method does not allow for explicit argumentation, especially since instinct and intuition are an important aspect of this way of decision making [46].

The actual approaches that Bannister and Remenyi distinguish are the fundamental, composite and meta approach [46]. The

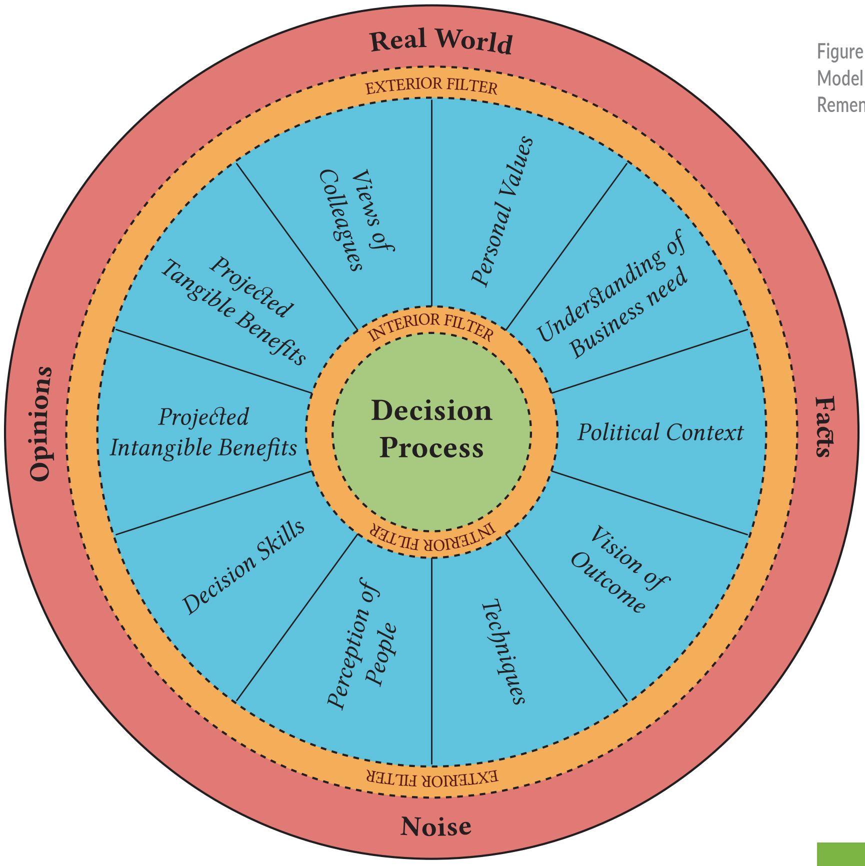


Figure 3 – 3 Decision Process Model by Bannister and Remenyi [46].

Figure 3 – 4 Common criteria for asset investment decisions.

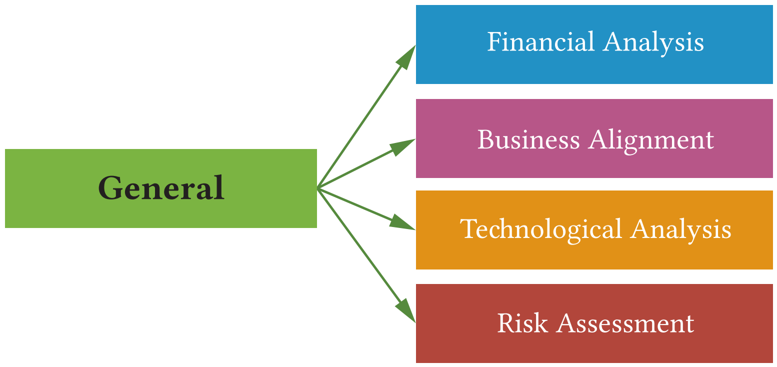
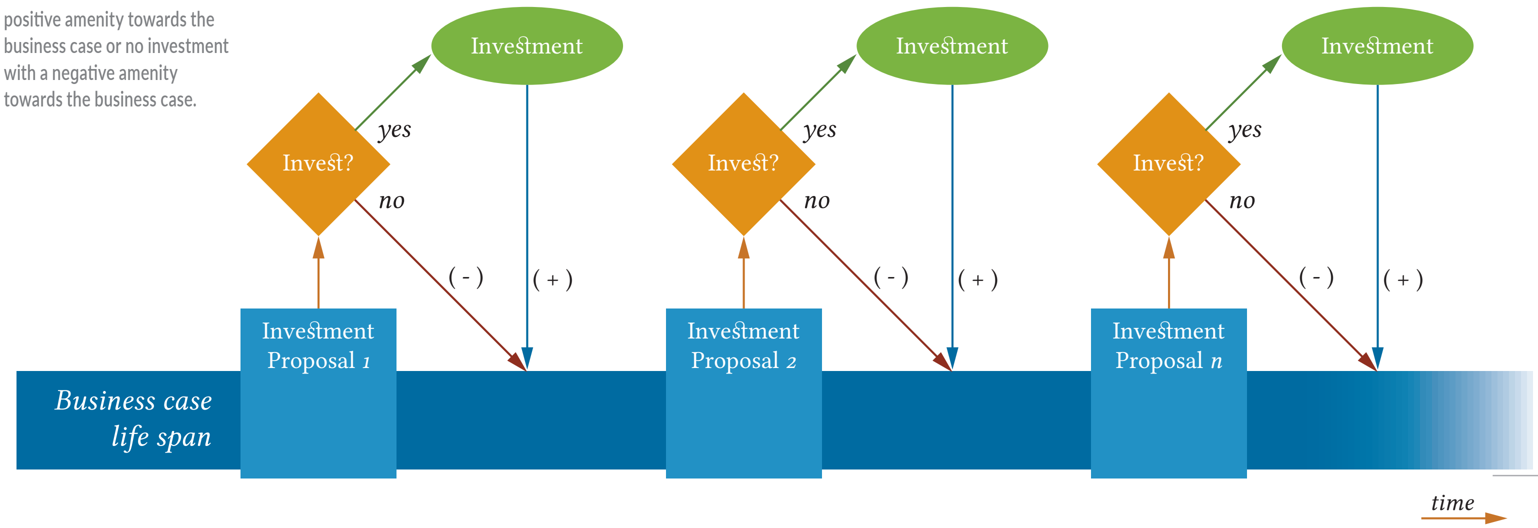


Figure 3 – 5 Relation between the business case and investments through investment proposals (IP) and investment decisions. The decision leads to either an investment with a positive amenity towards the business case or no investment with a negative amenity towards the business case.



fundamental approach aims to reduce the decision parameters to a single measure while the composite method tries to create an overview of the various parameters aiming to provide a balanced overview of the decision problem. The meta-method does not use a predetermined evaluation technique but tries to identify the most appropriate evaluation technique for the decision problem.

Since choosing a different method for the decision-making process may lead to different decisions, choosing the appropriate decision methodology is important for the end result. Also, each method always includes some form of preference, either within the tool or in the form of the decision maker itself, and is therefore subjective by nature [48]. To solve this, one would want to know the best possible decision methodology before selecting that methodology. This is a decision problem in itself. Hence a paradox, qualified by Triantaphyllou as the Decision Making Paradox [49].

Asset Investment Decision Criteria

In decision approaches, various decision parameters will be used as guideline to base the decision upon. Depending on the approach, these parameters, or assessment criteria, are to a certain extent explicitly known. For each of the alternatives, between which a decision needs to be made, their performance per decision criterion can be determined. How it is determined is up to the methodology.

In investment decisions considering infrastructure assets or other technical products, certain criteria are commonly addressed. For example the financial performance in the form of investment costs or payback times. Other criteria are often based upon management or dependencies of the alternative. Examples are alignment of business objectives, technological requirements, risk assessments [50]. These criteria should represent the important aspects to base one's decision upon, but the importance of each criterion may differ from case to case. For example in the public sector stakeholders may be an important aspect as there are generally many involved, while a decision problem focussing on an internal commercial decision problem may have priority on the financial aspect only.

3.2.2. Investment Decisions within Business Cases

Within business cases, companies can determine the feasibility of projects by valuing the opportunities and risks of that project. As Berghout and Tan show, there are many different methodologies or approaches to business cases [51]. However, their greatest common denominator is that they are tools to shape or recommend decisions supported by costs, benefits, risk analysis and alignment of business objectives. Hence, these four elements are commonly found in business cases.

The business case is generally a strategy for the longer term that brings smaller projects forward that account for a certain part of the goal of the business case (figure 3–5). These proposals either lead to investments that contribute to the final aim of the business case, or declined investments, which possibly result in a negative impact on the business case. Besides the amenities resulting from these investment decisions, also other external factors will influence the business case over time and hence change its course. These external factors can be stakeholders that change their strategy or changes in the society that may even result in societal aversion against the aim of a business case.

In the European Union, investment decisions within the water, energy, transport and postal services sectors that surpass the threshold sum of €5.186 million need to result in public procurement [52]. The procurement procedure as defined by the European Union requires transparency towards the tenders. This means that the decision should be defendable based on clear criteria and decision methodology [53, 54]. It is therefore required that the resulting procurement process of an investment decision methodology has an equal form of transparency. This will help to explain the considerations and final decision to the contenders.

3.2.3. Investment Decisions in the Infrastructure Sector

As discussed before, the various infrastructure sectors such as power, water and IT can be characterised in the same way. Therefore, it can be assumed that their investment approaches can be exemplary for one another. For this reason, several approaches from these sectors have been analysed. These approaches were found during the literature research as described in section 2.2.

IT Investment decisions

Several scholars have written about IT business cases. According to Remenyi there are more factors to develop a complete IT business case besides a simple cost-benefit analysis [55]. He suggests five elements to develop a complete IT business case: business outcome, stakeholders, technology, strategic alignment and risk contribution. This characterisation is according to Remenyi not only exclusive to the field of IT but may serve as an example to other areas as well.

Berghout and Tan also focussed on IT business cases. They compared Remenyi's characterisation with many other suggestions and came to a comprehensive list of investment criteria [51] at various levels (figure 3–6). At the meta-level, they identified the organisational, technological and project constituents that comprehend a total of nine business case elements:

In reverse direction of the arrows, the model shows how the constituents impact the initial costs estimates of investments. Hence, these business case constituents are equal to the evaluation criteria of investment proposals. When relating to the general investment decision criteria mentioned section 3.2.1, the financial constituents are represented by the benefits and costs. The technological criteria are represented by the entire technological level. Its two constituents can be seen as the balance between technical supply and demand. The business objectives are of course found in the *Business Case Objectives*. *Stakeholders* and *Project planning & Governance* are similar to the aforementioned stakeholder appraisal. And risks are also present in this model. *Consolidation* covers the other constituents in a more 'conclusive' form. It is added by Berghout and Tan to secure the commitments to the project. This is also the reason that they have added some other constituents that can theoretically be grouped into a single one.

Water and sewage investment decisions

In the United Kingdom the Sustainable Water industry Asset Resource Decision (SWARD) project was initiated to be able to assess the sustainability of water and waste water asset development decisions [47]. Its aim was to embed sustainability in all its diversity based on a hierarchy with four main decision criteria and several lower level criteria (figure 3–7). These criteria were developed and evaluated by the water service providers and their stakeholders [47, 56–58].

Where Remenyi and Berghout do not include sustainability the SWARD approach is completely built upon a sustainability perspective by addressing the four main decision criteria directly from this perspective: i.e. it should be economic sustainable as well as technically sustainable. While the risk appraisal that Remenyi and Berghout identify as a separate criterion, the SWARD method embeds it within the financial and social sustainability criteria.

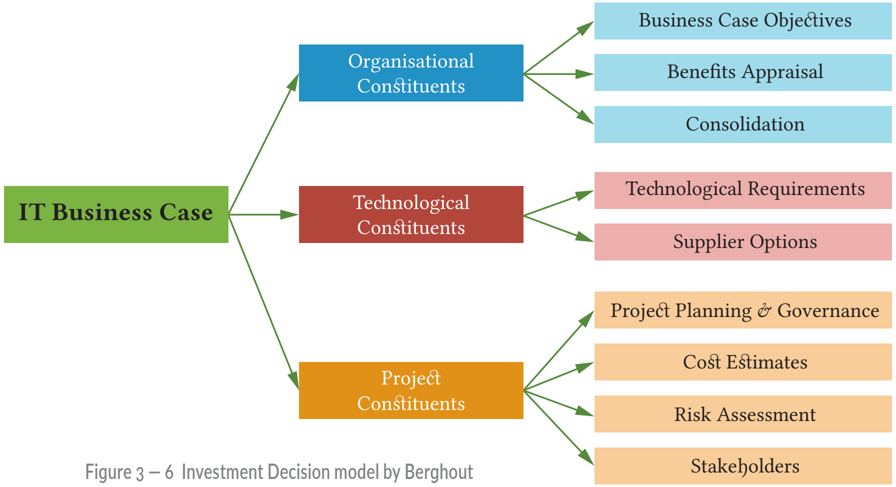


Figure 3 – 6 Investment Decision model by Berghout and Tan [51]. Most of the lower level elements are commonly found in other business case models. The *Consolidation* element is a 'conclusive overview' of the IT project accounting for the most essential elements of the business case. The *Supplier options* considers the availability of tried suppliers which are found to be dependable.

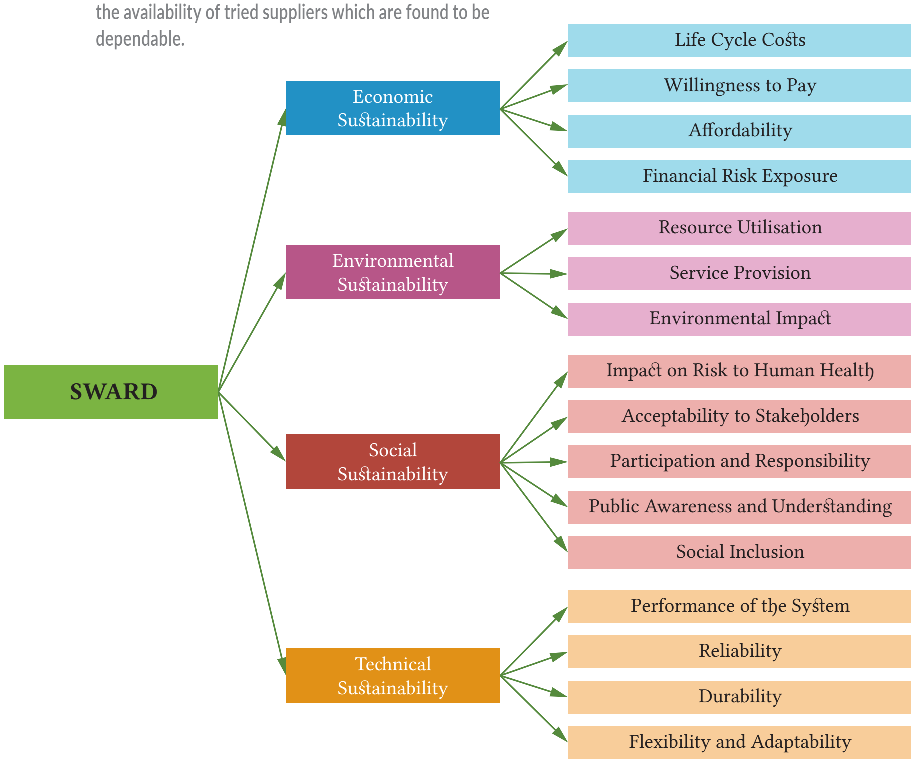


Figure 3 – 7 SWARD first and second level decision criteria. Adapted from Foxon *et al.* [57]. The second level decision criteria are high-level indicators of the methodology. Several of these indicators are commonly found in other methods. Others are more specific such as the *Resource utilisation* that covers use of water, energy and chemicals. The *Impact to human health* includes the accessibility to clean water and the exposure to toxic compounds. *Flexibility and Adaptability* covers the ability to make future adjustments to the system.

Conclusion

Looking at the various methods for investment decisions, there are various recently developed business case methodologies that explicitly account for more constituents than the basic three or four. Cumps *et al.* conclude that organisations which account for more than just the financial return as well as the value of the environment in relation to the business, seem to be better aligned and more innovative [59]. One could argue that increasing the number of constituents would therefore benefit the success rate of the project. However, increasing the number of constituents means a higher demand for information, more complexity and hence a more difficult decision process.

Before drawing conclusions on what this means for this study, the situation at Liander will be discussed as well as the explicit case of business cases that include sustainability.

3.2.4. Investment Decision within Liander

Within Liander, the Project Investment Board decides upon the investments proposals for investments in assets. These investment proposals follow a template in which several elements are obligatory to mention. The main elements that are included in proposals are:

» Bottlenecks to be tackled or opportunities to be taken (technical),
» A risk analysis of the current situation (risks),
» Possible solutions including mitigation of risks (all business values, see figure 3–8),
» Proposed solution (technical),
» Financial business case (financial),
» Portfolio (strategic)

To ease comparison with the models that were discussed before, the criteria that Liander covers are structured and presented in figure 3–8. As can be seen these elements are similar, though more concrete and a bit different. In comparison, the risk analysis is quite extensive while there seems to be a lack of explicit stakeholder appraisal.

The risk analysis is based on Liander's risk matrix (see figure 6–7). It contains six elements (quality of service, customer service, image, financial impact, safety and sustainability) on which the risk for Liander is indicated on a scale of five: from null to very high. The sustainability factor is currently a measure of carbon dioxide emissions measured in Euro. Currently, other forms of sustainability such as resource use or social impact are not included and hence not taken into account when a proposal is decided upon. An internal study has looked at whether material usage could be included in the matrix but the idea was postponed due to the complexity it caused.

The financial business case contains an indication of the net present value and the internal rate of return. The various investment decisions that were analysed (Appendix L) showed that none of these financial business cases account for the end of life of the investment that is proposed. However, the end-of-life (disposal) and removal of the old assets, to make room for and implement the new investment, is accounted for. From a sustainability point of view, there is no financial incentive in the current investment proposal that accounts for the waste production at the end of the investment. It can be argued that this is difficult to predict as these investments run for forty years and prices and technologies cannot be predicted for this time-frame. If even with discounting[4], it is financially not feasible to account for sustainability on this long term, a different element should be added to the business case. This will help to create an incentive to choose for sustainable options over non-sustainable ones.

When further analysing the investment proposals other assessment criteria, besides the default ones, were included. These were elements such as alignment to strategy, scalability, reliability, etc. There is however no standard way in which this was done. Sometimes a qualitative description was given, sometimes a simple overview with a valuation of these aspects.

3.2.5. Discussion on Investment Decisions

The approaches discussed by Berghout, Remenyi and the SWARD methodology are in general quite alike and comprehend similar criteria. However, their categorisation is different. SWARD and Remenyi use a similar categorisation model. Remenyi's model has more overlap with the current practices of Liander, such as separate risk valuation and the indicators used for the financial appraisal. On the other hand, Remenyi's model misses a sustainability element that the SWARD model is all about. Adding sustainability to Remenyi's model could therefore be a good starting point for a comprehensive model that is aimed for within this study. Embedding of sustainability in the business case model will be further elaborated and discussed in the next section.

Another point of discussion is the need for forecasting. Business cases considering assets with a long life span would benefit from reliable forecasting of the various forces

4. Discounting, or discounted cash flow, is a method to calculate the future costs and benefits to the current price levels. Liander uses a discount rate based on the WACC and depends on regulation. Currently it is at 4.6% meaning that the turnover reduces by half over 17 years [114].

influencing the business case. For example the technological advancement that may require early phasing out of assets, or the trend of increasing raw material prices that may change maintenance costs and the end of life valuation. Liander is cooperating with the University of Twente to develop better forecasts for their assets using asset life cycle management plans [60]. To be able to account for these forecasts, these forces could be included in the business case. Blanco, Olafsson and Trigeorgis suggest to account for this by including flexibility value in the financial appraisal of the business case. This requires capitalising the various forces, which may be difficult because of the quantitative interpretation of qualitative information.

3.3. Contextual Background on Business Cases for Sustainability

The need for sustainability in business cases is discussed by various scholars as it is expected to create competitive advantage through superior customer value [61, 62]. Salzmann *et al.* researched the relation of environmental and social performance in relation to the financial performance of the business case and concluded that there is no coherency within literature [23]. Various scholars identify causal relationships, positive, neutral and negative correlations. Salzman therefore argues that more studies are necessary. Next to that, he identifies the need for methods that tackle the complexity and operationalisation of the subject.

This section will briefly discuss the relations based on more recent studies and impact of sustainable business cases. Hereafter, common practices will be introduced. The aim of this research, to use circular economy as paradigm for sustainability within business cases, will be reviewed in the discussion paragraph.

3.3.1. Definition

Within literature, there is no clear distinction between *Business Cases for Sustainability* and *Sustainable Business Cases*, and these terms are sometimes used interchangeably. For clarity reasons, this thesis will use the following definitions:

Figure 3 – 8 Investment Decision elements within Liander. In case the investment costs exceed €500 thousand, especially the financial criteria are more extensive and include elements such as Maximum Cash Exposure and Economic Value Added.

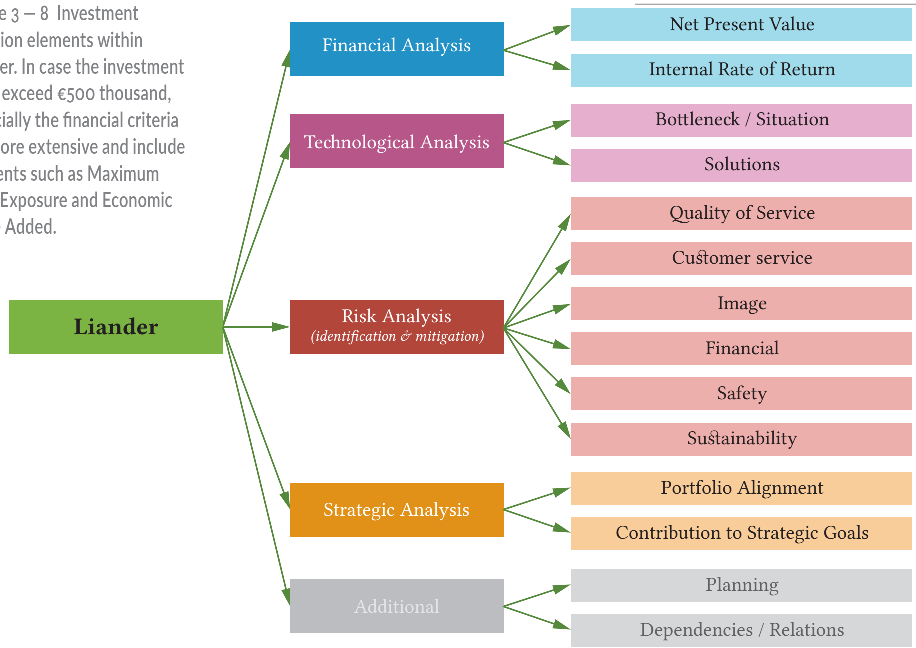
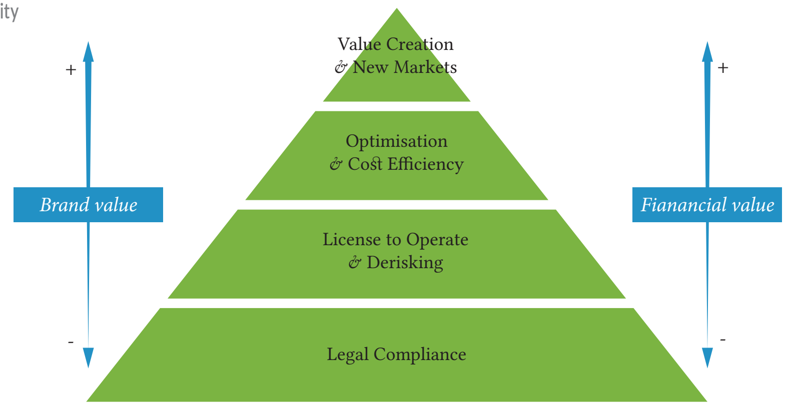


Figure 3 – 9 Sustainability Maturity Pyramid [64]



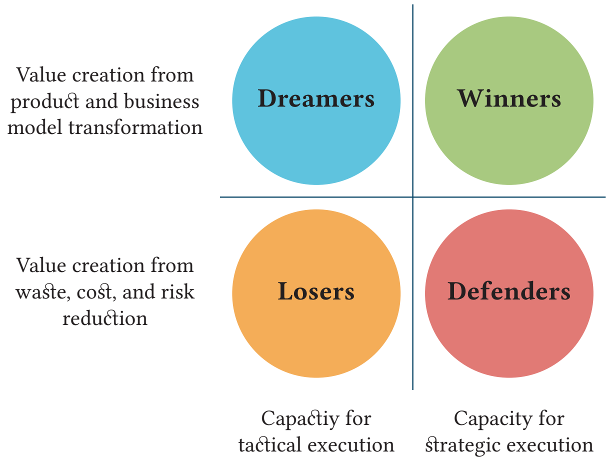


Figure 3 – 10 Making Sustainability a Winner: four categories of sustainable performance [66].

- *Business Cases for* Sustainability (BCS) indicates an environmentally sustainable oriented business case,
- *Sustainable Business Case* (SBC) is a business case in which sustainability is a holistic term and applies to all aspects within the business case such as economic, social and environmental aspects. This is often referred to as Corporate Social Responsibility (CSR).

Even though the focus of this thesis is environmental sustainability through Circular Economy, the business case should also be economic sustainable and Liander wants to consider social aspects as well. Therefore, the comprehensive form of sustainability is addressed within this chapter and thus referred to as a sustainable business case (SBC).

3.3.2. The Advantage of Sustainable Maturity

Companies may choose to become a more responsible and sustainable company for various reasons. For example, it may be a marketing or branding tool to influence the public. An example is McDonalds who changed their red colour in the logo to green [63]. Another reason may be that the company truly thinks that a sustainable future is the only way to go. However, either way, by becoming a responsible company, sustainability may create competitive advantage and financial benefits [64, 65]. The sustainability maturity pyramid illustrates this (figure 3–9). The levels of the pyramid range from a situation in which a company is pushed to achieve a certain benchmark of sustainability to a level where it can set its own benchmarks.

The maturity pyramid indicates that achieving higher levels of sustainability correlates to an increased brand value and an increased financial value. Of course, the actual increase in value is highly influenced by the actual practices of the company. Lubin and Esty have developed a categorisation on the actual sustainable performance and possible business outcomes [66]. They identify four types of sustainable performance based on a company's chosen strategy: losers, defenders, dreamers and winners. It comes down to the difference in how coherent and comprehensive the strategies are and whether there is enough capacity to execute that strategy.

Weber takes a different approach and focusses on the different benefits that arise from social corporate responsibility in business cases [67]. She categorises the various corporate social responsibility benefits by relating the nature of the indicator to the corresponding type of value (figure 3–11). Qualitative business benefits have only non-monetary benefits. However, these also contribute to competitiveness of the business, leading to economic success.

Weber argues that the costs of CSR are difficult to measure since there is currently no distinction in CSR and non-CSR costs within accounting systems and sufficient quantitative evaluations are missing [67]. In addition, Weber does not include environmental benefits or other externalities in her model, but concludes that more research is needed for improved CSR indicators and metrics. Hence the advantages and the need for including sustainability into the business is evident, however the question remains what the best practical method is. In the following section, several approaches on how to embed sustainability into the business case will be discussed. The next chapter will continue with introducing which indicators and metrics can be used.

3.3.3. Embedding Sustainability into the Business Case

There are few approaches developed on how to embed sustainability into the business case. Either on a strategic level or through a business case methodology. But as Salzmann *et al.* conclude there is a lack of descriptive studies on how to implement a sustainable business case [23]. In the previous section the SWARD methodology was already discussed (Water and sewage investment decisions), below four other methodologies will be discussed: the Triple Bottom Line, the Framework for Strategic Sustainable Development, a model developed by Epstein and Roy, and a methodology based on capitalisation of externalities. These methods came forward from the literature research. An initial review of these models learned that they could possibly be applicable to this study.

The Triple Bottom Line

The most common paradigm that relates sustainability with the business is the Triple Bottom Line. It was introduced by John Elkington in 1994 to integrate the social and economic dimensions of sustainability to enable 'real environmental progress' [8]. It considers the three main aspects that businesses should focus on to become a corporate social responsible company: economic, environmental and social value. However, the Triple Bottom Line is just a bottom line allowing for trade-offs instead of looking for the combined optimal solution that are actual effective solutions. It receives a lot of criticism considering practical implementation such as measurability of the social factors or the lack of integration between the three values [10, 11, 68].

Strategic Sustainable Development

The Framework for Strategic Sustainable Development (FSSD) is a method developed by Robèrt and The Natural Step. They argue that strategically including sustainability is necessary to make investments that will keep paying off in the future [62]. The framework approaches sustainability from a scientific angle stating that it derived its core 'system conditions' from four scientific principles:

1. Substances from the Earth's crust must not systematically increase in the ecosphere [5];
2. Substances produced by society must not systematically increase in the ecosphere [6];
3. The physical basis for productivity and diversity of nature must not be systematically diminished [7];
4. Fair and efficient use of resources with respect to meeting human needs [8].

These system conditions are not prescriptive rules but are supposed to guide the decision making process to avoid negative impact on business and environment [62, 69]. A tool developed

5. In a sustainable environment, there is a balance between the Earth's spheres. Hence, the concentrations of materials from the lithosphere should not systematically accumulate in the ecosphere. Especially because of delay and feedback mechanisms within the ecosphere, it is difficult to predict what concentrations may lead to unacceptable consequences [194].
6. Substances such as capital goods and waste which society produces may leak into nature. This leakage may not systemically increase and cause accumulation in nature. Pearce and Turner already described this through the mechanism of assimilative capacity of nature [194].
7. This is about the regenerative capacity of nature to process materials. This capacity should not be diminished through structural damage in the form of inhibition or destruction of these mechanisms. This allows for the first two principles to have sustainable counterpart as a source of new materials to the ecosphere as well as a mechanism to process the leakage from society [194].
8. The last principle is about the social part of sustainability. The human health, emotional and social needs should be fulfilled [194].

Figure 3 – 11 Five level model from the Framework for Strategic Sustainable Development[70].

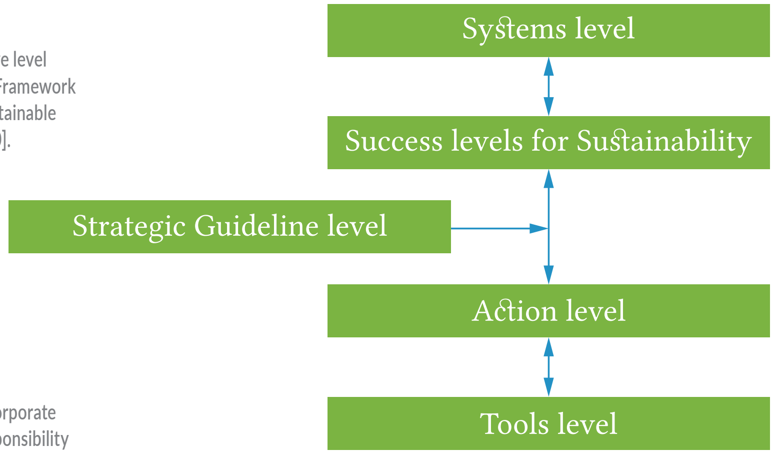
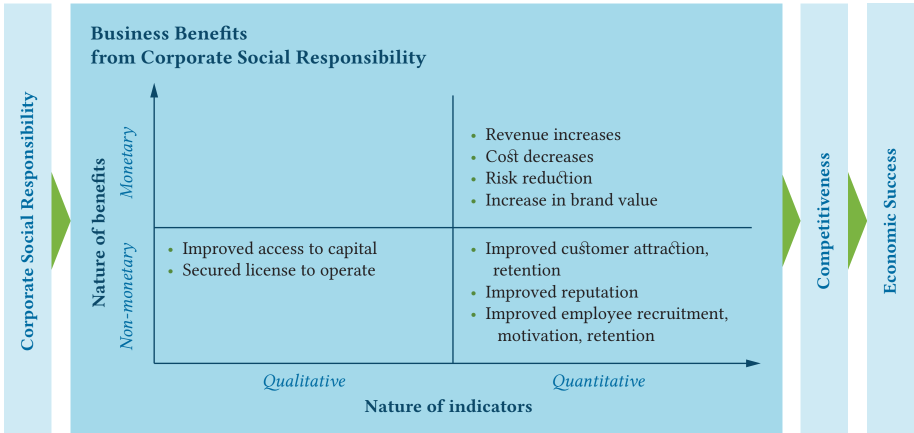


Figure 3 – 12 Corporate Sustainable Responsibility Impact Model [67].



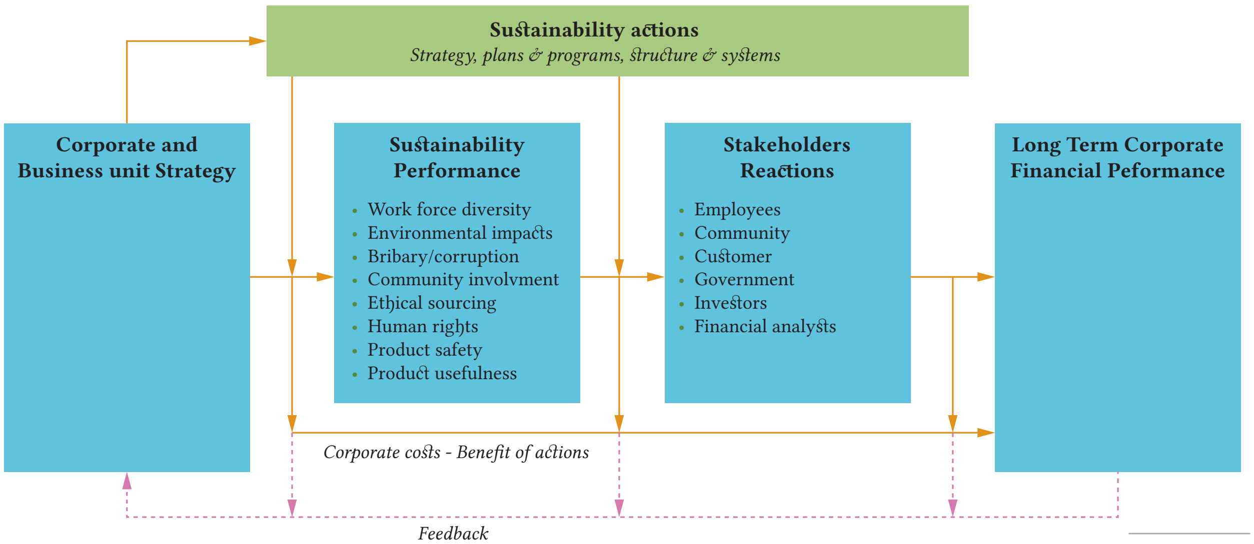


Figure 3 – 13 Drivers of sustainability and financial performance within a Sustainable Business Case [71]. It lists eight drivers that support sustainability.

for this is the Five-level model (figure 3–12) in which a sustainable system is illustrated and how the levels within this system influence each other. By starting at the systems level one should be able to derive the next levels and hence be guided in choosing tools and making decisions that finally support the system again.

Even though the FSSD promotes itself as a decision making tool, it only focuses on sustainability and seems to miss out corporate criteria such as financial and technical aspects. Also, it does not propose metrics that can help to make the decision or give focus on what elements to take into account when developing a sustainable business case.

Epstein's model

Epstein and Roy developed a framework that describes the drivers, actions and consequences of business cases for corporate social responsibility. They argue that understanding the relations between these aspects of the framework allow better integration of sustainability into the operational decisions as well as institutionalisation of sustainability within the company [71]. The framework they present contains constituents of both the FSSD framework and Remenyi's business case methodology. They identify five main components:

» Corporate and business unit strategy,
» Sustainability actions,
» Sustainability performance,
» Stakeholders' reactions,
» Corporate financial performance.

The framework starts with the business strategy influencing the sustainability actions and performance of the business. These three elements can be found in the FSSD methodology as well. Then Epstein argues that these actions and the performance result in a response from the various stakeholders that on its turn affect the long-term financial performance. These last two elements are aspects that are not in the FSSD methodology. However, they can be found as part of the main aspects of business cases (stakeholder and financial appraisal). The complete framework with all the drivers for a sustainable business case is depicted in figure 3–13.

Epstein also suggests various metrics for the drivers that they identified (appendix D.1). These drivers and metrics have their main focus on social and ethical aspects. The environmental aspects however, are not extensively elaborated on. Most metrics are also linked to direct impacts while externalities are not included.

Capitalised Sustainability

The fourth method to embed sustainability in the business case considers capitalisation of sustainability. This fits within the common practice of financial accounting of risks and other non-financial impacts within businesses. For example Liander does this within its risk matrix, in which it translates the various risks such as service, image and sustainability into a financial equivalent (see figure 6–7). Many other companies also translate their externalities into a financial element to include in their business case [72]. Doing this, helps to compare the various elements of their business case through a single indicator: money. However, as various scholars identify, monetary appraisal for impacts on natural and social capital is rather difficult because of theoretical and practical challenges [73–76]. For example, for indirect externalities such as smog and heating of river water there is no general available. Neither empirically defined nor agreed upon by governments or other organisations. Even so, various approaches have been developed such as the Natural Capital Approach (NCA) and TruCost [74, 77].

That monetary appraisal can benefit one's sustainability and business performance is shown by the carpet tile manufacturer Interface [78]. They are often taken as example for achieving a successful sustainable business case through natural capital accounting of their impacts. By capitalising all their environmental and social externalities, they have created an internal incentive to reduce the negative externalities of their company.

In the recent years, more organisations have started to look at implementing monetary appraisal of their environmental and social impacts. Currently the Natural Capital Coalition (NCC), consisting of companies and organisations like UNEP, WWF, Arcadis and the Coca Cola company, is trying to determine a methodology to achieve this [72, 79]. By aligning the method over several companies, they hope to create a general accepted practise and be able to compare each other's performance in a similar way.

3.3.4. Discussion

Embedding sustainability within the business currently has a focus at two levels: a more strategic level like the FSSD or Epstein's framework, or a specific business case methodology like SWARD or natural capital accounting. For this research, a more practical approach is sought. Concerning the practical implementation of sustainability into the business case, one would either choose to embed it within the current aspects, such as the financial appraisal, or by adding a separate new aspect that accounts for sustainability. In any case, metrics would be necessary to compare the impact of the investment decision scenarios. Within natural capital accounting, the metric would be financial only and may therefore seem the most practical option. However, there are currently no standards for financial valuation of the impacts, and calculation is difficult. It can even be argued that it is impossible because environmental systems cannot be substituted by technical or economical systems. In addition, damage to these environmental systems can be irreversible and thus money cannot compensate for it. Next to that capitalisation reduces the environmental and social impacts to a financial number thereby hiding the real impact for the decision maker. This could possibly lead to decisions that are financially defendable but environmentally or ethically questionable.

The SWARD model and the model developed by Epstein do suggest various indicators but do not mention specific metrics for all of them. The SWARD model is an extensive model with many indicators (appendix C.1). Resource utilisation, an important aspect of this research, is included this model, but alike the rest of the indicators focusses on water usage only and is therefore not directly suitable for an investment decision methodology for the assets of Liander. Epstein's model does not include resource utilisation at all. Therefore, more research is needed to determine what resource indicators are appropriate for an investment decision methodology for Liander.

Next to the need of transparency in procurement process as described in the previous section ( ), transparency is also becoming more important in relation to sustainability in public decision-making. The UNECE (United Nations Economic Commission for Europe) Århus Convention back in 1998 agreed on access to information, public participation in decision-making and access to justice in environmental matters. In 2003 the European Union adopted a directive that states that "public participation in the taking of decisions [...] (helps in) increasing the accountability and transparency of the decision-making process and contributing to public awareness of environmental issues and support for the decisions taken"[80]. By stimulating awareness of environmental issues by governments, one can assume that this awareness will grow beyond public decision-making and will affect decision making in non-governmental organisations. This societal force may become a non-negligible factor and best be responded to in a proactive way as the sustainability maturity pyramid claims (figure 3–9).

3.4. Conclusions

The previous paragraphs described the background of the Circular Economy, Business cases and Investment Decision methodology, and the relation between the two through Sustainable Business cases. Various conclusions can be derived from the background research and will be presented below.

Conclusions on the Circular Economy

There is currently no consistency in definition and the principles on the circular economy. Various differences can be identified that influence the definition such as the scope of implementation (micro, meso, macro), the public-private perspective (business and government) as well as the cultural perspective (Chinese or European). In combination with the literature research results as presented in paragraph 2.2 it can be concluded that literature with a European business perspective for micro level is scarce. More research is therefore necessary to develop an appropriate view on the Circular Economy from this perspective.

Looking at how the European Commission introduces the Circular Economy and the incentives for Liander to implement the Circular Economy one can conclude that within this research the scope of the Circular Economy is about resource sustainability on micro level. Practically this translates to how the Circular Economy relates to the material cycles of Liander's assets such as distribution transformers.

Conclusions on Business Cases and Investment Decisions

Within business cases, investment decision methodologies are a tool to fulfil the business goals and pursue a business that is viable on the long run. Various internal and external forces influence the viability of a business. The common forces and aspects to be included in the investment decisions are the financial situation, stakeholders, technological requirements and development, strategic alignment with the business and the possible risks that the investment decision may have. Within this study, these aspects relate to the infrastructure sector. However, they are not a generally applicable to all organisations as these organisations may be driven by different aspects and thus require a different focus.

Adding additional aspects may allow for a better forecast and a more comprehensive decision. At the same time, it increases complexity and complicates a fair, defendable and reproducible decision-making process: Bonini's paradox. For Liander this is an important element to take into consideration.

Liander currently uses a methodology that is financially and risk-centred. Embedding other aspects may help to give a more comprehensive overview but the complexity may require more time for writing and deciding upon the investment decision scenarios.

The decision making itself can be done through various approaches. The composite positivist is a method that fits within the required design of the decision methodology that Liander wants. It requires a predefined methodology with specified indicators. This helps to guideline the process and makes it understandable to the stakeholders of the decision process what the assessment criteria are. It is important however, that the chosen methodology will not be seen as an automated machine or black box that generates a single score that determines the outcome. Instead, the method should be seen to aid the process. The decision makers themselves should still deliberate upon the decision itself. The composite part of the method supports this aiding process as it creates a comprehensive overview of the various aspects on which the decision will be based. Thus, in terms of the design science methodology (2.1), the artefact to be created within this study is an investment decision aiding model.

Conclusions on Sustainability for Business Cases

As various scholars discuss there is a need to embed sustainability within the business case and investment decision methodology. Based on the sustainability maturity pyramid, the models developed by Lubin, Epstein and Pearce & Turner, one can conclude that pursuing environmental sustainability benefits financial and welfare aspects. In terms of the Triple Bottom Line, environmental sustainability therefore supports and influences economic and social sustainability.

The current available methods or methodologies to embed sustainability into the business case are not sufficient to realise the aims of this study. It needs to be a practical model with the appropriate metrics. The positivist composite decision approach as discussed in section 3.2 argues in favour of adding an extra element to the business case to account for sustainability.

Remenyi's model comes close but misses the separate sustainability factor. The model posed by Berghout and Tan also misses the sustainability element, but is a bit more complex due to the breakdown of various elements into additional aspects. SWARD is about sustainability but is very specific towards the wastewater industry. Another discussed possibility is to use environmental capital accounting. This method hides qualitative aspects of environmental sustainability as it translates it to a financial number. It also fails to comply with the design criterion of the positivist decision approach.

This means that one would want to use Remenyi's or Berghouts model as a starting point and add environmental sustainability as a separate element. SWARD, the FSSD method and Epstein's model propose various indicators and metrics to account for environmental sustainability. However, there is no coherency within these indicators and an explanation why these indicators were chosen is often missing.

Therefore, more research needs to be done to overcome the gaps in literature on what is actually meant with environmental sustainability and thus which metrics to use. Additionally, more research is required to tackle the problem of the Bonini paradox. The topic of environmental sustainability will be tackled within the next chapter. The Bonini paradox will continue to be discussed in chapter 5 in which the artefact of this study, the investment decision model, will be constructed.

3.4.1. Design Criteria

These conclusions and other findings discussed within this chapter have resulted in the following additional design criteria for the development of the investment decision methodology:

TAKE SUSTAINABILITY SEPARATE: Include environmental sustainability as a separate aspect.

AVOID BONINI: Design the model in such a way to avoid Bonini paradox.

LIMIT COMPLEXITY: Avoid complexity of sustainability within the model.

EMISSION TRADING OUT OF SCOPE: Keep the emission trading system out of the model.

METRICS: Appropriate metrics for the various constituents should be used, such that they match the common asset management scope and operations.

COMPOSITE POSITIVIST APPROACH: Use a composite decision making approach in a positivist application.

DECISION AIDING: The developed model should be decision aiding, not determine the decision.

4. Theoretical Framework

The previous chapter introduced the background on the Circular Economy, investment decision methodology and Sustainable Business Cases. Some gaps in literature were identified that are relevant for this study, especially considering the indicators for environmental sustainability. This chapter will develop a theoretical framework that describes these indicators. This framework will be used in the next chapter in which the model for a sustainable business case will be developed.

Outline Framework Chapter

As requested by Liander, part of this research is about how the Circular Economy can be embedded as sustainability paradigm. Therefore, the first section of this chapter will investigate how the Circular Economy paradigm can be translated into environmental sustainability. After that, this definition of environmental sustainability will be discussed and metrics will be proposed. The chapter will end with a discussion and conclusions on the developed theoretical framework.

Scope

The final aim of this theoretical framework is that it can be embedded into the investment decision methodology. It should therefore result in appropriate investment decision indicators and metrics without too much complexity. Within the theoretical framework, the focus is on environmental sustainability in relation to the Circular Economy. Other forms of sustainability like economic and social will be briefly mentioned but are not of main concern within this thesis, as there are plentiful of other methods available that account for them.

4.1. Circular Economy as part of Environmental Sustainability

As discussed in chapter 3.1, Circular Economy evolves from the notion that there is material scarcity on the Earth and that by becoming more efficient with material resources there may be economical and social benefits for the business. However, consistency on is lacking on the actual definition and principles of the circular economy. Especially in reports from western organisations, various *Key Performance Indicators* (KPI) or other metrics are mentioned, but they lack an explanation where these indicators originate. To get an overview of the indicator sets found during the research a comparison has been made. Table 4–1 shows this overview. Each of these indicator sets are discussed by scholars or applied in tools being marketed by various organisations. All of these sets try to support the Circular Economy or paradigms to which the Circular Economy is closely related.

When summarising these indicator sets they can be categorised into two groups. Approaches like Schoolderman, NDRC and Geng look at drivers considering material flows in relation to economic output, consumption and emissions. The second group with Bastein, Circle Scan and the Cradle-to-Cradle product standard, has a more holistic approach that includes social impact, energy and material usage as well as emissions. However, economic output is not always taken into account.

Table 4 — 1 Indicators per scholar, method or tool. In case of multiple levels of indicators the top level (drivers) are indicated. A complete overview can be found in Appendix C.

Author or method	Topic	Scope	Indicators / drivers
Bastein *et al.* [32]	Environmental impacts of increased circularity in metal and electrical sectors.	Micro (product)	1. CO_2 Emissions 2. Use of Freshwater 3. Land use (ecological footprint) 4. Raw Material Equivalent
Circular Scorecard [81]	A scoring method to determine in which fields a product can be optimised.	Micro (product/ project)	1. Energy 2. Materials 3. Ecosystems 4. Culture and Society 5. Value Generation
Circularity Calculator (EMA) [34]	Economic impact based on relative indicators of linear versus circular product, measured in dollars.	Meso (Industry)	1. Material inputs 2. Labour inputs 3. Energy inputs 4. Carbon emissions 5. Balance of trade
Cradle to Cradle [82]	Product Standard 2013 for Cradle-to-Cradle certification.	Micro (product)	1. Renewable Energy and Carbon Management 2. Water stewardship 3. Material Reutilisation 4. Material Health 5. Social Fairness
CSR Performance Ladder [83]	Performance ladder measures the performance of a company on corporate social responsibility.	Micro (company)	1. Working conditions 2. Human rights 3. Fair business 4. Consumer Affairs 5. Environment, resources, energy, emissions 6. Involvement development society
Geng *et al.* [84]	Indicator system at meso and macro level	Macro and meso	1. Resource output rate 2. Resource consumption rate 3. Integrated resource utilisation rate 4. Waste disposal and pollutant emission
MEP indicator system [29]**a**	Indicator system by the Chinese Ministry of Environmental protection.	Meso	1. Economic development 2. Material reduction and recycling 3. Pollution control 4. Administration and management
NDRC indicator system [29]**b**	Indicator system by the Chinese National Development and Reform Commission.	Meso (region)	1. Resource output rate 2. Resource consumption 3. Integrated resource utilisation 4. Reduction in waste generation
Resource Passport, Damen, M.A., [85]	Method to keep track of all related product information across its life cycle.	Micro (product)	1. General Scarcity information 2. Mining information 3. Product information 4. Company information 5. Technology information
Schoolderman *et al.* [19]	KPI's for businesses, value creation. Economically driven.	Micro (company)	1. Short cycles (repair, reuse, recycle) 2. Long cycles (life cycle, consecutive cycles) 3. Cascades 4. Pure heterogeneous cycles

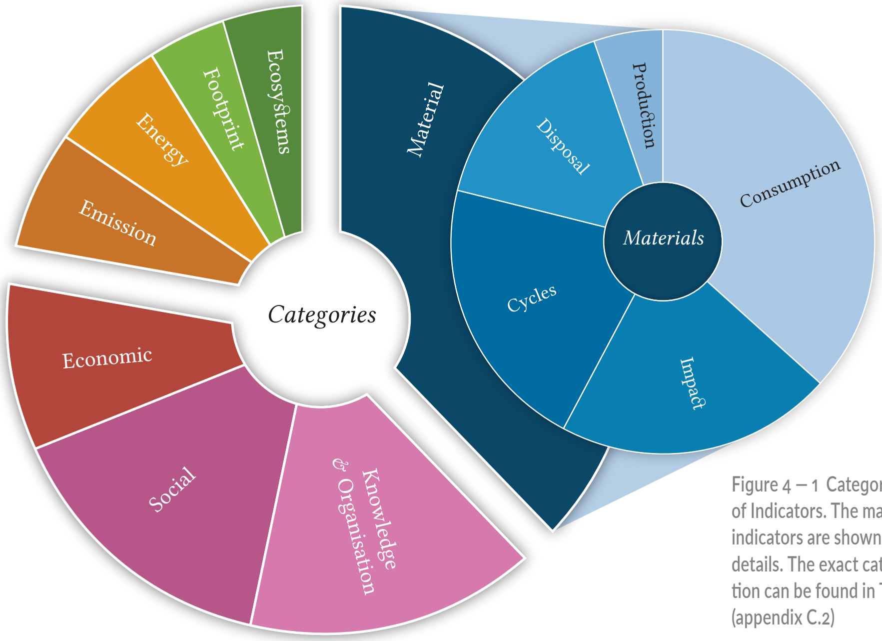


Figure 4 – 1 Categorisation of Indicators. The material indicators are shown in more details. The exact categorisation can be found in Table 11–5 (appendix C.2)

4.1.1. Categorising the Indicator Sets

The indicator sets of table 4–1 can be further analysed through keyword categorisation. This is done through conceptual grouping. The indicators that describe the same purpose or benefit a similar goal are grouped together. This was done through the following categorisation procedure. First, the meaning and scope of the indicators is investigated. The least detailed, but distinct indicators are taken separate. These form the initial conceptual groups. The other indicators are then added to the groups within which scope they fit. The remaining indicators are set as separate group or taken together in a remainder group.

Figure 4–1 shows the results from this categorisation. There are eight main categories identified of which the *materials* category accounts 37% of the indicators. The other categories that consider environmental aspects are the *ecosystem*, *footprint*, *energy* and *emission* categories. All together they account for more than 50% of the indicators found in literature. The three remaining categories (*economic*, *social* and *knowledge & organisation*) are not describing environmental aspects but can be found within other business case constituents such as the financial, stakeholder and risk appraisal.

The *materials* category can be subdivided in five categories: material *consumption*, material *loops*, material *impact*, *disposal* of materials and material *production*. When analysing these five categories various observations can be made. For example, the three phases of material life cycle are separately present: *production*, *consumption* and *disposal*. The material *impacts* consider the impact on consumption and disposal while the material *loops* category is related to all three. It overarches the life cycle and is more of a descriptor of how material flows can look like.

This analysis supports the conclusion that material usage is an important indicator within literature on the Circular Economy. Further support is found in the other categories in which derivatives of the material category are found such as information on material health or mining information. These were not shared under the main materials category, as they did not consider the physical processing of materials.

4.1.2. Category Evaluation

When looking at the environmental categories and how they relate to each other, the following analysis of each category can be made. The analysis will have a focus towards a comprehensive framework for sustainability with the aim of embedding it in the investment decision model. First, the four environmental categories will be briefly discussed, after which the *Materials* category will be focussed on.

Energy and Emissions

The *Energy* and *Emissions* category are often closely related. Often, energy usage causes a large part of the emissions due to the use of non-renewable energy sources. Probably for this reason, these categories are interchangeably used within the

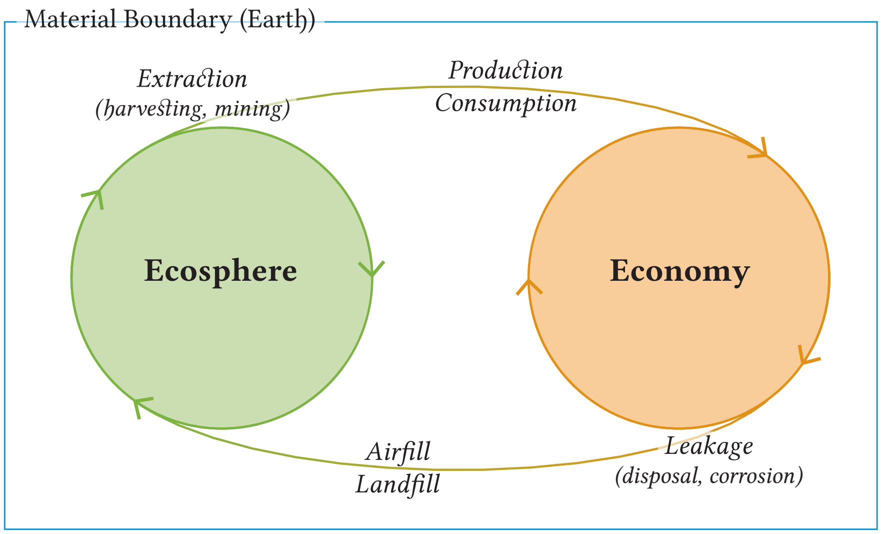


Figure 4 – 2 Material exchange between the ecosphere and the economy. In nature, the material has a certain ecological value. The value is taken out of nature and translated into economic value.

indicator sets. Within Liander this also holds true for a large part: the energy losses in the grid account for 90% of Liander's CO_2 emissions [15]. This focus on emissions is largely motivated by governmental policies to reduce the CO_2 emissions. Therefore, companies often report on their CO_2 footprint. However, energy usage from non-renewable sources does not only influence the emissions but also affects the material usage. For the production of this type of energy, a lot of gas, coal and oil are used. This irreversibly reduces the global stock, increasing the scarcity of those resources.

When looking at energy usage from renewable sources, material and energy are only used during production, maintenance, disposal and to build the necessary infrastructure. Consequently, there is no variable amount of CO_2 emissions during production phase; sun, water and wind are always present. Since energy usage can be accounted for within a carbon footprint (see next section) and material usage, it would remove an extra indicator to evaluate the sustainability performance benefiting the research aim of reducing complexity within assessments.

Footprint

The term environmental footprint often represents the amount of space a person or company needs. In general, it can account for two different things: the demand on the *biocapacity of the Earth* and the *ecological footprint*. The biocapacity is the Earth's biologically productive area (available stock) such as water and land, while the ecological footprint indicates the Earth's area required to generate renewable resources and act as sink for waste [86]. The ecological footprint is similar to the assimilative or carrying capacity defined by Pearce and Turner [30]. Important is that a footprint is measured in the relation to the Earth. One could then hypothetically calculate how many Earths are necessary if everyone would live in a similar way.

Companies generally refer to the carbon footprint in their environmental reporting. Actually, the carbon footprint is a measure of the demand on the Earth by burning fossil fuels [87]. The current systematically increasing greenhouse gas (GHG) emissions [88] affect the carrying capacity of the Earth. However, CO_2 as greenhouse gas is also assumed to have a secondary effect on global warming. These effects are estimated to have far larger consequences than affecting carrying capacity [88]. It can therefore be argued that the carbon footprint can be better accounted for as a secondary environmental impact than within footprint category. This will be further discussed in the next section on identification of the key indicators.

Ecosystems

The fourth category considers the *Ecosystems*. Ecosystems are important interacting systems within the environment that sustain life. They use non-living elements such as minerals as resource and can regenerate these resources so that the ecosystem can last to exist. External impacts (externalities) can disrupt this system causing problems in regeneration of resources and finally inhibiting the continuation of life. Examples of disruptions are temperature changes due to global warming, toxic waste or eutrophication. Tools such as Life Cycle Assessments (LCA) can help to determine the impact on Ecosystems.

Material Resources

The material resource category, as broken down in the smaller chart, contains indicators on the entire life cycle of materials. These indicators consider the impact during mining, processing, usage, disposal and recycling, both from an economic and ecological perspective. Even though these indicator sets are very extensive, companies do not tend to report that extensively on their resource usage other than the financial appraisal of assets, stock or other invested capital. Liander has started to report on their material usage in 2013 but only focussed so far on waste disposal [15]. Their aim is to add the incoming flow of materials to their reporting, as well as the actual impact of material usage throughout the supply chain.

Holistic perspective on material usage

The use of material resources may affect various environmental aspects. Before raw materials have an economic value, they are present in the Earth's ecospheres (hydrosphere, lithosphere, atmosphere and biosphere) and may have a specific function there. For example phosphorous may support local ecosystems. Once extracted from nature, the materials will substitute their ecological value for economic value. This process may cause ecological scarcity of that material, possibly disrupting the ecosystem where it was extracted. However, ecological scarcity also influences the value of the material within the economy: if demand is higher than supply the price will rise.

Once the material has entered the economy, it may perform a certain function as long as it holds its value. This value may reduce because the material deteriorates or the demand reduces. This may lead to disposal of the material from the economy back into the ecosphere. Another option is recycling or upcycling. This may renew the value of the material such that it stays useful within the economy. During the life span that the material is in the economy, it may slowly leak back into the ecosphere. In case the disposal or leakage considers material for which the ecosphere does not have the carrying capacity to process them easily, the ecosphere acts as a sink for these materials. This is for example the case for various types of plastics but also too much CO_2 emissions. In case the material is of a characteristic that the ecosphere can process, the ecosphere may help to regenerate the resources that were extracted before. Figure 4–2 shows the model that has been developed to show this process and hence the relationship between materials, the ecosphere and the economy.

4.2. Identification of Key Indicators for Sustainability

Based on an analysis of the Circular Economy paradigm in the previous section, five main categories were identified that relate to sustainability: energy, emissions, footprint, ecosystems and materials. As indicated the energy and emissions category can be accounted for by the other three. This would help to create an additional business case constituent that can be described simply with just three indicators.

The question is whether these three remaining categories (footprint, ecosystems and materials) can account for environmental sustainability in a comprehensive way without overlooking important forces or externalities. Figure 4–3 is an abstract model that has been developed which tries to show that by putting these three elements in relation to one another they can achieve this goal.

The resources within this model are the building blocks of the economy and affect the environment in three ways. These are the three

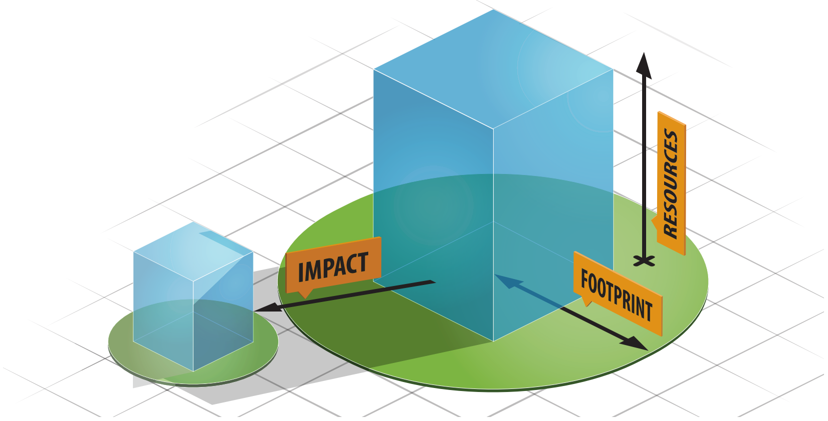


Figure 4 – 3 Abstract depiction of three elements of environmental sustainability: The resource usage (building blocks), the footprint of the product (the required space), and the impact (the shadow it casts on other objects).

proposed key indicators for environmental sustainability based upon the Circular Economy paradigm:

1. Material usage: The quantitative effect on global *stock* of materials (stock within ecosphere and economy);
2. Ecological Footprint: The quantitative effect on the global *capacity* to generate new materials and act as sink (fisheries, forests, land, water and air);
3. Environmental Impact: A qualitative effect of economic activity on other elements in the environment such as the ecosystems.

One could argue that the footprint could account for resource usage as well because of its subtractability characteristic . However, within this research it has been chosen to keep the materials, being building blocks of the economy, separate from the footprint as they can account for distinct regimes. These are the current *stock* and the regenerative *capacity*. Hence, it reduces the complexity and creates different incentives for a sustainable business case.

The *material usage* accounts for resources that can be categorised as private goods since extraction of these goods is rivalrous and exclusion is feasible [89, 90]. This is because people can generally not easily extract them from the ecosphere and hence processing them is restricted to those that have the knowledge and tools to do so. Since they are private goods, their economic value is market dependent and usage is more economically motivated.

1. Subtractability is a characteristic of goods used within the characterisation of goods by Elinor Ostrom. It indicates the that the consumption of a good by a person affects the total available to others [90].

The *footprint* also focusses on the use of resources that fulfil a certain ecological function. Exclusion is not feasible for these non-private goods. In comparison with *material usage*, these resources are more abstract considering their physicality. However, their availability to the ecosphere can be decreased. Generally these are called common pool goods and public goods [89, 90].

Both the material usage and the footprint are a quantitative measure, the *impact* indicator is however a qualitative measure. It may affect the stock of the various resources not immediately, but affects its functioning or quality in the longer run. These can be effects caused by global warming, eutrophication, radiation, etc. The effects of these impacts are generally accepted to be negative but their exact effect is difficult to pinpoint and measure.

$$RS = \left(\frac{\left(\begin{matrix} \textit{\% of the product considered} \\ \textit{recyclable or compostable} \end{matrix} \cdot 2 \right) + \left(\begin{matrix} \textit{\% of recycled or rapidly renewable} \\ \textit{content in the product} \end{matrix} \right)}{3} \right) \cdot 100$$

(4.1) Reutilisation Score by the Cradle to Cradle [82]. The left side of the numerator considers the potential waste produced over the entire life cycle. The right side considers the materials used for the product.

4.3. Measuring the Key Indicators

To use these three indicators for the environmental sustainability constituent of an investment decision, there is a need for corresponding metrics such that they can be evaluated. These metrics maybe of a qualitative or quantitative nature, as long as assessment is coherent and practical.

To determine the footprint and the impact indicator various methods are already available. Within businesses, Life Cycle Assessments and Footprint calculations are commonly used. For material usage, this is not so evident. There are various indicators found that account for material usage but there is no clear common ground amongst them. As discussed in section 4.1.1 they can be subdivided in five distinct groups (*consumption*, *loops*, *impact*, *disposal* and *production*). Ideally, these should be combined into a single overarching indicator.

To suggest an appropriate assessment method for material usage from a Circular Economy perspective more research needs to be done. This will be further discussed in the following paragraph.

4.3.1. Defining the Resources Indicator

A secondary literature review has been performed as starting point for identifying possible metrics for resource usage. The literature research framework can be found in section 2.2. It resulted in 273 articles on material and resource accounting. The analysis of these articles resulted in various methods and tools such as material flow analyses, reutilisation scores and eco-efficiency calculations (Appendix E.3 and E.4).

Common tools that are discussed are material flow analyses (MFA). An MFA is a comprehensive method that maps out the material flow through the economic value chain, sometimes in relation to the ecosphere. Its advantage is its comprehensive overview on meso or macro level, but does not give a measurement on the business' performance considering material usage. Methods like the comprehensive reutilisation score [91] are derived from an MFA and have been proposed for application within Circular Economy in China, but are rather complicated to evaluate.

A method that can indicate a company's performance on material usage is the Cradle-to-Cradle reutilisation score. It takes into account the inflowing and outflowing materials, and hence creates the incentive for the company to act responsible to both sides of its supply chain. The score is biased as it values the outflowing materials twice the inflowing materials. Besides, it does not account for the material impact category as identified in previous section. This would be about valuing material accumulation and scarcity.

Even though the reutilisation score may not cover the Circular Economy paradigm fully considering material usage, it can be considered a relatively simple and understandable metric. It aims to incentivise eco-effectiveness towards the producer of that product.

4.3.2. Application of Indicators of Liander

Liander's current approach to sustainability focusses on the carbon footprint. As discussed in paragraph 4.1.2 the carbon footprint can better be shared under the impact indicator. Liander would therefore already have a partial evaluation of their environmental sustainability of their business cases.

Next to that, Liander has executed several LCA's for various assets (for example assets containing SF_6 gas) and is currently investigating whether these assessments should be used more often. It would be beneficial for a more comprehensive evaluation of the environmental impact indicator, but depending on the actual LCA method chosen, it may be a labour intensive method in relation to smaller investment decisions.

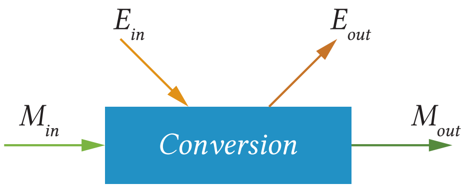
The ecological footprint indicator is an indicator that Liander is currently not assessing. Since their business revolves around infrastructure in and on land, it will leave a certain footprint on various ecosystems. It may therefore be a useful tool to extend their environmental assessment.

The material use indicator is an indicator that is closely related to the Circular Economy paradigm that Liander is currently focussing on. Within various tenders, they are looking to embed principles of the Circular Economy. To further secure these aims the next step would be to include this indicator within their business cases and hence investment decisions.

4.4. Discussion

The focus of this theoretical framework is to determine indicators and metrics for environmental sustainability based on the Circular Economy paradigm. It can be argued that, especially because of the lack of scientific papers on the principle of the Circular Economy, a different approach would have resulted in different indicators.

Figure 4 – 4 Material conversion as finite element approach to material value chain analysis.



The C value is a multiplication of the ratio of resourceful incoming materials, and resourceful outflowing materials. Resourceful incoming materials are defined as the amount of materials of recycled or non-scarce virgin source. Resourceful outflowing materials are defined as the amount of materials that are recyclable and that do not accumulate on the long term in either economy or ecosphere. These flows should be evaluated over the entire life cycle of that specific material. Hence, the ratio based on the total 'turnover' of materials in the process.

(4.2) Initial developed metric for Circular Economy; with C = circular value; m = mass of material, r = recycling contents; v = virgin material content; S = scarcity factor; r_{pot} = recycling potential and A =accumulation factor.

$$C = \frac{\sum_{material} m_{in} \left(r + v \cdot (1 - S) \right) \times \sum_{material} m_{out}\, r_{pot} \left(1 - A\right)}{{m_{tot_{in}}}^2}$$

4.4.1. Material Usage Metric

The proposed material usage metric (Equation 4–1, reutilisation score) is, as discussed before, not optimal. It is relatively biased as it favours outflowing material over incoming materials. Next to that, it does not cover all the commonly accepted principles of the Circular Economy (appendix E.2) such as recycling level.

For this reason an initial proposal for a more comprehensive metric has been developed. This metric is not directly based upon a comprehensive material flow analysis as most tools or methods are, but on a finite element method approach. The overall value chain of a material is broken down into finite elements to remove the complexity such as feedback loops, recycling level and other aspects within value chains and flow analyses. The single model element (figure 4–4) that was defined for this approach is a dynamic element in which material is converted from one form to another with the help of energy. A full explanation can be found in Appendix F.

From this finite element method, a few conclusions can be drawn about the generally accepted principles of the Circular Economy from an environmental perspective:

» Based on material or energy usage, there is no general premise that indicates which level of recycling (XR) is better .

2. SF6 gas (Sulfur Hexafluoride) is an electric insulating gas often applied in electricity distribution assets. It is however considered a very strong greenhouse gas, much more potent than CO2.

3. It depends very much on the type of material whether reuse would be preferred over refurbishment or recycling. In some cases certain levels of recycling would require a lot

» Energy usage can be approached as material usage. Preservation of materials is the most important within a closed system. This is with the notion that preserved material may not accumulate in either the ecosphere or economy (see figure 4–2) and scarcity in either of the two should be prevented.

Materials that are downgraded during recycling will ultimately accumulate and hence lose their economic and potentially ecological value.

From these conclusions, a metric has been developed (Equation 4–1) that is a ratio between the inflowing and outflowing materials but values them according to their type (virgin or recycled content) and their recycling and accumulation potential.

This metric is however, an initial proposal to measure circular value and act as material usage indicator. Further verification and evaluation of this metric through case studies is needed. A first evaluation of the metric has been done for the case study within this study.

4.5. Conclusions

Analysis of current literature on the Circular Economy resulted in many different indicators that are currently being used to determine an organisation's performance on the Circular Economy. In general the largest group of indicators described material usage, while other indicators either described other environmental aspects (for example ecosystems), social aspects, economic performance, or preconditions such as knowledge. That many indicators also account for social aspects is in line with one of the first models of a Circular Economy by Pearce and Turner. They showed that material management has an effect on social welfare.

The number of perspectives on Circular Economy that include material usage as indicator supports the perception that it is a key element of the Circular Economy paradigm. Incorporation of material usage is in most cases based on the awareness of the increasing material scarcity. Again in line with the ideas of Pearce and Turner [30].

of energy to achieve this, while a lower level of recycling would require less energy. For example gypsum is very brittle and is therefore easier to recycle than to reuse.

The theoretical framework resulted in three key indicators that describe environmental sustainability from a Circular Economy perspective. These are the following three indicators:

- Material usage,
- Ecological footprint,
- Environmental impact.

Many companies that already execute LCA assessments or calculate their carbon footprint can use this for evaluation of the environmental impact indicator. For ecological footprint, footprint calculations can be made. For material usage, it is proposed to use the Cradle-to-Cradle reutilisation score. More research on a metric that also accounts for material accumulation and scarcity is suggested.

4.5.1. Design Criteria

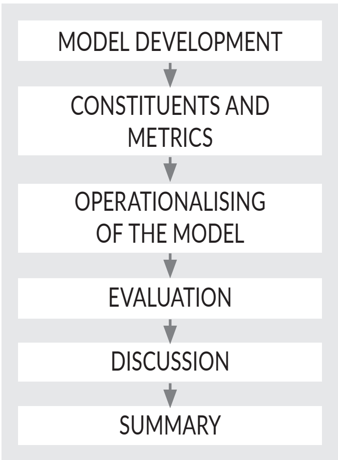
The final additions to the list of design criteria are the following criteria based on the theoretical framework:

MATERIAL USAGE: Account for material usage in the environmental sustainability constituent.

ECOLOGICAL FOOTPRINT: Account for the ecological footprint in the environmental sustainability constituent.

ENVIRONMENTAL IMPACT: Account for environmental impact in the environmental sustainability constituent.

5. Conceptual Model for a Sustainable Investment Decision Methodology



Outline Model Development Chapter

This chapter will introduce a conceptual model for a sustainable investment decision aiding (SIDA) methodology. The model will be based upon the design criteria that have been identified throughout the research and include the sustainability component as described in the theoretical framework in chapter 4. After the conceptual model is introduced, an operationalised version of this model is proposed. In the discussion of this chapter, the models will be evaluated based on the design criteria.

Scope

The scope of the model concerns the holistic approach of a sustainable business case as previously discussed in section 3.1.1. The model will however have a focus on sustainability based on the framework from previous chapter. This is because of the novelty of this element within business cases and the subsequent decision methodology. The other aspects of the model (such as financial, strategy and risks) will be discussed but area suggestion of how they can be applied. In the end, the decision maker is free to choose or adjust the indicators according to the situation.

5.1. Development of the Conceptual Sustainable Investment Decision Aiding Model

The conceptual model that has been developed throughout this research is an expansion of already existing business case models by incorporating sustainability. The incorporation of sustainability as well as other characteristics in the final model is based upon various design criteria. These design criteria have been identified throughout study. They are based upon literature research, meetings with various stakeholders and experts, the case study (chapter 6), and through iterated development of the actual model. The complete list can be found in Appendix G.

One of the criteria resulting from section 3.2 is that the developed model should be a composite positivist model that guides the decision process by making the assessment criteria clear and understandable. Next to that, it should aid the decision makers in their final judgement. Combining this with the sustainability element, the developed model is a Sustainable Investment Decision Aiding (SIDA) model.

5.1.1. Basis of the Conceptual Model

To develop the conceptual SIDA model the research focussed on existing models and how they can be used as template to be expanded with sustainability. The most important selection criterion for these models is that they are closely related to the infrastructure sector to accommodate for the specific characteristics that also apply to Liander's assets. Secondly, the model should already contain constituents that account for the general elements for a financial and social sustainable business case. Examples are financial appraisal and stakeholder appraisal.

To select the basic constituents as template for the model, a comparison is made between six different models. Table 5–1 Selected frameworks with their main constituents shows these six selected methods. Four of these models have been discussed before in chapter 3. In addition, two models relevant for Liander have been included in this analysis. These are the investment decision model as discussed section 3.2.4, and the TECK methodology. Liander currently implements this methodology in their asset life cycle planning. Even though this methodology does not consider the actual business case or investment decision models, it does align with the long-term aim of making decisions considering the asset population. For example, the life cycle plan can be seen as a strategic document that may lead to the decision to make new investments. The TECK methodology itself gives a specific interpretation to the life cycle plan through the aspects that it looks at. These are technology, economy, compliancy and commercial [60].

When evaluating the various methods from table 5–1, there are some noteworthy similarities and differences. Most frameworks consist of four or five constituents, while the framework that Berghout proposes constitutes of three categories with a total of nine constituents. In line with the design criteria, one would want to select a framework that has a limited number of constituents to avoid making the decision process overly-complex. On the other hand, too much simplification causes multiple aspects to be reduced to a single indicator, increasing the possibility of bias and inappropriate representation of these

Table 5 – 1 Selected frameworks with their main constituents

Remenyi [55]	**Berghout** [51]	**SWARD** [47]	**Epstein** [71]	**TECK** [60]	**Liander**
◦ Financial ◦ Strategy ◦ Stakeholders ◦ Technology ◦ Risk	◦ Business case objectives ◦ Benefits appraisal ◦ Consolidation ◦ Technological requirements ◦ Supplier options ◦ Project planning ◦ Cost estimates ◦ Risk assessment ◦ Stakeholders	◦ Economic ◦ Environmental ◦ Social ◦ Technical	◦ Strategic ◦ Sustainability actions ◦ Sustainability performance ◦ Stakeholders ◦ Financial	◦ Technical ◦ Economic ◦ Compliance ◦ Commercial	◦ Risks ◦ Financial ◦ Technical ◦ Strategic ◦ Custom

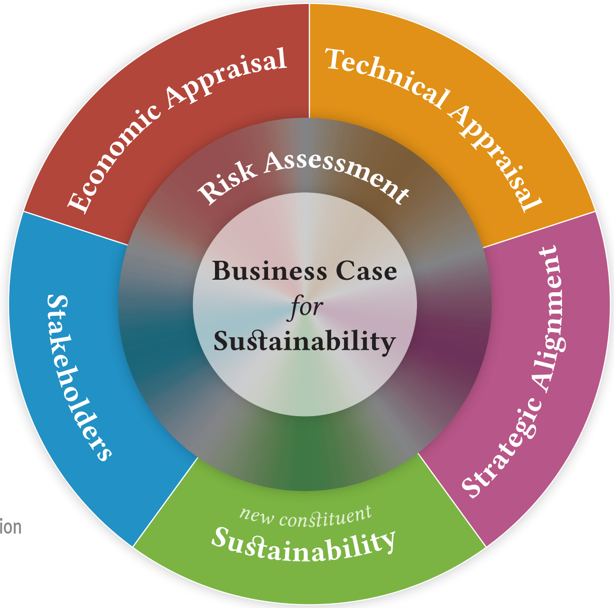


Figure 5 – 1 Conceptual Sustainable Investment Decision Aiding Model with the six constituents.

aspects. A balance should therefore be found within the number of constituents and the scope they describe.

More noteworthy observations are discussed below. Those discussed were selected to be included in the investment decision model. The remaining constituents, which have not been included, are *consolidation*, *project planning*, *sustainability action* and *custom*. These were found to be superfluous or complicating the model.

Basic Constituents: Financial, Technical and Stakeholders

Clearly, the financial, technical and stakeholder elements are important factors throughout the selected frameworks and will therefore be part of the conceptual model. Especially because these three elements account for important and distinct scopes of the business. The financial appreciation considers the business outcomes as Remenyi and Berghout call it. The technical appreciation considers the functional, physical and operational requirements and demands. The stakeholder constituent considers the various levels of direct and indirect stakeholders involved in the project. These may be colleagues, supply chain partners, institutions and citizens.

SWARD, TECK and Liander's method do not explicitly account for stakeholders, but within the SWARD methodology the social constituent can account for stakeholder appreciation, and within the TECK method the compliance can account for the stakeholder perspective. Liander values their interdependency on stakeholders generally implicitly within decision proposals.

Strategic Appreciation

The strategic element of the business is mentioned in three frameworks. Within the business case, it is important to focus on both the short and long-term business goals. Profit maximisation is often a short-term goal, but on the long-term, a company wants to stay financially stable, create valuable collaborations with stakeholders, and may also want to focus on research and development, increased market share, social impact or sustainability. To achieve these goals a strategy is

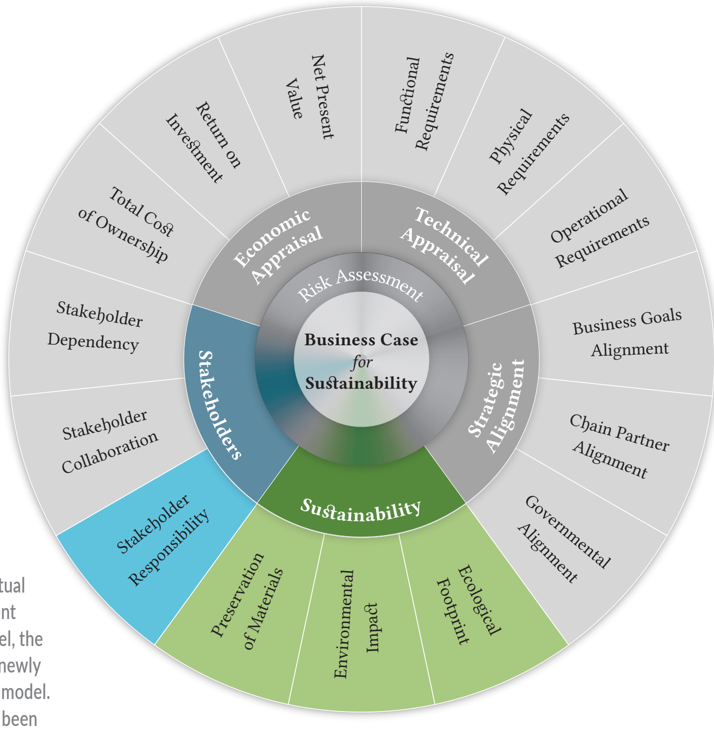


Figure 5 – 2 Conceptual Sustainable Investment Decision Aiding Model, the green blocks are the newly added aspects to the model. The blue blocks have been slightly adjusted to account for social sustainability.

necessary, especially because small changes in the market, technical complications or other short-term forces may cause decisions that undermine the long-term goals. Therefore embedding strategic appreciation within the investment decision helps to keep a company on track. Especially for factors that work by the virtue of a stable environment such as sustainability, strategic alignment is important. Strategic alignment helps to create this stable environment as changes can be forecasted more easily. The change can than be anticipated upon by adjusting to or diverting it.

Risks Appreciation

For the infrastructure sector, and especially the energy utilities, risk management is very important. The risks that are often valued relate to technical certainty, safety and finances. Within Remenyi's framework for example, the risks are appraised upon the other four constituents, making the risk constituent stand somewhat apart from the rest. Liander's current model can be seen in a similar way. The risk evaluation is based upon various indicators such as quality, finances and safety [92]. To align the conceptual model with literature and current practices, the risk appraisal will be done upon the other constituents of the model.

Appreciation of Sustainability

Appreciation of sustainability within the business case is the new dimension to be added to the model. Of the three main levels of sustainability[1], economic sustainability is already accounted for in the financial constituent. Social sustainability can be accounted for within the stakeholder constituent through the form or responsibility.

Considering the third level of environmental sustainability, a new constituent will be added to the model based on the framework from chapter 4. This will result in a model that can create a balanced but comprehensive overview of the various constituents. Environmental sustainability will therefore be the sixth constituent of the conceptual model:

- Technical appraisal,
- Financial appraisal,
- Stakeholders,
- Strategic alignment,
- Risk assessment,
- Environmental Sustainability.

The risk assessment is unlike the other constituents not a constituent that has its distinct scope but builds on top of the other constituents. In other words, for each constituent the risks are assessed resulting in a comprehensive risk analysis of the case. Figure 5–1 depicts this model.

1. Environmental, social and economic sustainability based upon Elkington's Triple Bottom Line (people, planet, profit) [8].

5.2. Conceptual Model Constituents and Metrics

The six proposed constituents as discussed in the previous paragraph have a lot in common with the already existing frameworks. However, two differences with typical frameworks such as Remenyi's are the addition of sustainability constituent and the extension of the stakeholder constituent with a social factor. The focus has been on the environmental sustainability constituent based on the theoretical framework from chapter 4. For all other constituents a selection of three common indicators is suggested. Other business case models such as Remenyi's also use these indicators. In case these are not appropriate for a certain application, they can be adjusted.

5.2.1. Newly Added Constituents and Metrics

Next to the sustainability constituent, a specific social element has been included in the model. This is done based on the design criteria and explicit aim of Liander to consider social impact. The definition of each constituent and their indicators are described below. Figure 5–2 shows the conceptual model of the SIDA methodology, including the indicators per constituent. The newly added elements are shown in colour and will be discussed in this section.

a) Environmental Sustainability

The sustainability constituent is based on the framework developed in chapter 4. This paragraph is a short recapitulation of the results from this framework and how they are applied to the SIDA model.

The sustainability constituent accounts for environmental sustainability in a way that many companies already use in their annual reports but have not yet embedded in their business cases. For example, the Dutch Railways won in 2014 various prices to be one of the first to do this [93, 94]. In most annual reports, the ecological footprint and environmental impact are referred to. To be able to govern these environmental aspects better they are also part of the model for sustainable investment decisions. Next to these two elements, the model also includes a third indicator: preservation of materials, which is mainly derived from the Circular Economy paradigm. The other constituents represent other forms of sustainability such as financial and social sustainability.

Preservation of Materials

The minimum sustainable trend possible is to keep the current amount of materials available in relation to the demand. This prevents resources from becoming scarce. To measure this indicator one should look at the prevention of material loss throughout the entire life cycle. Loss of materials means a loss of building blocks and hence of value for both economy and ecosphere. Loss can therefore be seen as the destruction of materials, for example through incineration or through decay, or by the transformation of materials into a state in which they will not have any value for either economy or ecosphere anymore. A method to measure the preservation of materials, or the inverse prevention of materials loss, is by means of the reuse potential [95] (see appendix E.3). It identifies future potential of the resources within the various cycles. A metric that overarches the lifecycle of materials is the Cradle-to-Cradle reutilisation score (equation 4–1).

Ecological Footprint

The footprint indicates the amount of resources needed that are not consumed but used only. Examples are land, water and air use. This usage reduces the amount of unoccupied resources causing a reduction of the regenerative and assimilative capacity. These do not always have an immediate economic value attached to them or cannot be easily measured using the reuse potential. For these resources, a better measurement would be footprint measurements: how many Earths we need if everyone would require the same amount.

Environmental Impact

The environmental impact indicator accounts for externalities influencing the health of the environment. It does not consider the use or reuse of resources as the first two indicators within the sustainability constituent cover these. The externalities are often secondary or lower level effects that can be tangible or intangible. Examples are global warming, eutrophication or acidification affecting ecosystems.

A way to measure the environmental impact is the usage of life cycle assessments (LCAs) [96]. This is a tool that can be seen as a more qualitative measure as it gives a relative result instead of an absolute number. It is therefore also important to use the same LCA methodology for each of the alternatives that are being assessed within a single study.

b) Stakeholders

In favour of including a social factor in the SIDA model, the stakeholder constituent has been slightly adjusted by adding an additional indicator. The complete constituent now considers all impacts, dependencies and effects that the organisation has on its stakeholders and vice versa.

In particular, this constituent considers all internal and external stakeholders such as employees and citizens, as well as public and private stakeholders such as governments and supply chain companies. The adjustment of this constituent in relation to the current models is the addition of social responsibility. The social impacts of one's investment are increasingly becoming more important throughout various sectors. Within the infrastructure sector, this element is often postulated but has not yet been included in models. An example is nuisance towards local residents. This adjustment is now accounted for within the stakeholder constituent under the stakeholder responsibility indicator.

Stakeholder Responsibility

The first indicator of the stakeholder constituent considers the responsibility of the organisation towards the stakeholder, and has been added based on social sustainability. It includes the dependency of the stakeholder on the organisation but also on which (social) externalities the investment decision may pose on the stakeholder. An example is social responsibility towards citizens being influenced by positive and negative externalities such as job creation, health or social inclusion. Social responsibility is a complex topic on its own. To determine appropriate metrics additional research would be required. Since it does not fit within the scope of this study it is suggested to use the indicators posed by a different framework such as FSSD [97].

5.2.2. General Indicators and Metrics

Besides the newly added indicators, the SIDA model still encompasses other constituents that have not been thoroughly investigated and changed within this study. Therefore the following indicators and metrics will be similar to the indicators found in the models previously discussed in this thesis. The selected indicators are representative for their constituent but can be adjusted if necessary.

a) Stakeholders

Next to the stakeholder responsibility discussed in the paragraph before, the stakeholder appraisal should also account for other levels of stakeholder involvement. Examples are the criticality of dependency and the collaboration between the stakeholders.

Stakeholder Dependency

Commonly valued within business cases are stakeholder dependencies and collaboration. The stakeholder dependency indicates how dependent the organisation is on a specific stakeholder and hence on its supply chain. Being dependent is not per se negative. It may in certain cases. Therefore, this indicator should be evaluated in combination with the criticality of the stakeholder. In case of critical stakeholders on which the organisation is dependent, for example because there are no possible alternatives, this should be a point of attention in the decision making process. Especially in case the stakeholder is in a relative volatile environment such as a foreign country with which there are not well-established relationships, it may require extra care.

Stakeholder Collaboration

The third indicator for the stakeholder constituent considers the quality and intensity of collaboration between the organisation and its stakeholder. Good stakeholder collaboration is important for the possible need to resolve issues during the lifetime of an asset. To enable incremental development of the supplies and services, effective stakeholder collaboration is also a prerequisite. This will allow for increased technical performance, higher returns or other secondary effects on the various other constituents. The quality of collaboration can be assessed in the form of ease of access, openness, willingness to share information, amount of dialogue, and the mutual trust.

b) Economic Appraisal

The economic appraisal is maybe one of the more important constituents. Without a viable financial result, the business would cease to exist on the long run. The economic appraisal or the business outcome as Remenyi defines it [55], consists often of traditional capital accounting methods. Within IT the most common are the Return on Investment (ROI), Payback period, Internal Rate of Return (IRR) and Economic Value Added (EVA) [98]. However from an asset management perspective there are often other elements included such as the Decreased Costs, Increased Productivity and Total Cost of Ownership (TCO) [98]. The indicators proposed within this model are therefore a combination of those two perspectives: linked to the actual project as well as the overall business performance.

Net Present Value

The net present value is a useful technique within this scope. It helps to indicate whether the investment will repay itself and by how much in absolute terms. This is done by determining the discounted cash flow over the lifespan of the investment. With the respective assets, this can be quite important due to their long lifecycles.

Return On Investment

The return on investment tells something about the financial return of an asset and hence about the investment's profitability. The return on investment is often measured as a percentage and can be seen as an efficiency metric. The advantage of the return on investment is that it allows for determining threshold requirements on a general basis due to its relative character. This may therefore make comparison of various investment proposals easier.

Total cost of Ownership

The total cost of ownership is an estimation of all costs of an asset over its entire lifetime. This includes direct costs such as the investment, as well as maintenance, but also indirect costs during usage of the asset. For example in case of Liander, the CO_2 emissions are indirect costs that can be accounted for by the use of certain assets. Concerning material usage, it is suggested to include the end of life benefits of an asset as well as waste and scrap are increasing in value and therefore contributing to a positive total cost of ownership.

c) Technical Appraisal

The technical appraisal indicates the technical performance of the subject of the investment decision. The technical appraisal should account for the design criteria of increasing lifespan and maintainability. The technical constituent can be approached from two angles: from the different life cycle stages or the difference in physical, functional and operational requirements. From a more general level, the latter perspectives are preferred since the life cycle stages are not always the same for each product nor are by definition clearly framed to prevent overlap. Therefore, the technical appraisal will be assessed based on the functional, physical and operation requirements. To get a comprehensive overview of the technical appraisal, the assessment of these requirements should take into account all life cycle stages of the product. It may however be the choice to frame the assessment to smaller scope.

Physical requirements

The physical requirements consider the physical characteristics of the product and the physical characteristics of its environment. These can be the weight, dimensions, contents of toxic materials of the product, but also temperature, moisture level and pressure. In case of a service, the physical characteristics may be the space or energy required for the service.

Functional requirements

The functional requirements can be interpreted as the required performance the product or service has to deliver from a technical point of view. More generally, this is the process or conversion the product or service is expected to effectively execute. For example in case of distribution transformers, this would be the required transformation step, the required capacity and the necessary flexibility towards load variations.

Within the Circular Economy paradigm, performance is an aspect often focused on within suggested business models or tools. Examples are leasing, the Performance Economy [43] or Best Value Procurement. The latter is a tendering tool that focuses on long term performance and tries to minimise negative impacts [99].

Operational requirements

The operational requirements consider mainly the use phase of the product and the non-physical operating requirements. The physical operating requirements are accounted for by the physical requirements discussed above. The operational requirements rather assess the availability, reliability, maintainability and supportability of the product. With that, the life span is included in the operational requirements determining how long a product is expected to last. The design criteria *increase lifespan* and *maintainability* are therefore represented within these functional requirements.

d) Strategic alignment

Strategic alignment of the investment decision is important as it takes into account the strategic developments of the organisation, its partners and the government. It differs from the stakeholder constituent in the sense that it does not evaluate current practices or influences, but looks at a longer-term alignment of influential forces on the business case.

Business goals alignment

The investment decision should be aligned with business goals to make sure the investment and its business case stay relevant during their life span. In case of non-aligned investments, there would be increased risk that the investment becomes superfluous. However, non-aligned investments may also counteract the business goals and have a negative impact on the operational management or specific business processes.

Chain partner alignment

Chain partners are important to be aligned because they are a fundamental part of business process. Without suppliers or customers, the business would become obsolete. Therefore, it is important to stay aligned to these chain partners and follow developments. On the other hand, these chain partners should be able to follow the developments of the business to make sure these developments can be implemented and become executable.

Governmental alignment

Governmental alignment considers the alignment of the investment with legislative, executive and juridical powers. This could consider trends in society that may be translated into new legislation, new regulating authorities, or other political forces that can influence the business, the business case and hence the investment.

e) Risks & Opportunities

The *risks* differ from the previous constituents in the sense that it is not a performance-based criterion but rather indicates the possible risks of the previous constituents. The risk assessment should include not only the possible effect of each criterion but also the possible frequency and the likelihood at which the effect may occur. Within the investment decision, risk reduction is important to become more certain of the outcomes of the investment on the long term. Furthermore, the risks constituent can also account for opportunities. These can be seen as positive risks. The following indicators for the risks analysis are suggested:

Technical risks

The technical risks may be found in the physical, functional and operational requirements. These risks can be caused during manufacturing or operation. However, a changing environment may also affect the required capacity or the operational conditions and increase risks of overload or other failures.

Stakeholder risks

Stakeholder risks can be risks that compromise the collaboration between the stakeholders, the risk of increased or decreased dependency as well as the risk of a changing responsibility towards the stakeholder. Examples of stakeholder risks are the changing image of the organisation, changes in the process affecting collaboration, stakeholders going bankrupt, etc.

Economic risks

The financial appraisal can have increased risks when market uncertainties influence the total cost of ownership and consequently the revenue of the investment. The valuation of flexibility and strategy is also important within the analysis. These valuations help to indicate the added value when decisions are deferred or postponed. But there are also risks related to this. Risks in the form of increased investment costs and reduced competitive advantage for example.

Sustainability risks

The sustainability risks may be translated into the chance of creating an unsustainable situation, such as an insufficient amount of resources to continue operation. The reuse potential covers a risk that can be financially translated (appendix E.3). In case the reuse potential is kept at the same level, the value of the resource will remain. However once there is no future reuse potential any more, the economic value of the resource may be lost and a capital bubble may arise. For the environmental impact the risks may be alike the risks of material preservation. In case of unsustainable negative externalities, this may backfire into legislative or practical restrictions for the business. This can possibly reduce the financial benefit of the investment and other business processes.

Strategic risks

The last risks to assess are the strategic risks. They may occur when the investment is not strategically aligned with the business, with chain partners or governmental institutions. This could compromise the expected revenue of the investment or the business as a whole.

5.3. Operational Model of the Sustainable Investment Decision Aiding Model

The operational model is a translation of the conceptual model (figure 5–3) into a decision making tool that can be applied in the investment decision operations. The operational model needs to comply with the relevant design criteria as determined throughout the research. These operational design criteria can be found in Appendix G. However, the design criteria give room for various forms of the decision-making tools. As Triantaphyllou discusses, the best known tool cannot be determined a priori without biasing the result of the evaluation [49], the decision making paradox. Next to this issue, the main aim of the tool is providing the decision makers with a comprehensive but practical overview of the various scenarios.

Important to acknowledge is that the constituents of the conceptual model comprehend different forms of information. Some are qualitative such as the stakeholders, while others are more quantitative such as the financial aspects. Fuzziness of information is therefore a problem for implementing a mathematical approach. Possible methods that tackle these problems can be found within multicriteria decision making theories.

Multicriteria Decision Making

Common tools used for evaluating a decision problem are Multicriteria Decision Making (MCDM) methods [100]. For example Remenyi [55] and Ashley [58] use this. These methods have as main aim to create an overview (composite) of the various assessment criteria and evaluate these either implicitly (hermeneutic) or explicitly (positivist). In line with the design criteria, which state that the developed model should be of composite positivist approach, an MCDM method would be an appropriate method. MCDM methods often result in matrices or tables in which various aspects are scored according to certain criteria. This matrix provides a comprehensive overview of the assessment and allows to identify the possible trade-offs. Depending on the actual method, this form of MCDM can result in a deterministic final score, or it could remain a structured overview aiding the decision maker in obtaining a comprehensive view of the decision problem. Within this study, the focus is on aiding the decision maker, and hence the MCDM will be treated as a Multicriteria Decision Aiding Method (or MCDA method). Table 5–2 shows an example of an MCDA assessment based on the conceptual SIDA model.

Common MCDA methods are ELECTRE (Elimination and Choice Expressing Reality) methods [100, 101]. The ELECTRE methods have mainly been developed in Europe and are still commonly applied in European countries. Including the use in real-world problems within environment, water management and transportation industries. The methods are becoming more widely spread across other continents.

These methods are said to be strong in decision problems that consider a combination of data types, incomplete data, quantitative forms of data and are not required to postulate the best action [100]. These characteristics are required for the operational model. A thorough application of the ELECTRE method requires the use of mathematical set theory allowing logic to derive a recommendation from the analysis. Even though this may be too extensive for an operational model to be applied within asset management operations, the ELECTRE method does postulate various features that are useful for the operational model. These are:

- » Use of preference modelling,
- » Relative encoding,
- » Veto threshold,
- » Discrimination thresholds.

These features will be discussed below.

Preference Modelling

Preference modelling can be used to indicate per assessment criteria which scenario or alternative is preferred. This requires at least two scenarios to be judged such that the assessments can be put in relation to each other. The argumentation given for the assessments should be based on clear and positive reasoning. Within MCDA, methods there are four preference levels determined: indifference, strict preference, weak preference and incomparability.

The *indifferent* qualification applies in case the preference of the scenarios is equivalent and the strength of reasoning to favour either of them is indistinguishable. A *strict preference* can be used to describe that one scenario is clearly favourable over a second scenario. The *weak preference* describes a situation in which there is a slight positive reason to favour one scenario over another. However, the reasons are insufficient to clearly state that the preference is strong. Nor are the strengths of the reasons distinguishable. The last preference level considers *incomparability* in which insufficient positive arguments can be given for either of the scenarios. This may also apply in case there are negative reasons to disapprove one of the scenarios.

Relative encoding

Relative encoding applies to the scoring, valuation and scaling of a certain characteristics of assessment criteria. This allows for various types of information to be valued within their own scope and scale. These scales do not necessarily describe the true value of the assessment criteria but can

2. The abbreviation is derived from the French equivalent: Elimination Et Choix Traduisant la Realité.

be abstracted forms of the information that is depicted. Depending on the applied decision, making method it may be useful to encode the information into numeric scales. It is however important to note that the scales are relative and various assessment criteria cannot be compared between each other. Only a comparison between the various scenarios can be made per assessment criterion.

Veto and Discrimination Thresholds

The ELECTRE method discusses various thresholds that can be applied during the evaluation process. The first one is called the veto threshold. This considers the dismissal of a scenario in case the valuation of a certain assessment criterion gets below a certain threshold. This threshold may differ per criterion, but should be the same within that criterion for each scenario. The veto threshold can be extended by defining strong and weak thresholds. A strong threshold would immediately dismiss a scenario, while dismissal based on weak thresholds would require the crossing of multiple weak thresholds.

Another type of threshold is a discriminating threshold. These do not result in dismissal or approval of a scenario but help to score the scenarios. Small ranges or minimum differentiation within the values of an assessment could be an argumentation for different scores. However, if they are approached as scores that fall within predefined categorical

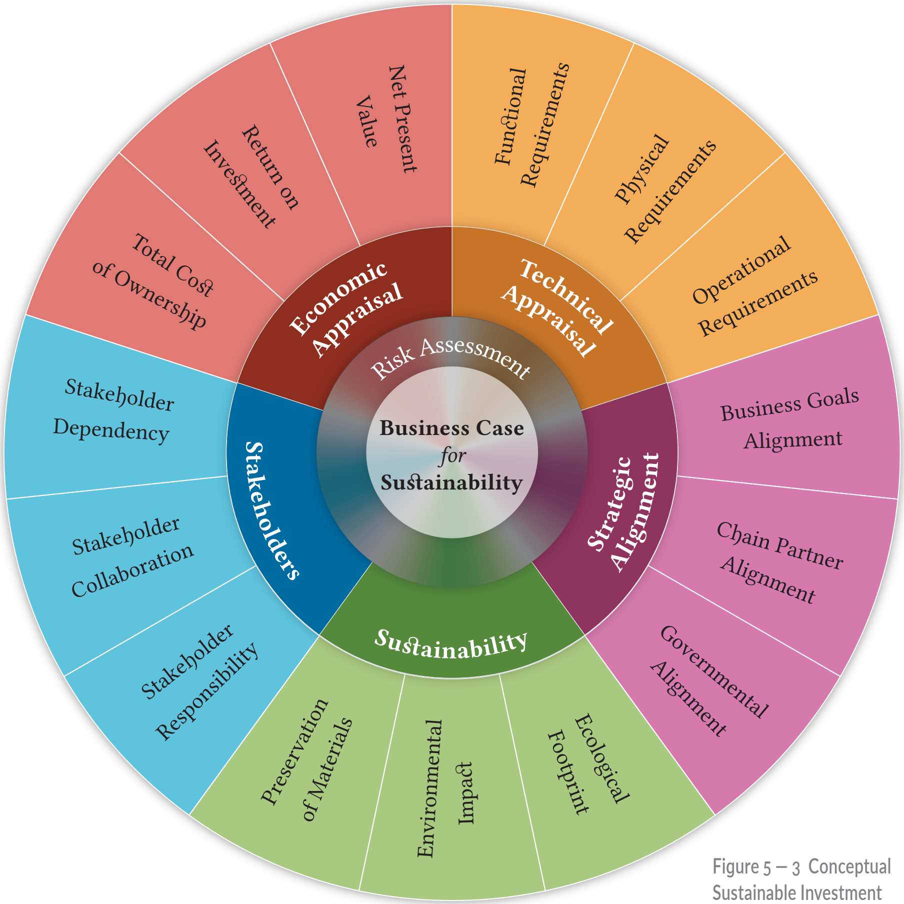


Figure 5 – 3 Conceptual Sustainable Investment Decision Aiding Model for a Sustainable Business Case with main constituents on the outside and the risk appraisal, based on the main constituents, on the inside.

Constituent	Assessment Criteria																	
	Technical Aspects			Economic Appraisal			Stakeholder appraisal			Sustainability			Strategic Alignment			Risks				
Indicators	Functional requirements	Physical requirements	Operational requirements	Net Present Value	Return on Investment	Total Cost of Ownership	Stakeholder dependency	Stakeholder collaboration	Stakeholder responsibility	Preservation of resources	Environmental impact	Ecological footprint	Business goals alignment	Chain partners alignment	Governmental alignment	Technical risks	Economic risks	Stakeholder risks	Sustainability risk	Strategic risks
Current Situation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Change Provider	0	0	0	0	0	0	0	0	-1	-1	-1	-1	0	0	-1	0	-1	-1	-1	0
Apply Insulation	1	-2	1	-1	1	2	0	-1	0	0	-2	-1	1	0	2	-1	1	-1	1	1
Invest in PV Cells	1	-1	1	1	2	1	0	1	0	1	-1	1	1	0	2	1	-1	-1	1	1

Table 5 – 2 Example of a Multicriteria Decision Analysis for the SIDA method. A fictive analysis for energy saving options for an apartment. The current situation is a benchmark. The assessment of the various alternatives is relative to this, hence the benchmark is set to index=0.

boundaries, the scores can be argued to be equal. The discrimination threshold relates to the indifference level within preference modelling.

Certainty of Information

One of the issues of assessing the criteria is the certainty of information. This problem can partially be tackled by preference modelling or in the subsequent decision making method such as a weighted sum method. However, it may be valuable information for the decision maker to know that a certain piece of information is uncertain and hence affecting the certainty of the assessment. To incorporate this into MCDA method, it is best to keep this information separate from the actual scores. By making use of secondary information queues, such as colour coding or proportionality, a clear distinction with the primary information queue can be useful. Especially to keep the information used to substantiate the arguments distinctively represented within the assessment. Additional notes besides the application of the tool can be made to indicate uncertainties.

5.3.1. Scoring the Assessment Criteria Indicators

With the various assessment tools available, the actual scoring method needs some further explanation to be able to apply it to the SIDA methodology.

In case there are more than three or four scenarios that need to be assessed, the assessment may become a laborious job. Therefore, it is suggested that an initial selection of the scenarios is done through preference modelling as discussed in previous section. This is a non-biased method, comprehensible for all actors involved in the decision making process. This method scores each of the scenarios qualitatively in relation with the benchmark only. That makes it quick and easy to do while avoiding discussion on exact data and other details. The drawback is that there may not be exact arguments available why one scenario is preferred over another.

In case there are only a few scenarios left to be assessed, more distinctive scales can be applied. For example the adoption of categorical or linear scales, either quantitative or qualitative. In this case the evaluation should not only be done in relation to the benchmark but reciprocally with all alternatives. This makes this form of evaluation more time consuming but allows for ordering or sorting the various alternatives while keeping a single overview. In this case, it is suggested to score the benchmark neutral on all assessment criteria. If the alternatives are scored in a range from positive to negative values in relation to the benchmark, the scenarios can also be compared to each other. Making the scale have a limited number of values enforces the use of discrimination thresholds. Examples of ranges for scales are -3 to +3 or from - - to + +. A numbered scale may however give the impression of linearity within the scoring. For example alternative A that scores 2 while alternative B only scores 1, does not necessarily mean that alternative A is twice as good as B.

Various scoring options could give a more precise overview of the alternatives than others. However, they may make the decision process more complex. For example, the scales of the various assessment criteria could be related to each other with a single unit such as Euro's. This would allow the summation of the scores across the entire assessment. Another option is that per assessment criterion an absolute scale is used. For example, the financial indicators use money while sustainability indicators use carbon dioxide levels. However, there are various drawbacks of these approaches. First, within absolute scoring it should be taken into account that comparing different units is more difficult. Secondly, different availability of information per scenario may make comparing the scenarios inadequate and unfair. Also, for some constituents, such as stakeholders or strategy appraisal, no common agreed quantitative equivalents are available. This means that the information cannot be scored in absolute values and thus discriminative relational scales are necessary anyway.

After the thorough assessment, in which all scenarios are scored in relation to each other, a final selection can be made to further ease the decision

Table 5 — 3 List of conceptual design criteria

Type	Design Criteria	Focus on
Contextual	Micro (asset related)	scope
	Dutch/European scope	scope
	Applicable to electricity distribution infrastructure sector	scope
	Sound theoretical background	theory
	Adaptable to other asset types (scope flexibility)	scope
	Use Circular Economy as basis	theory
	Asset management perspective	scope
	Based upon decision making theory	theory
Functional	Avoid Bonini paradox in decision making	constituent
	Need for appropriate metrics	constituent
	Use a composite decision making approach in a positivist application	constituent
	Include environmental sustainability as a separate aspect	constituent
	Avoid complexity of sustainability	constituent
	Include financial case	constituent
	Take risk assessment into account	constituent
	Take stakeholders into account	constituent

process. This could be the application of the veto threshold. It allows to reduce the number of alternative scenarios in case a certain indicator or assessment criterion does not satisfy the bare minimum.

The complete assessment could then result in an operational model as presented in table 5–2. The aim of this model is to aid the decision makers. It enables trade-offs to be identified and potential advantages in relation to the current situation. A trade-off in table 5–2 is for example that a better *financial performance* is at the cost of *stakeholder* or *sustainability* performance considering the *Insulation* scenario. The overview may also help in determining veto on certain criteria and hence reduce the number of options.

5.4. Evaluation of Design Criteria

To see how the developed conceptual and operational model match with the design criteria that were identified throughout the research an evaluation has been carried out. The complete list of design criteria is shown in Appendix G, categorised by conceptual and operational level, their type and their focus. The specific design criteria that apply to either of the models are presented in table 5–3 and table 5–4.

5.4.1. Evaluation of Conceptual Design Criteria

The design criteria that were used to base the conceptual model on are presented in table 5–3. The design criteria are categorised in two dimensions, their type and focus. Most of the design criteria are contextual criteria that either focus on the scope or on the required theory. Next to the contextual criteria, already several functional criteria were identified that describe the inclusion of certain constituents within the conceptual model.

Contextual criteria

The scoping and theory of the conceptual model have been appreciated during the background research. This has been done by focussing on specific research topics such as Circular Economy and scoping the asset investment decision theories around infrastructural assets. Various other design criteria such as avoiding the Bonini paradox are derived from these initial criteria.

The design criteria on the Dutch and European scope have partially been appreciated by keeping track of the locality of the papers or theories and basing conclusions on these results. For example, the results of the literature review results on the Circular Economy (see figure 2–4 in chapter 2.2) show this. The criterion on scope flexibility is difficult to evaluate at this stage. This is because the criterion can only be evaluated through empirical research that is not available at this stage. The case study in chapter 6 will deal with this.

Functional criteria

The functional criteria for the conceptual model have had their main impact on the structure and contents of the model, especially in the form of the constituents. The criteria on the Bonini paradox and structuring of complexity have led to several design choices on a number of constituents and their defined domain range. Next to that, a separate theoretical framework has been developed to accommodate for the design criterion on environmental sustainability. This framework also accounted for the use of a composite decision making approach, continued to be implemented in the operational model. The criteria considering the financial case, risk assessment and stakeholder appraisal are also embedded in the conceptual model based on current practices and existing models.

Table 5 – 4 Operation design criteria and their focus

Design Criteria	Focus on
Account for CO_2 emissions	indicator
Aligned with RAMS methodology	indicator
Applicable tool to show trade-offs	tool
Create transparency in decision making process	tool
Differentiate between functional and physical requirements	indicator
Practical for decision makers	tool
Support a positive economic benefit	indicator
Support flexibility appraisal in investment decision	indicator
Support more efficient material usage	indicator
Support reduction of energy usage	indicator
Support reduction of material usage	indicator
Use Material Usage, Ecological Footprint and Environmental Impact as indicator for the environmental sustainability constituent.	indicator

5.4.2. Operational Design Criteria

The operational model is based on specific design criteria also. These were identified throughout the research, based upon literature and the case study at Liander. The design criteria applicable to the operational model can be found in table 5–4. There are criteria that focus more on the application of the tool, while others focus more on the contents in the form the actual indicators of the constituents.

Various design criteria that consider the application of the operational model require empirical research to evaluate them. These design criteria will therefore be discussed in chapter 6, Evaluation of the Sustainable Investment Decision Aiding Model.

Most of the design criteria that consider the indicators for the operational model describe what should be accounted for in the valuation of the model. Other criteria aim to create incentives through applying the model, such as the incentive to reduce energy usage and material usage. Most of these required incentives are directly or indirectly part of the metrics throughout the various constituents. For example, the RAMS methodology is indirectly included in the operational requirements of the technical constituent. Likewise, the CO_2 emission criterion is embedded in the environmental sustainability constituent through the environmental impact indicator.

5.5. Discussion on the Conceptual and Operational Model

Within this paragraph, several points of discussion concerning the developed conceptual and operational model will be presented.

Application of the Conceptual Model

The developed model is a means to give insight into the trade-offs that the investment decision problem poses. It is a way of showing the differences between the various alternatives and does not give conclusive answers to the problem. It should therefore only be used as a supportive tool and to create transparency for the final decisions.

The fact that it is a relative tool means that two different assessments cannot be compared to each other. In case one would want to do this, an absolute scale should be found for the assessment. The chosen indicators for the various constituents are applicable within the current context of energy infrastructural asset investments. These are chosen to create a balanced view of a certain constituent. However, it may be possible that for certain investment decisions not all proposed indicators are applicable. The model leaves the decision maker to choose more, less or different indicators. Although, to prevent bias, the new indicators should keep the balance of the constituent, be applicable to each of the evaluated scenarios, and be clearly defined before the various scenarios are being assessed.

Another possibility is to use a capitalised model altogether. A capitalised model would be an extended TCO model that includes the impacts of all constituents translated into capital value. However, there are still various impacts that are difficult to capitalise such as social and ethical side of the investment. It is therefore left out of the scope of this study.

Financial Flexibility

Total costs of ownership can be rather hard to predict as the future costs and benefits are based on assumptions. Especially in the case for the energy sector, forecasts may go beyond the forty years while prices of raw materials, emissions and waste vary per day. For this financial flexibility may be a useful tool.

Financial flexibility can be useful to enable adjusting the business case to these changing environments over the asset lifetime. To be able to consider flexibility in the investment decision assessment two forms of flexibility can be included. These are strategic value and flexibility value.

The strategic value is about future competitive interactions and the value a business may gain or lose from that. In general the strategic value is the possible future economic appraisal in relation to competitors [102]. It focuses therefore not only on the internal revenue of a product but looks at the economic impact the product has on a higher level. A suggested method to determine the strategic value of an investment decision is the Game Theory [103, 104].

The flexibility value measures the opportunity costs to defer the investment decision or revise it in the future. It indicates the ability to alter the investment decision depending on for example new technological developments. The Real Options Valuation (ROV) is a method that is often suggested as method to determine the flexibility value [105–107]. Financial flexibility can be a useful tool but requires more research on the applicability and practicality within the business case.

Embedding Environmental Sustainability

Embedding sustainability into the business case is one of the main aims of this research. This has been achieved by adding an additional constituent to the asset investment decision model. It should be noted that including additional aspects might allow for a better forecast and a more comprehensive decision. However, at the same time it creates extra complexity and consequently complicating a fair, defendable and reproducible decision-making process: the Bonini paradox. Adding more constituents should therefore be done with care, and to avoid part of the complexity, each of the constituents should have a distinct domain that they account for, meaning to prevent overlap.

A complexity problem on the level of sustainability itself considers the actual definition of sustainability. Within this research, the focus has been on using Circular Economy as basis for this definition. This helped to account for various design criteria such as increasing material efficiency, prevention of accumulation, prevention of scarcity and the environmental impact. However, the public and scientific view on sustainability constantly changes. Several years ago, there was a focus on impact of pesticides, acid rain and banning of CFCs. Since the climate change discussion has erupted the focus has shifted to reduction of CO_2 emissions [108, 109]. The circular economy now focusses more on resource scarcity. It can be expected that within a few decades there will be other environmental or social topics that have gained attention, for example coming from the new field of Earth System Sciences. It is therefore important to allow for adjustments of the business case throughout its lifespan.

Assessment of Criteria

A final point of discussion is the presentation of uncertainty of the assessments within the operational model. Uncertainty is a difficult but important topic to address within the MCDA methodology. Presenting uncertainty of information within the developed model can therefore be a useful addition for a more comprehensive overview and result in decision with fewer risks.

As uncertainty can be expressed in terms of risk, it may be argued to include this in the designated risk constituent of the developed model. However, this form of risk can overshadow the actual financial or technical risks as the uncertainty is based on sensitivity and not on substantive arguments.

As suggested in paragraph 5.3, indicating uncertainty can be done by including additional information queues into the operational model or through including footnotes. Using additional information queues such as colour coding should be done with care as it may easily bias the decision making process [110]. Common issues are the wrong usage of the supporting information queues. For example, using a red colour to indicate uncertain data causes this uncertain data to have a dominant presence over uncoloured certain data. Therefore, non-subtle usage of supporting information queues may cause a focus on secondary information instead of the primary. This may all lead to misguiding the decision maker, consequently making the decision process more difficult. An adequate form of indicating uncertainty may therefore change per investment decision and decision maker. It would be useful to further research this through empirical studies.

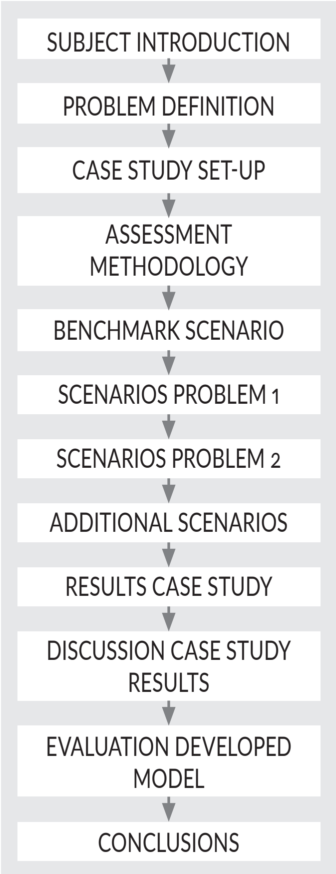
5.6. Summary

The conceptual model for investment decision making has been based upon common models used within the infrastructure sector such as Remenyi's and the SWARD model. In the conceptual model environmental sustainability has been added as new constituent based on the theoretical framework as presented in chapter 4. This results in a conceptual sustainable investment decision model with the following six constituents of which the risk constituent is layered on top of the other five.

1. Technical Appraisal,
2. Economic Appraisal,
3. Stakeholder Appraisal,
4. Environmental Sustainability,
5. Strategic Alignment, and
6. Risks

This conceptual model has been translated into an operational MCDA model using the ELECTRE methodology. The structure and contents of the conceptual model match most design criteria that have been identified throughout the research. To evaluate some of the design criteria empirical back up is necessary. This will be done through a case study on distribution transformers. The next chapter will discuss this and include the evaluation of the remaining design criteria.

6. Evaluation of the Sustainable Investment Decision Aiding Model – A Case Study



Outline Case Study Chapter

To test and evaluate the developed investment decision model for applicability in a real world example and against the design criteria, an investment decision problem concerning distribution transformers is used as case study. The case study is provided for by Liander and therefore the data are based on the population of distribution transformers that Liander manages and maintains.

This chapter will discuss the case study, the application of the investment decision model and the case study results. It will first introduce the case study background, problem definition and set-up, after which the several scenario alternatives to be evaluated will be explained. In total three groups of three alternatives are studied resulting in a total of nine alternatives. The first group considers the current install base, the second focusses on alternative components of the transformer, and the last group looks at alternative technologies not relating to the technical components. After the application of the conceptual model, the results of the case study will be discussed and the model itself evaluated.

Scope

The scope of the case study considers the distribution transformer population of Liander. A short introduction on distribution transformers within Liander will follow in the next paragraph. The most common transformer in Liander's population is an oil-immersed 400kVA distribution transformer with copper windings. This is the type of transformer that will often be referred to and be used as benchmark in the investment decision methodology. Furthermore the scope includes the first order tier supply chain partners. Concerning the sustainability of the transformers, the energy usage of these supply chain partners has not been included as this information was too uncertain and difficult to retrieve.

6.1. Distribution Transformers within Liander

This paragraph will give a short overview of common figures of distribution transformers and the maintenance scheme of these distribution transformers within Liander. More background information on distribution transformers and Liander's population of distribution transformers can be found in Appendix I.

The energy grid as operated by Liander consists of a transmission and distribution grid. The transmission grid is a regional grid operated between 10V-50kV and powered by the regional energy producers and the national grid operator. The distribution grid (figure 6–2) consists of a high voltage (3kV-20kV) and low voltage (400V) and distributes the energy within the residential neighbourhoods. Distribution transformers (figure 6–1) take care of the transformation step within the distribution grid.

De 'size', or rated load, of the transformer differs depending on the required capacity that a certain area or neighbourhood requires. The nearly 30,000 distribution transformers that Liander operates range between 100kVA and 2,500kVA in size [111]. Their cost price mainly depends on the material contents of copper, steel and oil. The average price of distribution transformers is around €10,000.

Most of the transformers have a life time of forty years or more, and due to their relative simple mechanic construction and a lack of moving parts, they require little preventive maintenance. The life cycle of an individual transformer is guided by the criteria depicted in figure 6–3. One of the important criteria considers the load of the transformer. In case it has exceeded 100% of the average rated load and the temperature has been higher than 82°C, it will be replaced by a larger transformer. The transformer taken out will be further assessed for possible redeployment or disposal. An important redeployment criterion is the 1970 construction year threshold. This is a strategic choice to avoid having old assets in the grid (approximately 40 years), and thus all transformers that were constructed before this year will not be redeployed. In case the transformer has been qualified to be redeployed in the grid, the maintenance that takes place considers a thorough inspection and possible changing of the oil. This maintenance takes places in-house in Liander's own workshops.

With the current maintenance scheme Liander operates its distribution transformers with a high reliability of 99.98% [112]. This comes down to an average of seven failures per year. On average the population of transformers grows by 1% each year of which 40% is a redeployment [112]. This results in a population that has an average age of 20 years of which over 80% is younger than 45 years. Most transformers are deployed for at least 40 years.

6.2. Problem Definition of the Case Study

The asset management of distribution transformers has identified two main problems considering sustainability that can be interpreted as investment decision problems. The first considers the current install base and is about whether or not to defer the investment decision to replace old distribution transformers. The second is about investment in new transformers and mainly considers the choice of technology for new transformers. Both issues will be further explained hereafter.

6.2.1. Decision Problem 1: Replacement of Old Transformers

Distribution transformers are assets within the electricity grid that last over forty years. They are very reliable and require little maintenance. However, these old transformers are not as energy efficient as new ones. The question is whether new transformers should replace older, inefficient transformers, even though they have not yet reached their technical end of life. First of all this is a form of capital destruction since the transformer is still fulfilling its function properly. Secondly, replacement has a possible negative effect on the Circular performance of the transformer. The recycling process of the transformer leads to inherent material downgrading and material loss. On the other hand, reduction in energy losses means that less mineral resources are

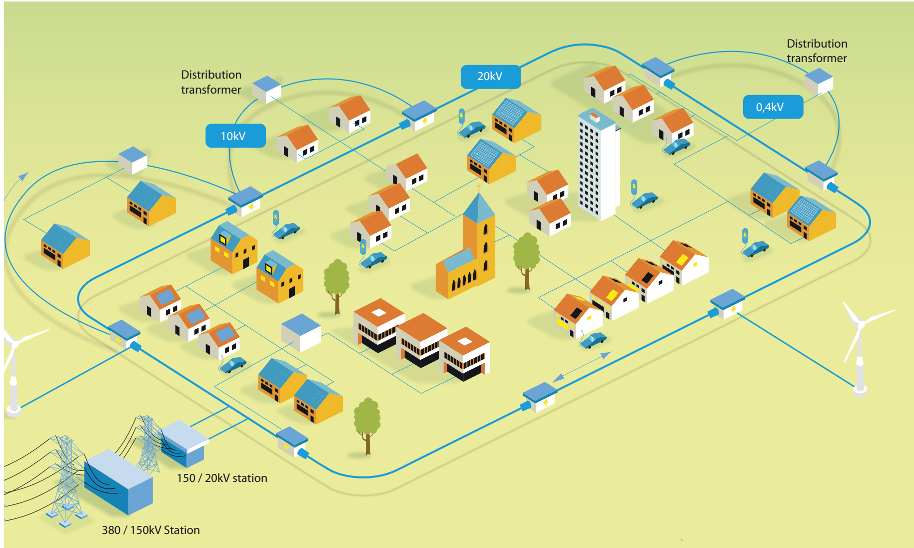


Figure 6 – 2 Illustration of a distribution grid as operated by Liander.

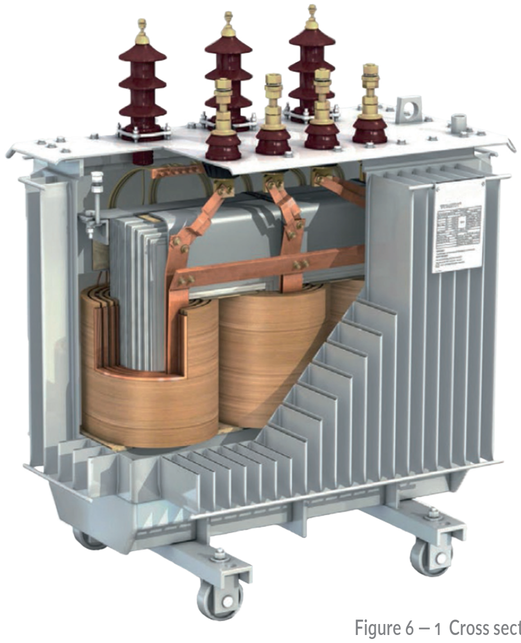


Figure 6 – 1 Cross section of a distribution transformer similar to those operated by Liander.

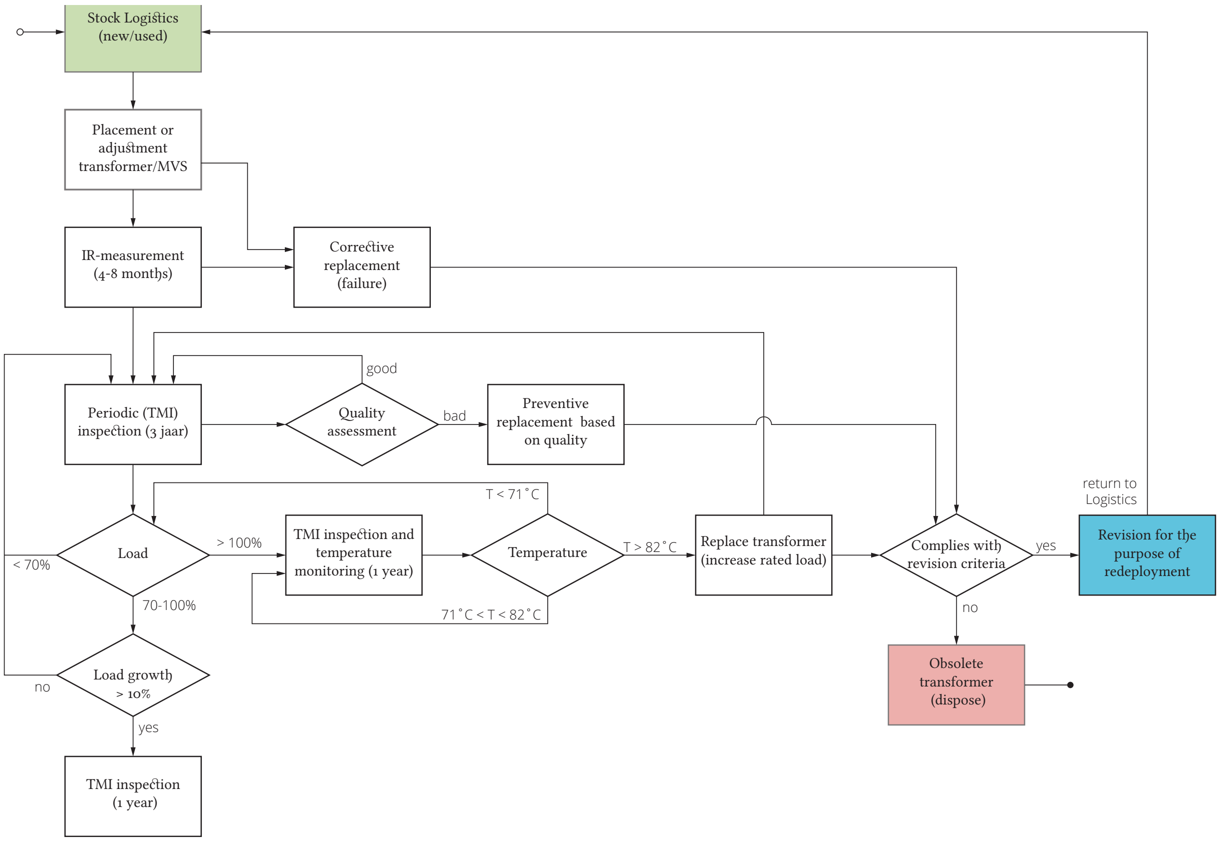


Figure 6 – 3 Flow diagram life cycle of a single distribution transformer within Liander. Adapted from the Levenlooplan Distributie Transformatoren [112]. TMI = Thermal Maximum Inspection

incinerated to compensate for the energy losses. This results in the following question:

What is a feasible moment is to replace old transformers considering all investment criteria. To be more precise: is the current threshold of 1970 a desirable threshold, or should, because of sustainability or other investment criteria, this threshold be changed.

6.2.2. Decision Problem 2: Investment in New Distribution Transformers

Every year new transformers are added, mainly due to growth of the power grid in size and capacity requirements. For asset investments within Liander, there has been an increased focus on sustainability considering energy efficiency (loss reduction). Since the beginning of 2014, circularity has been added as another factor that should be accounted for within the life cycle of the asset. Suppliers are currently mainly focussing on technologies to increase energy efficiency such as amorphous[1] cores, or transformers that can handle a greater variation in loads through automated tap-changers. However, the current suppliers do not have a consistent and sufficient answer in favour of the Circular Economy. Based on meetings and correspondence with suppliers it became apparent that innovation is mainly enabled through second tier suppliers, offering new types of materials and meeting efficiency requirements posed by grid operators and government. Other innovations incentives are not present. The question on investing in new distribution transformers is then as follows:

Which type of distribution transformer would be an economical but sustainable choice considering energy and material usage over its full life cycle?

6.3. Case Study Set-up

The case study is set-up to test and develop the SIDA model as developed in chapter 5. To do this, several investment alternatives are needed as input scenarios for the model. These are derived from the defined problems posed by Liander supported by literature and developments within the market.

For both defined decision problems, the same benchmark will be used. The benchmark is the currently contracted distribution transformer that represents the latest installed transformer population, a 400kVA oil-immersed distribution transformer. The benchmark will be further discussed in section 6.5.

The alternatives considered for the first investment decision problem, will look at different subpopulations within the current install base. The aim is to look for a point at which there is a feasible tipping point for replacing the old transformers for new ones, and hence, whether the current 1970 threshold is desirable.

The second problem considers which technology to choose when investing in new transformers. The case study will look at different technological options that are currently gaining attention within the market. The goal of the case study concerning this decision problem is to give insight in which technologies are the best options to invest in from a holistic point of view.

Next to the scenarios used to tackle the defined problems, several other scenarios are tested that relate to future development of the electricity grid. These scenarios were put forward during several events such as the WCM Summer School and the Circular Economy Boostcamp for which Liander provided a case study.

6.4. Assessment Methodology and Determining Scores

For each alternative information has been collected to discuss and value their performance within the model. The information is gathered through various means, such as company data, expert opinions or experience, as well as from supply chain partners and literature. All this information has been processed and discussed in various sessions with experts within Liander (Appendix M). This leads to the final assessment as presented in table 6–3, table 6–4 and table 6–5. Together with experts the prefinal assessments have been cross-checked.

The process of evaluating the information into the final assessment is rather difficult and cannot easily be generalised for the decision problems and the indicators. This is because the three different decision problems require a different perspective on the alternative and consequently requires different information. Next to that, each constituent may result in different forms of information. The financial appraisal consists mainly of quantitative data such as TCO and ROI, while stakeholder appraisal is qualitative. Because of these differences, the assessment has been done as a relative assessment within the indicator over the three alternatives within the decision problem in relation to the benchmark. This means that alternatives between the various decision problems cannot be compared. Hence the presentation in three separate overviews; table 6–3, table 6–4 and table 6–5.

It must be noted that these assessments are limited because not all information could be retrieved on the entire life cycle of each alternative. In these cases, either these elements were neglected, assumptions were made or experts were consulted from Liander or from supply chain partners. Even though the assessment may therefore not be complete, as much as possible has been done to enable this case study to support the evaluation of the SIDA model and answer the questions posed by Liander.

1. Amorphous cores are commonly made of MetGlas (a $Fe_{78}B_{13}Si_{9}$ alloy) [130]. Due to quick cooling process, the material forms a crystalline structure that causes the electric and magnetic properties of the material.

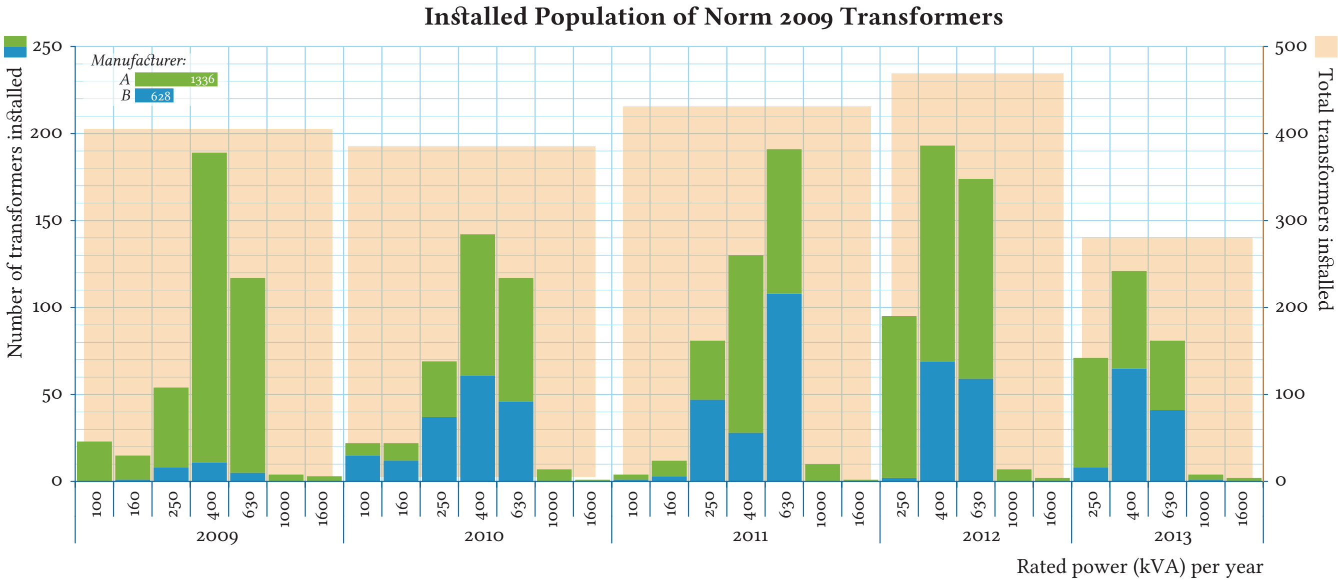


Figure 6 – 4 Installed population of Norm 2009 transformers broken down per rated power (kVA) over the last years.

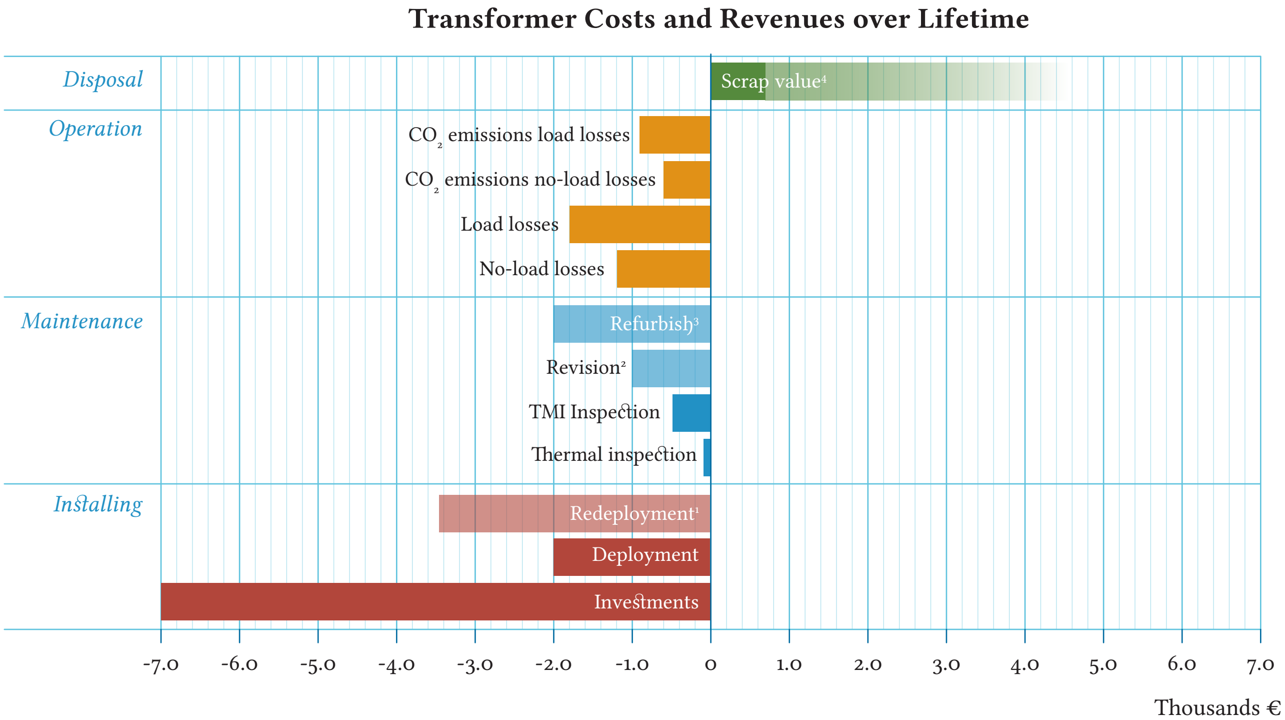


Figure 6 – 5 Indicative average transformer costs within Liander for a single 400kVA transformer. Based on company data [112, 114]. (1) Redeployment is placement of transformer from stock that has been used before. (2) Revision is not applicable to all transformers. (3) Refurbishment is not applicable to all transformers. (4) Current revenues from scrap is ~€750, the actual material value is much higher.

In the next section, the benchmark will be introduced. In the succeeding three sections, the different scenarios will be described per decision problem. For each scenario, the main findings will be discussed that are relevant for the investment decision model. More detailed data and information on which the assessments were made can be found in Appendix J. The full assessments can be found in Appendix K.

6.5. Benchmark Scenario and Results

The benchmark scenario considers the distribution transformers manufactured by the suppliers that won the tender in 2009. This transformer conforms to the specification also developed in 2009 by the main DNOs in the Netherlands and is therefore called the Norm 2009 transformer [113]. Liander has currently two major suppliers for distribution transformers.

6.5.1. Analysis

The current Norm 2009 population consists of around 2000 distribution transformers that have been installed since 2009. The most common transformers are rated at 400 and 630kVA. This population is illustrated in figure 6–4.

Technological Appraisal

The Norm 2009 transformers are optimised from a technical (and economic) point of view. Most of the physical, functional and operational requirements are accounted for in the Norm specifications. For example, the maximum energy losses may be only 515W for no-load losses and 3750W for load losses. For the current average maximum load of 40% over a period of 2500 hours [114], the average energy loss per transformer is around 5.27MWh/year.

Economic Appraisal

The current suppliers of the Norm 2009 won the tender based on the offered specifications in relation to the price per transformer. This means that the current costs of the transformer are already relatively low.

The current Net Present Value of the benchmark considers only the investment and the annual costs of the energy losses and the CO_2 emission costs related to those energy losses. When taking into account the value of the material that can be sold as raw materials at the end of its lifetime, extra benefits can be added to the NPV. Estimation of these benefits is rather difficult, but alike the rest of the NPV, it should be based upon current forecasts, with the knowledge that it may change over time. The World Bank and McKinsey [115, 116] are organisations that try to forecast the commodity prices, these are used for benefits as illustrated in figure 6–5. Currently Liander makes on average €750 per disposed transformer. This is what the recycling company pays. However, the actual value of the material contents of the transformer is much higher. The cost price of a transformer is for over 90% based on the actual material content. Especially the expensive materials in the transformer (copper, aluminium and steel) barely degrade during its lifetime and the value can therefore be assumed to stay nearly the same. The biggest problems against effectuating this, is the oil contamination and the recycling process that causes further contamination and thus devaluation of the material and the costs of the recycling process.

Stakeholders

From a technical point of view, the main stakeholders for the Norm 2009 are the manufacturers that supply the transformer, the service provider for maintenance and Liander itself for operating it. Performance wise, other stakeholders are citizens whose energy supply is dependent on the transformer and authorities controlling the quality and distribution of the electricity. Finally, there are the shareholders who also focus on quality of service but mainly on loss reduction and a financially healthy organisation. These roles of the stakeholders do not change much per scenario nor does the responsibility of Liander towards those stakeholders.

However, the dependency on, and collaboration with the suppliers changes per scenario. For the benchmark, the dependency on the suppliers is just on these two that won the tendering contract. Even though the suppliers only take responsibility for the manufacturing process, it is important that the suppliers are reliable. This helps to quickly respond to needs and allow just-in-time delivery to prevent a large stock of transformers.

Based on correspondence with suppliers and experts, it can be stated that collaboration with the suppliers is currently relatively low. Wishes and requirements are shared, however it is not common to have mutual

Part	Material	Average Mass / kg	Percentage
Coil and connections	Copper	360.5	26%
Core	Steel (CRGO)	510.0	36%
Coolant and insulator	Mineral Oil	210.0	15%
Tank	Steel	310.0	22%
Coil insulator	Kraft Paper	8.0	1%
Other (bushings, etc.)	various	11.5	1%
Total		**1410.0**	**100%**

Table 6 – 1 Material contents of a 400kVA Norm 2009 distribution transformer. CRGO is Cold Rolled Grain-Oriented steel and has good magnetic properties.

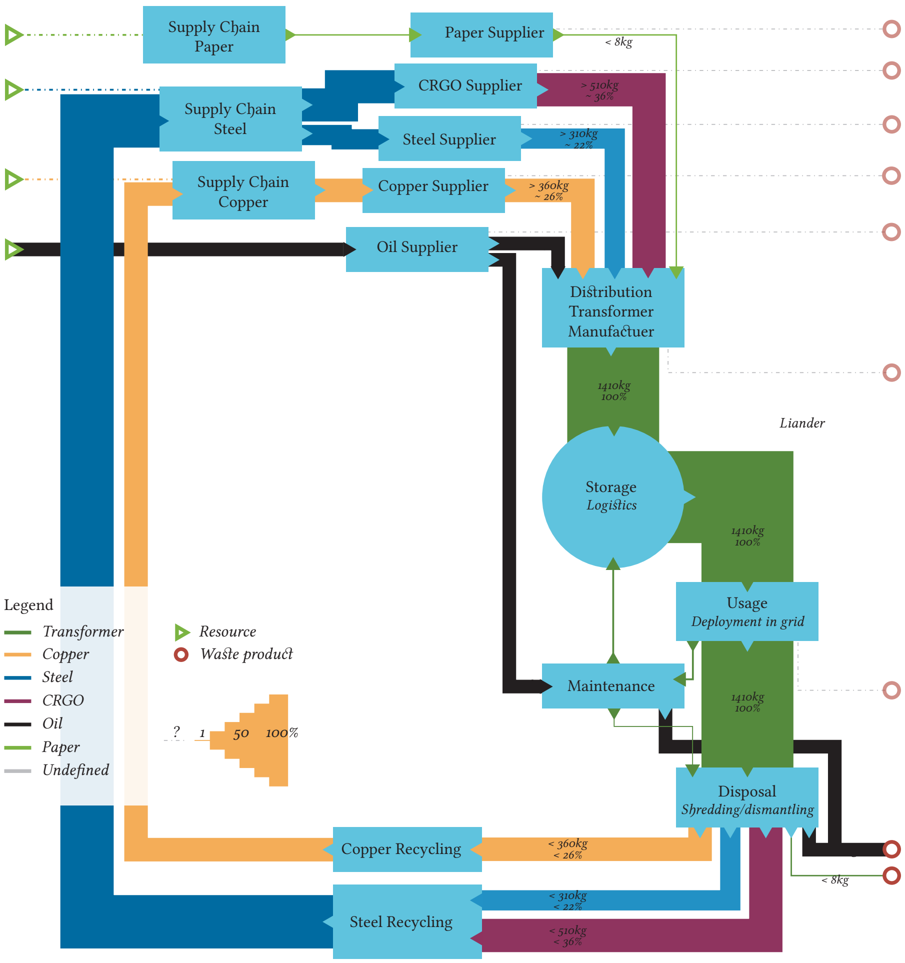


Figure 6 – 6 Material flow in percentage mass for the Norm 2009 distribution transformer. Note that this flow diagram is independent of time. Hence most material within this cycle is currently accumulating in the use phase as these transformers are still in operation.

(6.1) Calculation example for the circular value of a Norm 2009 400kV transformer. The exact sustainability values per material are shown for copper only. Appendix F.3 explains the formula and the variables.

$$C = \frac{\sum_{material} m_{in} \left(r + v \cdot (1 - S) \right) \times \sum_{material} m_{out}\, r_{pot} \left(1 - A\right)}{{m_{tot_{in}}}^{2}}$$

Sustainability ratio values for copper:

$$C_{copper_{in}} = (360.5 \cdot 30\%) + \left(360.5 \cdot (1 - 30\%) \cdot \frac{32}{1000}\right) = 116.23kg$$

$$C_{copper_{out}} = (360.5 \cdot 53\%) + (1 - 1\%) = 189.15kg$$

Total circular value:

$$C_{value} = \big((116.23 + 279.89 + 7.77 + 170.13 + 8 + 8.63) \quad \text{Inflow (of copper, core. coil, oil, tank, ...)}$$
$$\times (189.15 + 454.41 + 0 + 276.21 + 0 + 2.88) \big) \quad \text{Outflow (of copper, core, coil, oil, tank, ...)}$$
$$/ \; 1410^{2} \quad \text{Total material flow}$$

Table 6 – 2 Calculation of Circular value according to equation 4-2 for a 400kVA Norm2009 transformer.

MATERIAL	IN FLOW					OUT FLOW				SUSTAINABILITY RATIO		RESULT
Part	Mass in		Recycled	R/P	M_{scarce}	Mass out		Recyclable	M_{acc}	In	Out	Circular value
	kg	%	%	year	%	kg	%	%	%	kg	kg	
Copper	360.5	26%	30%	32	97%	360.50	26%	53%	1%	116.23	189.15	0.274
Core (CRGO)	510.0	36%	52%	60	94%	510.00	36%	90%	1%	279.89	454.41	
Mineral oil	210.0	15%	0%	37	96%	210.00	15%	99%	100%	7.77	0.00	
Tank	310.0	22%	52%	60	94%	310.00	22%	90%	1%	170.13	276.21	
Paper	8.0	1%	10%	1000	0%	8.00	1%	99%	100%	8.00	0.00	
Other	11.5	1%	50%	500	50%	11.50	1%	50%	50%	8.63	2.88	
Total	**1410.0**	**100%**				**1410.00**	**100%**			**590.64**	**922.65**	

collaboration for the development and maintenance of the distribution transformer nor develop new business models.

Sustainability

The sustainability of the benchmark will be based on the circular value that considers the preservation of materials and the reuse potential of the materials. Energy usage is kept out of the calculation, as sufficient data are not available. However, some relevant findings will be mentioned and taken into account within the assessment.

The material contents of the benchmark transformer is roughly estimated based on the current contract with a transformer supplier and an analysis done by the business unit *Rest en Afvalstoffen Centrum* (Residue and Waste centre). The complete overview can be found in appendix J.1, a summary is found in table 6–1 and translated into a material flow diagram (MFA) illustrated in figure 6–6.

Using equation 4–2 and data from table 6–1, a report of the International Resource Panel [117] and the US Geological Survey [14] an estimated circular value of 0.274 was computed for the benchmark. The example calculation is shown in table 6–2 and equation 6–1. The computation of the circular value for other transformers is shown in appendix J.3). All uncertainties and assumptions that were within the data are kept the same for the circular value calculations for the other transformers, for example the materials needed to produce the required energy required for manufacturing, use and disposal as well as the recycling potentials. Comparing the circular value with the MFA (figure 6–6) it should be noted that the MFA does not account for the unsustainable use of materials coming into the system. A fair comparison would be between the MFA and the circular value of the outgoing materials only (0.654). This circular value does comply with the figure. It can be mainly explained by the insulating oil that is not kept within the system and burnt after usage, the remainder is accounted for by other small material losses.

The other two sustainability factors are the environmental impact and the eco-footprint. The environmental impact considers externalities on the environment that are not resource related. For the transformer the main impacts are CO_2 emissions caused by the energy usage, noise pollution and heat generation. Noise and heat generation are relatively small compared to the effect the CO_2 emissions have.

These CO_2 emissions are mainly caused by the energy usage during production and energy losses during the use phase of the transformer. To estimate these carbon emissions, the embodied energy is a measure that indicates the energy required for the production of that specific material from cradle to gate [118, 119]. For fuels the energy return on (energy) invested (EROI) is often used [120]. Based on these two measures, the required energy for production of the benchmark transformer is estimated to be 35GJ [121–123]. Using the default CO_2 equivalent factor defined by the European Union of 91 gCO_2eq/MJ [124], the production of the separate components of the transformer are roughly estimated 3 tonnes of CO_2 equivalents. The carbon emissions resulting from the use phase are based on the load and no-load losses over the average lifetime of the transformer (see 6.5.1). This results in about 760GJ of energy losses over a lifetime of 40 year, being an equivalent of 70 tonnes of CO_2eq. Even though there is a large uncertainty within these calculations as exact energy sources, production locations and other influencing factors are not exactly known, the use phase accounts for a significant higher order of magnitude carbon emissions more.

Strategic Alignment

The strategic alignment of the Norm 2009 transformer with the company goals mainly considers the system average interruption duration index (SAIDI), safety and sustainability [112]. Considering safety and the SAIDI the current Norm 2009 transformers are well performing. Considering sustainability the amount of CO_2 emissions is still rated high, and several internal studies have been conducted to tackle this issue [114, 125, 126].

The chain partner alignment is mainly focussed at the two suppliers of the Norm 2009 distribution transformer. Liander is aware of the current developments and the perspective of the suppliers on the market. However, based on meetings and a visit with the suppliers, there seems to be a gap between what Liander wants to request from the suppliers and what they can offer in terms of innovations. Even though this was not as explicitly the case for the Norm 2009 transformer, this is a relevant strategic factor for a new tender that may be initiated within one or two years.

Liander is following the legislative developments closely and currently conforms to them. Liander is also aligned with the new European regulation on ecodesign requirements for distribution transformers [127]. This regulation states the maximum energy losses that distribution transformers may have.

Risks

Liander assesses the risks against its own Asset Management Risk matrix depicted in figure 6–7. It does this against the six core business values: quality of service, customer service, image, finances, safety and sustainability.

Considering the benchmark, the main risks are within the sustainability business value due to the indirect CO_2 emissions. When looking at the risk categories of the investment decision model the main risks that can be identified consider sustainability in the form of material losses and a lack of strategic alignment between suppliers and Liander.

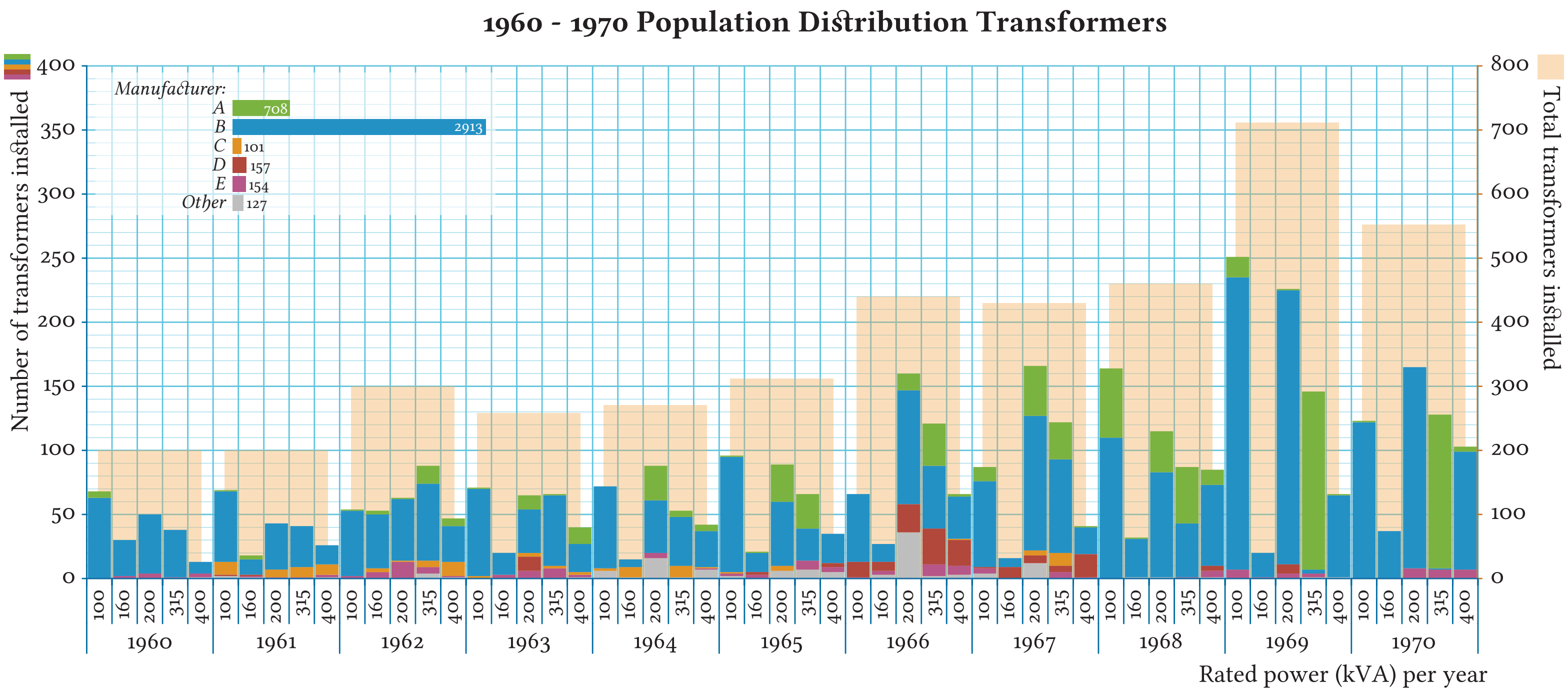
It is important that these factors are not counted double in their main constituent and the risk appraisal. Therefore, the main constituent should focus on the actual performance of what is known. The risk appraisal on the other hand, should account for the possibilities that arise. These can be risks (negative assessment), or opportunities (positive assessment). Considering sustainability this means that in its main constituent the actual performance in the form of carbon emissions, life cycle assessment or circular value can

Risk matrix Liander Asset Management

Potential Consequences								Potential chance on incident with impact								
								Very Unlikely	Unlikely	Possible	Likely	Regularly	Yearly	Monthly	Daily	Permanent
Category	Quality of Service	Customer Service	Image		Financial	Safety	Sustainability	Never heard of in Industry	Heard of in Industry	Several times in Industry	Happened within Liander	Happened several times within Liander	One to several times per year within Liander	One to several times per month within Liander	One to several times per day within Liander	One to several times per day in area of Liander
			Media	Politics				< 0,0001/yr	≥ 0,0001/yr	≥ 0,001/yr	≥ 0,01/yr	≥ 0,1/yr	≥ 1/yr	≥ 10/yr	≥ 100/yr	≥ 1000/yr
Disastrous	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	M	M	H	H	VH	VH	VH	VH	VH
Serious	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	L	L	M	M	H	H	VH	VH	VH
Severe	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	N	N	L	L	M	M	H	H	VH
Moderate	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	N	N	N	N	L	L	M	M	H
Small	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	N	N	N	N	N	N	L	L	M

Figure 6 – 7 Liander Asset Management Risk Matrix.

Figure 6 – 8 1960-1970 Population Distribution of Distribution Transformers, based on company data [111].



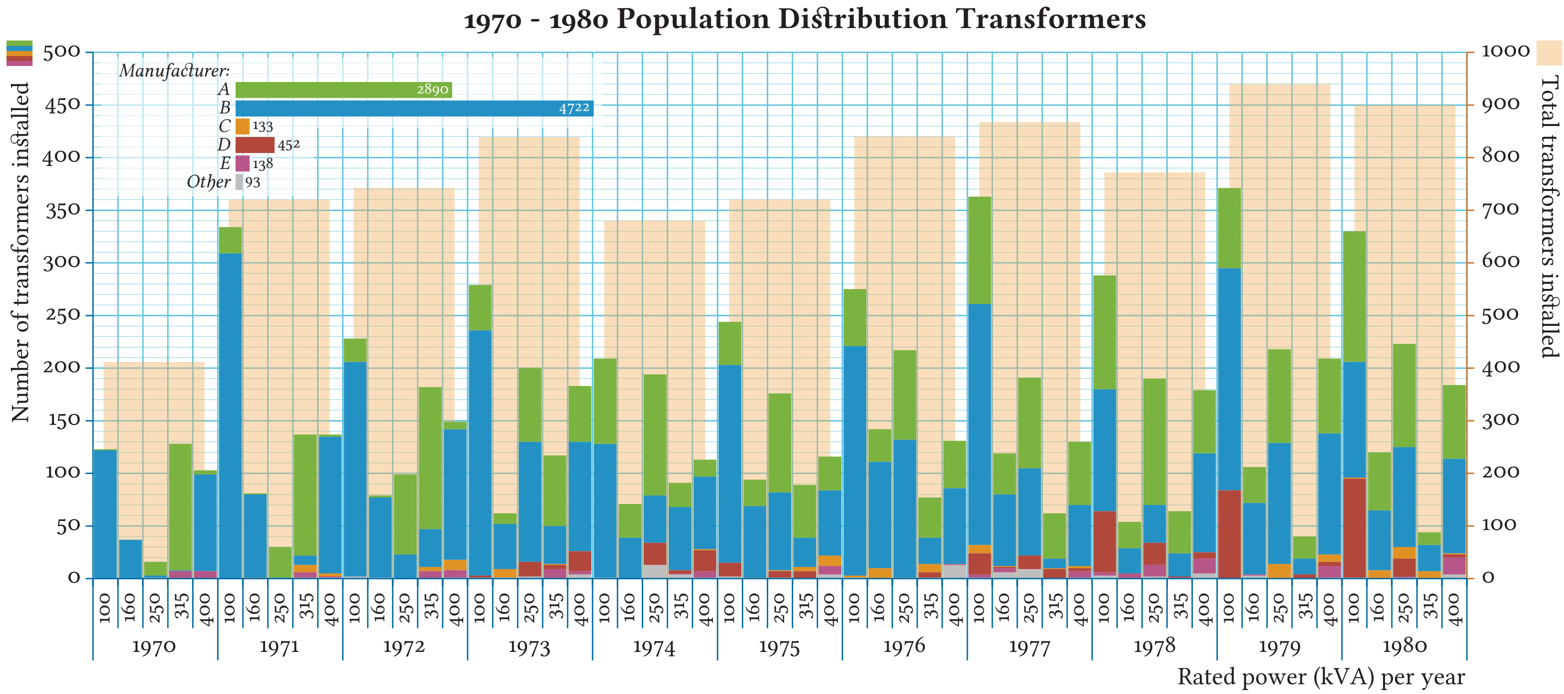
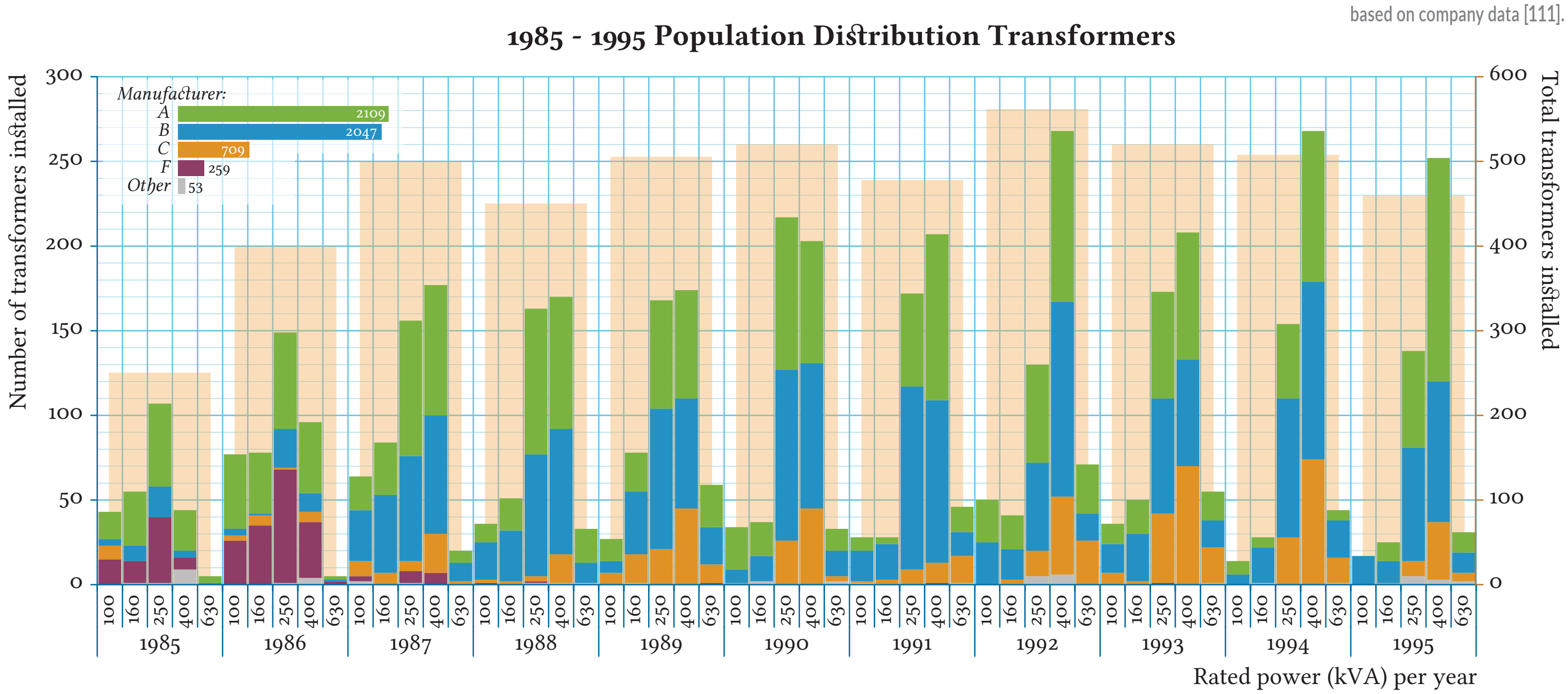


Figure 6 – 9 1970-1980 Population Distribution of Distribution Transformers, based on company data [111].

Figure 6 – 10 1985-1995 Population Distribution of Distribution Transformers, based on company data [111].



be the indicator. While in the risk appraisal of sustainability the possibility of future negative or positive effects, such as possible toxicity or recycling opportunities, can be accounted for.

6.5.2. Summary and Scores Norm 2009 Transformer

As the Norm 2009 transformer is the benchmark, a relative score cannot be given. However, when looking at the transformer it can be concluded that its technical performance is sufficient for the current situation although upgrades may be necessary to accommodate for the decentralisation of the energy production. Financial performance is good as energy losses have reduced over the recent years. Its main costs are investment and deployment, while scrap value could potentially be higher. The sustainability performance is also fine, although the mineral oil has some negative effects in relation to the Circular Economy, but the transformer has a long life span with little impact during this time except for the indirect carbon emissions. On strategic level it complies with the current strategies of Liander and EU legislation on electrical devices [127]. Stakeholder alignment can be assessed as okay. The dependency on manufacturers is not critical as it is spread over multiple companies, but collaboration for the Norm 2009 has not been extensive. Social responsibility is also estimated well, as noise, space and SAIDI are minimised. The risks are on average very low, although sustainability and strategic risks are a bit higher.

6.6. Scenarios and Findings for Replacing Old Distribution Transformers

The scenarios for replacing old distribution transformers are based on subpopulations within the current install base. The main phasing out criteria that are currently used are based on maximum load and age of the transformer. Especially the age of the transformer is a point of discussion.

Transformers built before 1970 that are still in great condition are removed from the grid because of their age. By looking at three different subpopulations in relation to the benchmark, the investment decision model will look at the differences between the populations and see whether there is a specific need to indeed replace transformers from before 1970. Based on the overall population (figure 11–23) and the current phasing out criteria the following three populations are investigated: 1960-1970, 1970-1980 and 1985-1995. The 1960-1970 population is the population that will be phased out based on the 1970 criterion; the 1970-1980 is therefore the population that will slowly become the oldest within the grid. The 1985-1995 is a population just preceding the first norm transformer from 1995. An analysis of the subpopulation between 1980 and 1985 was skipped to have three strategic relevant subpopulations covering the same time span of ten years.

6.6.1. Transformer Subpopulation 1960 – 1970

The 1960-1970 population (figure 6–8) is currently being phased out and is not being reused. Through this mechanism, the current subpopulation counts around 4100 transformers. In comparison with the benchmark population, the rated powers are quite lower: from 400kVA and 630kVA within the benchmark, to 100kVA and 200kVA here. Another main difference is the number of manufacturers. The benchmark has only two suppliers while in this population there are 18 different ones. Many of these transformers also have additional non-standard features such as oil-conservators or temperature gauges. These components increase the possibilities of failure.

In general, the average maximum load is around 61% of the rated power and the total energy losses are between 10 and 11MWh/year [114, 126].

6.6.2. Transformer Subpopulation 1970 – 1980

The population manufactured between 1970 and 1980 consists of roughly 3200 transformers (figure 6–9). The share of supplier A has clearly grown. The most common transformer is still rated at 100kVA; however there is an increase in the higher end at 315 and 400kVA. The total energy losses are now around 8.5 MWh/year and the average maximum load has dropped to 55% - 60% of the rated power [114]. These transformers also contain non-standard components like the 1960 population.

6.6.3. Transformer Subpopulation 1985 – 1995

The third population is the last population before the first Norm transformer was introduced in 1995. There has been another clear increase in the average rated power of the transformer to 250kVA and 400kVA while the number of suppliers has diminished in this period. The average energy loss is now at 8MWh/year and the average load between 50% and 55% of the rated power [114]. Again, this population of transformers still contains non-standard components increasing the possibility of failures.

6.6.4. Summary Different Age Population

The main influencing factor on the assessment of the older sub populations, in relation to the benchmark, is that they have higher energy losses. This results in higher operational costs per unit time to compensate for the extra energy required and costs of carbon emissions. These additional indirect carbon emissions also effect the sustainability indicator negatively. The older transformers have a higher level of degradation and consequently score slightly worse on sustainability than newer transformers. The technical appraisal is especially for the older transformers worse due to higher differentiation in transformer types, oils, components etc. This makes maintenance such as revision more difficult. Physically they are still okay,

Constituent	Technical Aspects			Economic Appraisal			Stakeholder appraisal			Sustainability			Strategic Alignment			Risks				
Indicators	Functional requirements	Physical requirements	Operational requirements	Net Present Value	Return on Investment	Total Cost of Ownership	Stakeholder dependency	Stakeholder collaboration	Stakeholder responsibility	Preservation of resources	Environmental impact	Ecological footprint	Business goals alignment	Chain partners alignment	Governmental alignment	Technical risks	Economic risks	Stakeholder risks	Sustainability risk	Strategic risks
Benchmark	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1960	-1	0	-1	0	1	-1	-1	0	0	-1	-1	-1	-1	0	-1	-1	-1	-1	-1	-1
1970	0	0	-1	0	0	-1	0	0	0	-1	-1	-1	0	0	-1	0	0	-1	0	0
1985	0	0	-1	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0	0	0

Table 6 — 3 Assessment for current install base of distribution transformers. Explanation of the assessment can be found in Appendix K. The benchmark (a Dutch Norm 2009 transformer) is set to index 0 as assessments of the scenarios are relative to this.

functionally they start to become limited due to the low capacity they have on average. Considering strategic alignment, the old population of 1960-1970 still complies with the current EU legislation standards on ecodesign for new transformers. As these standards increase over time, they will soon fail them. However, this subpopulation already fails the company's own standard of the 1970 threshold. The 1970-1980 subpopulation also complies with the current EU standards for new transformers, but alike the 1960 population, they will soon also fail these. Finally, the risks of the 1960 population are estimated to be a bit higher than the others due to the larger variation in transformers. Acting adequately on functional changes is therefore more difficult in this population. In addition, the static characteristic of transformers increases the risk that they may not comply with new legislation or new sustainability insights.

Overall the 1960 population scores negative on most indicators, the 1970 population scores significantly better but still negative, while the 1985 is close to the benchmark Norm 2009 transformer.

6.7. Scenarios and Findings on Technologies for New Transformers

The alternatives used for the decision problem on new investments focus on technological innovations. Three alternatives are chosen that focus on different components of the transformer: the core, the coil and the insulator and coolant. These are transformers with amorphous core, an aluminium coil and bio-oil.

6.7.1. Transformers with an Amorphous Core

The core of the benchmark transformer is made from the commonly used cold rolled grain oriented (CRGO) steel. An alternative for the CRGO steel is an amorphous alloy. This alloy mainly contains iron, but due to its amorphous state, it conducts the magnetic flux much better. It is claimed that the no-load losses can be reduced up till 70% compared to the Norm 2009 transformer [128–130]. This would reduce the total carbon emissions from 135 to 72 tonnes of CO_2 over 40 years, a reduction of 53%. Next to that, the production process of amorphous metal requires much less energy due to the simpler production process [131]. Hence, the calculated circular value is expected to be higher than the Norm 2009 transformer. However, in the current calculation energy usage was not included due complexity and uncertainty. Without energy appraisal the amorphous transformer scores a little less (0.265) than the Norm 2009 (0.274) due to the issues with the brittle characteristic of amorphous material (Appendix J.3).

From a financial point of view, the investment costs would be around 20-30% higher than a normal CRGO transformer. If, over a lifetime of 40 years, an amorphous transformer would have an investment cost of 130% of the Norm 2009 and a no-load reduction of 50%, the total cost of ownership would just be a little less (figure 6–11) than the Norm 2009. When the amorphous transformer would reach a 70% no-load loss reduction and the investment costs is

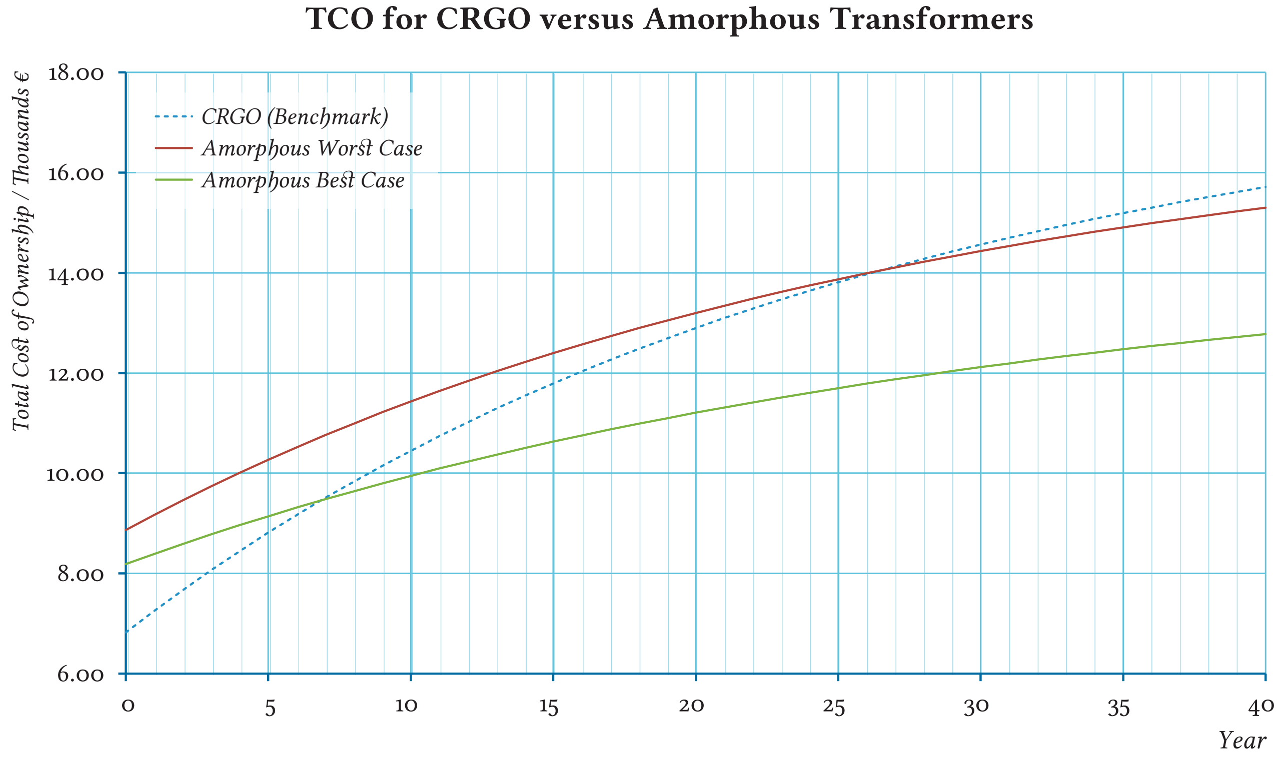


Figure 6 – 11 Total Costs of ownership for the amorphous transformer versus the Norm 2009 benchmark transformer.

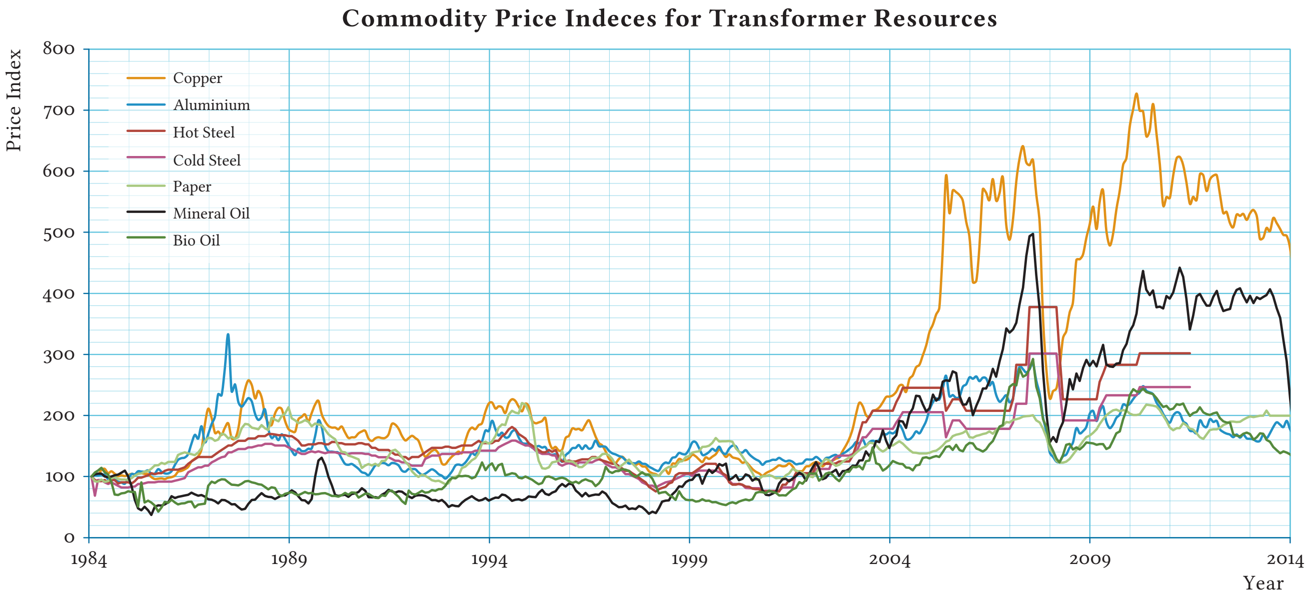


Figure 6 – 12 Transformer Commodities price indices since 1984 [133–140].

only up by 20%, the total cost of ownership over 40 years would only be 80% of the current Norm 2009.

However, recent performance tests carried out by Kiwa (an organisation for testing and certifying electrical components) several amorphous transformers from various suppliers did not pass the minimum required specifications. Especially the specifications considering safety and quality of the energy grid. Next to this, the amorphous core is very fragile and labour intensive. The fragility requires very careful handling and stable conditions. Too many vibrations may cause damage to the core contaminating the oil and reducing its insulating capacity. A last problem is that an amorphous transformer produces more noise than a comparable CRGO transformer. To compensate for the extra noise, the location where the transformer is installed may require more insulation to reduce noise levels.

6.7.2. Transformers with Aluminium Coils

Although aluminium has a lower conductivity than copper, using aluminium for the coils instead has been a widely used practice. Aluminium has the advantage of being lighter and cheaper, but to reach the same rated power a greater volume of aluminium is necessary [132]. This has effect on the dimensions of the transformer and other components. For a 400kVA transformer the overall weight would probably increase for a full aluminium coil. For this reason, many aluminium transformers only use aluminium on the low voltage side.

The advantage of aluminium is the lower price per kilogram [133]. Besides, its reserve to production ratio is greater, making raw material available for a longer period and its price volatility is not as great as for copper. Figure 6–12 illustrates this by showing the price indices for the different transformer resources since 1984. Considering the circular value of the material use, an aluminium transformer is slightly higher compared to the benchmark and scores 0.2776 (appendix J.3). This increase in mass of oil is compensated by the relatively good scoring increase in core and tank steel as well as the aluminium.

Olivares-Galván *et al.* conducted a research to determine the trade-off between the ratio of raw material costs versus the total cost of ownership ratio between aluminium and copper transformers. Figure 6–13 illustrates this trade-off. A tipping-point is found for three different transformers rated at a relatively low power. They concluded that aluminium is a good alternative for transformers below 190kVA considering the total costs of ownership.

6.7.3. Bio-based Oil as Insulator and Coolant

Many small and large studies have been conducted on the use of bio-based oil or natural esters instead of mineral oil as insulator and coolant for a distribution transformer [141–149]. Most common conclusion is that the rate of aging of the insulating Kraft paper is reduced (figure 6–14). This is a critical factor in the duration of the lifespan of a transformer. Once the paper loses its tensile strength and polymerisation short circuits may occur within the coils causing the transformer to breakdown. Bio-based oil may therefore increase the lifespan of a transformer.

Besides the lifespan extension, bio-based oils are claimed to have other advantages over mineral oils. They have a higher fire point reducing the risk of ignition, a higher solubility allowing more moisture without affecting the performance, and it is free of corrosive sulphur. Next to that, bio-based oils have a lower dielectric dissipation factor and a higher breakdown voltage making them more efficient. These requirements are especially important at higher voltages and loads. Bio-based oils are therefore said to perform better at nominal operations.

The environmental impact of bio-based oils is an important topic. Mineral oils are a scarce resource since they are non-renewable. However, bio-based oils are produced from vegetable resources possibly competing with food production. However, the bio-based oils have the advantage that they can bio-degrade after usage while mineral oils are currently incinerated. This causes the circular value of a bio-based oil transformer to be substantially higher at a score of 0.454 (appendix O).

6.7.4. Summary Material Alternatives

The different material alternatives have different impacts on the various constituents of the investment decision model. The technical appraisal is overall negative for the amorphous core because of the recent tests that were carried out. Further development could change this situation. The aluminium and bio-oil alternatives score slightly higher. The bio-oil will not need additional preventive measures against leaking as mineral oil needs. The financial appraisal is especially for the amorphous transformer positive. Even though the higher investment costs, the TCO is lower due to the lower energy losses. These losses are double counted through energy compensation and costs for carbon emissions. The stakeholder appraisal is for the amorphous transformer currently assessed negative in comparison with the benchmark. This is because there are few manufactures of this material creating critical dependency. Next to that stakeholder responsibility is also assessed lower because of the increased noise production. Both aluminium and bio-oil score slightly higher than the benchmark because of ready availability of these alternatives and less social impact due to a safer product. The sustainability scores are generally positive. For the amorphous core, the circular value is slightly under that of the benchmark. But, when including the energy usage during production and use, the amorphous core is assumed to score much better. The bio-oil also scores better than the current benchmark as result of the decreased degradation, the increased recyclability and hence the preservation of materials. For aluminium, there is a slight increase in sustainability based on the circular value. Use of less scarce aluminium s positive in relation to the use of scarcer copper, even though recycling is a little harder. The strategic alignment of the three alternatives all score slightly positive, except for

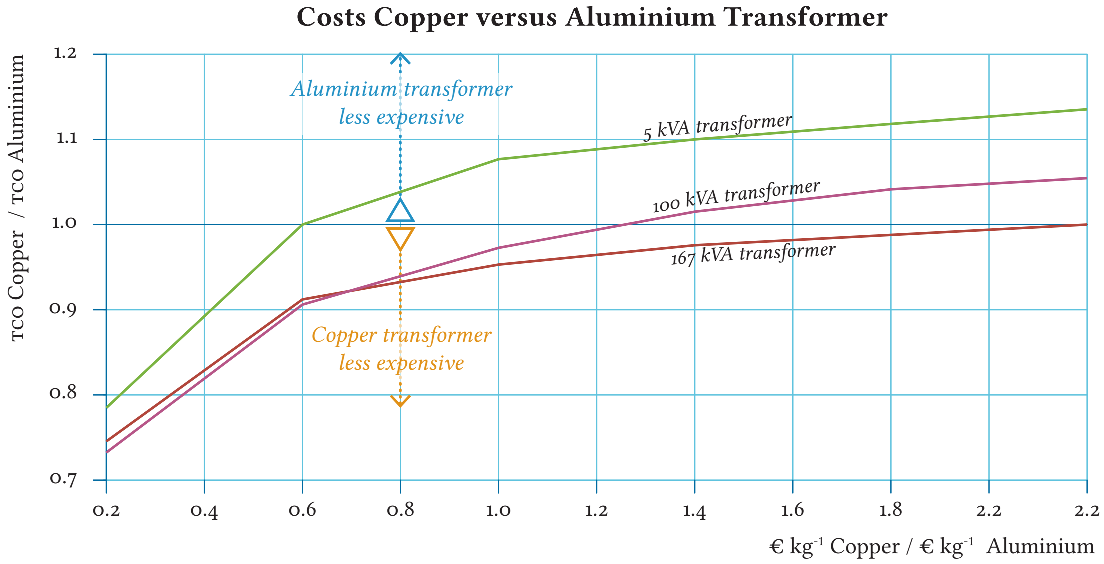


Figure 6 – 13 Ratio of TCO of copper transformer over aluminium transformers as a function of the copper/aluminium price ratio [132].

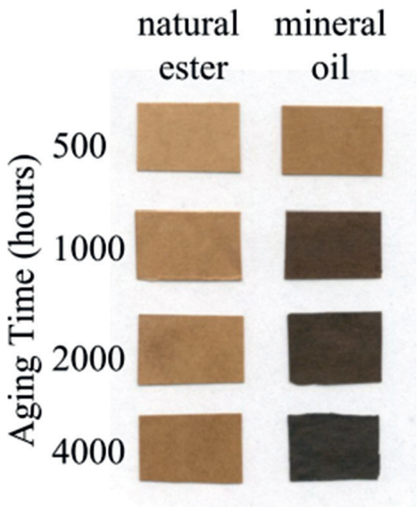


Figure 6 – 14 Kraft paper insulation after being aged in natural or mineral oil at a temperature of 150°C [145].

Constituent	Assessment Criteria																			
	Technical Aspects			Economic Appraisal			Stakeholder appraisal			Sustainability			Strategic Alignment			Risks				
Indicators	Functional requirements	Physical requirements	Operational requirements	Net Present Value	Return on Investment	Total Cost of Ownership	Stakeholder dependency	Stakeholder collaboration	Stakeholder responsibility	Preservation of resources	Environmental impact	Ecological footprint	Business goals alignment	Chain partners alignment	Governmental alignment	Technical risks	Economic risks	Stakeholder risks	Sustainability risk	Strategic risks
Benchmark	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aluminium	1	0	0	0	0	0	0	1	0	1	0	0	1	0	1	0	0	0	1	0
Amorphous	0	-1	-2	0	0	1	-2	0	-1	1	1	0	1	-1	1	0	-1	0	2	0
Bio-oil	0	1	0	0	0	1	0	1	1	2	0	0	0	0	1	1	0	0	2	1

Table 6 – 4 Assessment for distribution transformer alternatives (component related). Explanation of the assessment can be found in Appendix K. The benchmark (a Dutch Norm 2009 transformer) is set to index 0 as assessments of the alternatives are relative to this.

the amorphous on chain partner alignment. This is because current suppliers to Liander are not ready to supply an amorphous transformer that passes all requirements. For the other indicators, the business strategy and governmental strategy are in line with these alternatives because of legislation targets and cost reduction. The risks of these transformers are generally positive as they move ahead of possible problems in the market or changes in sustainability perspectives and legislation. Only the amorphous transformer has a negative assessment on economic risks due to the uncertainty of its return on investment.

6.8. Additional Scenarios and Findings for the Electricity Grid

Three additional scenarios are added to the case study as result of the World Class Maintenance (WCM) Summer School. During the Summer School, several solutions were proposed based on the same case study. To assess them they will also be evaluated as an investment decision problem using the conceptual model from chapter 5.

6.8.1. Installing Transformers in Parallel

The first scenario is to install transformers in parallel. This divides the voltage, and hence the load, from one transformer over two transformers. Since the load has effect on the temperature which translates again into the rate of aging, this process is slowed down. Besides this effect, the total load-losses are also reduced since these load-losses are dependent on the maximum load squared.

The proposed solution considers the use of old transformers that are taken out of the grid due to the current age criterion for phasing out. This prevents the need for investments new in assets. The main problem of this scenario is the space requirement for placing transformers in parallel. Especially in urban areas, space is scarce and there will be little or no room for an extra transformer.

An additional advantage of placing transformers in parallel is the reduced risk of power cuts in the subsequent distribution grid. This will translate in a better performance on SAIDI and create opportunities to test innovations safely without compromising energy service.

6.8.2. Buffers for peak shaving

The increasing variation in load due to the decentralisation of energy production and the increase in energy demand for electric vehicles is a problem

Assessment Criteria																				
Constituent	Technical Aspects			Economic Appraisal			Stakeholder appraisal			Sustainability			Strategic Alignment			Risks				
Indicators	Functional requirements	Physical requirements	Operational requirements	Net Present Value	Return on Investment	Total Cost of Ownership	Stakeholder dependency	Stakeholder collaboration	Stakeholder responsibility	Preservation of resources	Environmental impact	Ecological footprint	Business goals alignment	Chain partners alignment	Governmental alignment	Technical risks	Economic risks	Stakeholder risks	Sustainability risk	Strategic risks
Benchmark	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parallel	1	0	2	1	1	0	0	0	0	1	1	1	0	0	1	1	1	0	1	0
Buffers	1	-1	2	0	1	1	-1	1	-1	1	1	1	1	0	1	-1	1	-1	0	1
CO_2 Neutral	0	0	0	1	1	0	-2	0	0	2	2	2	1	0	1	0	-1	-1	1	1

Table 6 — 5 Assessment for distribution transformer alternatives (non-component related). Explanation of the assessment can be found in Appendix K. The benchmark (a Dutch Norm 2009 transformer) is set to index 0 as assessments of the alternatives are relative to this.

that the current install base is not designed for. Instead of replacing the transformers, the distribution grid could be enhanced with energy buffers that reduce the load on the transformer when either supply or demand is too high.

Possible buffers that could be used are the batteries of electric vehicles (EV). When plugged in, energy could be temporarily stored in case supply is too high and energy can be withdrawn in case the demand is increasing. However using the batteries of electrical vehicles may pose a couple of problems. The first one is that they are not always plugged in and available to use for peak shaving. Secondly, batteries have a limited amount of charge-discharge cycles. Using them as energy buffers would reduce the lifetime of the battery. Dedicated buffers at residences may require an additional investment but will be more reliable than dynamic buffers like electric cars.

6.8.3. Use of CO_2 Neutral Energy Losses

Currently every megawatt hour of energy loss costs €25 of CO_2 emissions. These costs can be eliminated by buying renewable energy to compensate for the energy losses. Depending on the cost price of renewable energy, this change can be a financial benefit. However, buying renewable energy from the market increases the demand and competes with consumers. A socially responsible way is to invest in the production of renewable energy instead. This will require an initial investment but a lower cost of CO_2 emissions and a possible decrease in costs on the energy losses themselves. This more ideal solution is however not possible due to government legislation. Since Liander is a DNO, it is not allowed to produce energy. Therefore, this scenario is just about the less social responsible alternative of buying renewable energy on the market.

6.8.4. Comparing Technological Alternatives

As these three scenarios are not competing, they should not be compared relatively to each other but just to the benchmark. The parallel placement of transformers is assessed relatively positive on most constituents. This is because of increased performance on SAIDI, enabling maintenance without disruptions, reduced energy losses and thus reduced costs and carbon emissions. Also, degradation of the transformers will go slower due to load-balancing. All of this has a general positive influence on the risk assessment and therefore creates windows of opportunities for testing and innovations.

The buffers alternative shows a more mixed assessment in comparison with the benchmark. Some indicators like the economic appraisal and sustainability score better due to reduced load variation on the distribution grid reducing energy losses and degradation of the distribution transformers. In this case, the use of dynamic buffers provided by consumers (such as EVs) is assumed to be used. In case dedicated buffers need to be invested in, the economic appraisal is expected to score negative. The stakeholder appraisal is negative as a critical mass of buffers is necessary to make this technology work well. This increases the dependency on a large number of consumers and the responsibility towards them. As new technologies or economic incentives may likely change the technical performance or stakeholder behaviour, the risk assessment for these constituents is estimated high.

The third alternative of carbon emission reduction scores in relation with the benchmark both positively and negatively. The use of renewable energy instead of the energy mix reduces the costs on carbon emissions and has further environmental positive effects on material preservation, environmental impact and the footprint. The negative assessment is mainly because of the scarce and variable amount of renewable energy available and hence making the dependency critical. The risk assessment is generally assessed positive as a current less sustainable resource is removed. This moves Liander ahead of various economic and strategic trends.

6.9. Results Case Study

Based on the applied model and the data gathering of the different scenarios, various conclusions considering the actual investment decision problems as well as the theoretical model can be drawn. The results of the actual investment decision problems will be discussed in this section. The theoretical conclusions of the conceptual model will be discussed in the next chapter.

6.9.1. Results on Replacing Old Distribution Transformers

The assessment for replacing old distribution transformers can be found in table 6–3. When comparing the various populations with each other per assessment criterion, a slight increase in valuation over the years can be noted.

In general, the sustainability results indicate a negative impact of the older populations. This is mainly due to the use of mineral oil as coolant and the fact that non-renewable energy is used to compensate for the relatively high energy losses. By using carbon neutral energy, the three subpopulations would already balance with the benchmark. Retrofitting the transformers with bio-oil and finding a non-accumulating purpose for the old mineral oil would make these transformers perform better on the sustainability constituent than the benchmark. This would only be useful if the old mineral oil gets a second life and hence does not undergo downgrading or significant material loss. Next to that, the logistics required to execute this process may counter the overall environmental or financial advantage.

The 1960-1970 subpopulation

The 1960-1970 subpopulation is the population that meets the current phasing-out criteria of the 1970 threshold and will therefore be further discussed.

Overall, the subpopulation is scoring lower than the two other subpopulations. Especially the revenue value, which is mainly caused by the energy losses. The stakeholder dependency and stakeholder risks are influenced by the fact that this subpopulation has relatively more suppliers than the other two populations. Most of these suppliers do not exist anymore. The cause of the remaining strategic criteria to score lower is the phasing-out criterion of Liander. These phasing-out criteria are based on a strategic choice to avoid having very old assets in the grid.

In case the phasing-out criteria would be neglected (and hence the relevant strategic business goals), the scores for the 1960-1970 population would be better but still be lower than the 1970-1980 population on stakeholder dependency, governmental alignment, and the economical, stakeholder and sustainability risks.

Conclusion

Linking these results back to the original case study research question, whether 1970 is a desirable threshold, the following can be concluded. The 1960 subpopulation clearly scores less than the 1970 population. This is mostly due to the historic growth of the grid that Liander maintains. Consequently, there is a large differentiation in transformer types and manufacturers. Technically these transformers are still functioning properly with very little failures. The age itself does therefore not seem to be the limiting factor but the standardisation requirements, capacity and efficiency requirements are. Therefore the 1970 threshold seems to be strategically defendable, but may need reassessment in the future when these driving forces for the phasing out criteria.

6.9.2. Results Technologies for New Investments

The assessment shows clear differences between the three technological alternatives. However, no generalisation can be made. The amorphous core scenario scores the worst, and in many cases lower than the benchmark. The bio-oil scores the best but does not differ much from the aluminium scenario.

Aluminium Windings

The aluminium alternative scores a little better than the benchmark. This is mainly driven by the physical characteristics and its material scarcity compared to the default copper windings in the benchmark transformer. Aluminium is less scarce and therefore rates better on the sustainability criterion. This is closely linked to the price variation that is much more stable than that of copper.

Amorphous Core

Amorphous distribution transformers have recently been stress tested and these results have greatly influenced the assessment of this scenario. Due to the negative result the operational requirements and the revenue value are both well below the benchmark. There are some studies on a combination of CRGO and Amorphous cores that try to overcome the problem of brittleness that amorphous metal has [150]. The stakeholder dependency is also rated low, as there are only a few suppliers of the amorphous alloy around the globe, which increases dependency on these few manufacturers. The negative assessment of the operational requirements could be determined to be a veto score eliminating this alternative.

Bio-based oil

The use of bio-based oil has a general positive influence on the assessment criteria. Especially the sustainability is increased. However, there is a small decrease in the operational requirements because investing in bio-oil transformers at the normal rate in which transformers are exchanged, means that during 50 years both types of oil will be present in the total population. This requires operational changes considering logistics and space when maintaining the transformer.

Conclusion

The case study research question for these three scenarios is about which of them would be an economical but sustainable alternative considering energy and material usage over its full life cycle. Unfortunately, not all material and energy usages could be retrieved from the full supply chain. However, based on the available information in literature, company experiences and interviews with supply chain partners some general conclusions can be drawn.

First of all, amorphous transformers are currently not an option, as they do not pass the stress tests. If they would, there is still some room for doubt whether amorphous transformers should already be invested upon. Especially because of critical dependency on manufacturers. Secondly, the fragility of the transformer that may cause a higher failure rate during the installation phase of the transformer (see figure 11–21, bathtub curve). Lastly, because amorphous transformers produce more noise, they require more insulation and space. This is not always available.

The transformer with aluminium windings scores a little higher than the benchmark on several constituents. It is a readily available option and is often applied partially by having the low voltage coil in aluminium and the high voltage in copper. The bio-oil scores better on the sustainability and stakeholder constituents than the benchmark. This is because the use of bio-oil has several positive effects. It avoids the use of scarce mineral oil, which is currently incinerated after usage, possible toxic effects of leakage are avoided and degradation of the transformer is at a lower rate. Within this assessment, the use of environmental responsible feedstock has been assumed. In case the source of the bio-oil is from a source that has negative impact on natural capital this assessment is not valid.

6.9.3. Results Additional Scenarios

The three additional scenarios that were assessed are physically non-component related. However ,they do influence the performance of the transformer as well as the overall energy distribution, stakeholder relations and other business case constituents. Due to the different nature of each alternative, there are no generalisations that can be drawn about all three.

Parallel Placement

Parallel placement of the transformers helps to reduce the load and extends the life of a transformer influencing the sustainability aspect positively. Also, advantage is gained at the technical aspect because currently installed transformers can be reused creating redundancy in the grid. No new knowledge is necessary while it allows for more flexibility in maintenance.

Buffers

The scenario in which buffers are added to the grid to achieve peak shaving is for some constituents relatively positive and on others negative in relation to the benchmark. Because of the addition of extra assets in the grid to connect the buffers, increase in costs are expected for materials and maintenance.
In this scenario, the availability of the buffers is uncertain because the batteries of EVs are assumed as the buffer. This has a clear negative effect on the stakeholder dependency and responsibility. The risks are therefore not unambiguously positive. However, the operational requirements are assessed very positive because it does reduce the operational intensity of the distribution grid and the required investments to increase the capacity of cables and transformers.

Carbon Neutral Energy Losses

The alternative in which carbon neutral energy is bought to compensate for the energy losses is also assessed both positively and negatively alike the buffer scenario. Its main difference is however, that for the buffer new assets need to be invested while for the carbon neutral scenario no new assets are invested but the energy is yearly purchased. This difference in ownership clearly shows in the stakeholder dependency. A large positive influence of this scenario is seen for the sustainability aspect in the model. The usage of carbon neutral energy prevents the burning of material and the accumulation of the emissions.

6.9.4. Secondary Results

The case study also resulted in a couple of secondary results. The Material flow analysis and the Circular value will be discussed.

Material Flow Analysis

The Material flow analysis as shown in figure 6–6 has been composed based on the known component masses of the norm 2009 transformer. The model may be misleading as the exact material used for one single transformer is not used for another transformer. This is because most material is returned to the global resource pool after recycling, allowing it to be used for other purposes. However, it shows that mathematically most of the material used is already flowing in a circular cycle. Even though this diagram gives insight in the current material flow it does not give a fair insight into the circular value of a transformer as the virgin material flows are not quantified. Hence, the diagram does not show how much material can be accounted for by recycled and virgin sources.

Circular Value of a Transformer

The circular value of the Norm transformer was calculated to be 0.2741. This value can be translated into 27.4% of the mass of a transformer being fully circular. Meaning that at least 27.4% of the mass is preserved, does not accumulate or is virgin material that is retrieved from renewable resources. Using bio-oil clearly improves the circular value as can also be expected from the material flow analysis. In the MFA, it shows that the mineral oil drains out of the system and is lost due to incineration. When using a compostable bio-oil the material can be preserved and regenerated using natural processes. Besides, it is assumed that the bio-oil is produced from abundant resources with an unlimited reserve to production ratio. Both factors increase the circular value from 27.4% up until 45.4%. This would meet the goal Liander set itself to have 40% of the bought kilograms of assets be circular by 2020 [44].

It must be noted that the current calculated circular values are only based on first order material use. Higher orders that account for the production process of components or to generate the required energy for the production process is not yet taken into account.

6.10. Discussion of the Case Study Results

Three decision problems have been assessed and evaluated using the conceptual model. Within the decision problem on the various technologies it should be noted that these technologies are not distinct alternatives. Various transformers have been developed that combine two or more of the technologies. For example aluminium transformers that use bio-oil as coolant. However, for the case study the choice has been made to pose these alternatives as the decision problem such that clear differences can be identified by means of keeping all variables the same but one.

Looking at the research and assessment, the scope was mainly kept to first order impacts. Impacts that can be partially accounted for by the investment decision that occur further down the supply chain were at this stage not equally known for all alternatives. This problem is the result of various reasons such as unwillingness of suppliers to share this information, suppliers that have not yet investigated these impacts, or the lack of information which producers are part of the supply chain. Liander is currently contacting more of these higher order suppliers such as copper smelters to initiate the dialogue on circular economy and acquire more information on the various impacts.

6.11. Evaluation Investment Decision Model

In chapter 5 there has been an initial evaluation based on the theoretical match between the conceptual model and design criteria. Some design criteria required a case study for further evaluation. These criteria will be evaluated once more. Next to that, other findings considering the application of the conceptual model will be discussed. These findings are based upon evaluations as presented in previous sections and Appendix K.

The three design criteria that required further evaluation are:

» Applicable tool to show trade-offs,
» Create transparency in decision making process,
» Practical for decision makers.

The application of the model within the case study created new insights with regards to the trade-offs defined in the problem definition. To get these insights an extensive research into the alternatives had to be made using various tools to retrieve the necessary information. In the case of Liander, some information was already available from previous studies. However, the issue was raised that, depending on the actual decision problem, this model could still require too much time to apply. It is therefore suggested that the actual constituents that will be assessed are clearly defined before the investment proposals are developed.

Other feedback given considered the necessity for a clear definition of the various constituents and their indicators. Even though definitions were given, it was for some difficult to determine what they would actually mean in this context. For that reason, supporting questions have been developed to support the line of thinking. These questions have been included in the manual for the investment decision model as can be found in Appendix H.

Another issue raised was the scoring method. Some people preferred a numerical scale while others preferred a more abstract scale such as plusses and minuses. This is an issue not inherent to the model. Instead, the decision makers that will execute that analysis should agree upon this.

In general, the resulting feedback was positive on the design criteria describing the need for creating overview of the trade-offs and creating transparency. Creating transparency is expected to become more easily as a simple table with additional notes may create easy supporting evidence for a decision. While previously this would have required more textual explanation considering the constituents that were not included before. Also trade-offs can be easily identified or falsified based on factual information and coherent assessment.

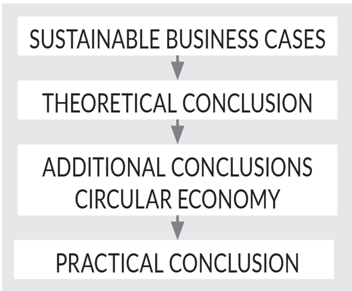
6.12. Conclusions

The execution of a case study supported the evaluation and development of the conceptual investment decision model. The conceptual model is found to provide a more comprehensive overview that supports the prevention of unsubstantiated theoretical discussions.

Next to the operational evaluation, the case study also resulted in findings on various investment decision problems within Liander. These findings do not give an absolute conclusion on the best alternative but should be looked at as a guide for possible future decisions on transformer investments. One of the main findings based on environmental sustainability support the use of bio-oils over mineral oils. The use of transformers with an amorphous core is greatly influenced by the low assessment on operational requirements and the stakeholder dependency.

7. Conclusions

Taking responsibility for the environmental impact has gained more attention by companies over the recent years. Because of legislation many organisations have started to account for carbon emissions, however some people say that this is not enough. The sustainability of a company is not only affected by the financial consequences of its carbon emissions but also on other aspects relating to the environment. Including a holistic approach on sustainability within the business may even lead to competitive advantage and stability of the supply chain, hence creating financial benefits.



Outline Conclusion Chapter

To effectuate this competitive advantage and these financial benefits, sustainability needs to be effectively accounted for and secured within business processes. This may be done within design stage of products, their business model or throughout the business case. Within this study, the business case has been taken as a business process to secure the element of sustainability.

This study researched this topic through the development of an Investment Decision Aiding methodology that includes sustainability (SIDA) for asset investment within Liander. The Circular Economy has been used as a guiding paradigm to define the sustainability constituent within the methodology. A case study on distribution transformers was used to test this. This chapter will discuss the main conclusions that can be drawn from the research as described in this thesis. First the theoretical conclusions will be discussed guided by the research questions (chapter 1.3) after which the conclusions on practical questions, discussed in the case study on distribution transformers, will be addressed.

7.1. Sustainable Business Cases

The main research question considers how Circular Economy can contribute to a sustainable business case within the field of asset management. A sustainable business case can be established both on the framework of the business case as well as on the execution of the business case such as through investment decisions.

Basic Characteristics of a Sustainability Business Case

Making the framework of a business case more sustainable requires it to account for all future opportunities and risks that may influence its success rate. Traditionally companies have been considering the financial aspect as it affects the total financial viability of the company. For companies within the infrastructure sector such as grid operators, reliability of their assets is just as important since they constitute the core business. To achieve this, technical characteristics, stakeholders, strategy and risks are important elements to consider as the business operations is dependent on them. Additionally environmental sustainability should be included as it affects the operations environment and the supply chain of the business. Not only stakeholders may request the inclusion of environmental sustainability into the business, it is also argued to increase the competitive advantage of the company. A sustainable business case is thus a holistic approach that accounts for all factors that influence the company's performance and the externalities the company has influence on.

Investment Decisions as managing tool for the Business Case

The research focussed on the use of asset investment decisions, as these are methods to execute the business case. They occur at the initial phase of the asset management cycle as well as throughout the life span of the business case. By changing the decision parameters and the valuation of the alternatives, the business case and the asset management organisation can be managed to account for the changing environment and make the asset base more robust, flexible and sustainable.

To align the investment decision with the business case, the decisions parameters should match the main constituents of the business case. Therefore, the developed sustainable investment decision methodology within this study considers the following six constituents:

- Technological appraisal
- Financial appraisal
- Stakeholders
- Environmental sustainability
- Strategic Alignment
- Risks

Reduce Complexity in Investment Decision Aiding

The decision making paradox, which says that the choice of the best decision methodology can only be determined after the decision has been made, argues in favour of a non-deterministic decision methodology that aids the decision making process by increasing transparency and make trade-offs visible. In combination with the Bonini paradox that describes the trade-off between a comprehensive but non-complex decision method, it is concluded that the decision making process should be supported by a multicriteria decision aiding method. Decision makers will have a comprehensible overview of the various alternatives enabling them to support their decision.

7.2. Circular Economy is part of Environmental Sustainability

The new constituent that has been added to the investment decision methodology is environmental sustainability. The aim of the research was to include the Circular Economy paradigm to account for a more sustainable business case that considers new factors such as resource scarcity and material reuse.

There is no Coherency within the Paradigm of Circular Economy

Within literature, there is no coherency on the definition or characteristics of the Circular Economy. Commonly addressed are the economic benefits of implementing the paradigm through new business models, focussing on recycling, or implementing methods from other paradigms such as Cradle to Cradle or Industrial Ecology. Differences also occur between the different sectors of application, the locality of application and the scope of application. A similarity between the perspectives of the Circular Economy is the need for effective use of materials through recycling or reusing, supported by the knowledge that materials are becoming scarce.

Circular Economy is part of Environmental Sustainability

Material scarcity is a phenomenon inherent to the Earth and hence to the environment we live in. Since all our materials in the economy are extracted from the environment, scarcity of these materials requires us to act responsibly towards the environment such that it can sustain our economy. Next to that, the materials that are excreted from our economy into the environment in the form of emissions and waste may have additional negative effects on future resource availability. It is therefore that Circular Economy propagates effective material usage, through reuse and recycling, and avoiding accumulation of materials useless to the economy or environment.

Next to material usage, two other aspects influence the environment. These are the usage of non-material resources and externalities causing physical changes in environments or organisms. These two can be identified as the ecological footprint and environmental impact. This results in the following three elements that define environmental sustainability based on a Circular Economy perspective.

1. Material usage: The quantitative effect on global *stock* of materials (stock within ecosphere and economy);
2. Ecological Footprint: The quantitative effect on the global *capacity* to generate new materials and act as sink (fisheries, forests, land, water and air);
3. Environmental Impact: A qualitative effect of economic activity on other elements in the environment such as the ecosystems.

7.3. Additional Conclusions on the Circular Economy Paradigm

Next to the conclusions relating to the implementation of Circular Economy as paradigm for environmental sustainability within business cases, more conclusions can be drawn on the theory of the Circular Economy.

Economic and Social Aspects of the Circular Economy are Secondary Effects

The Circular Economy promotes the efficient and effective use and reuse of materials to avoid the consequences of scarcity and waste. Economic reasons are generally given for advocating the Circular Economy, but these effects are a positive consequence of creating new business cases based upon the understanding that materials are scarce. It can therefore be argued that the economic effects of the Circular Economy are secondary to the environmental effects of the paradigm.

Equally, social effects can be seen as secondary effects of the Circular Economy as well. A social effect often promoted considers the creation of extra jobs. However, handling one's resources more sustainable may increase quality of life because of reduced pollution, increase in quality of nature and better availability and choice of products.

Ideally Energy Usage is not Important in the Circular Economy but Currently it Still Counts

Energy is used throughout the life cycle of materials, and therefore to keep them flowing in cycles. Energy is thus an important element to consider. Ideally, energy is retrieved from unlimited natural resources (renewables) such as the sun, wind and water. However, in case energy is retrieved from incineration of materials (non-renewables such as gas or coal), the process that uses this form of energy accounts for a higher order circular economy effect. A higher order effect means that making the choice for a certain resource, the choice includes the shared responsibility for the externalities that are caused throughout the supply chain. Hence, these externalities should also (partially) be accounted for within the decision.

Therefore, in case only renewable energy is used, the energy usage is not as important as it does not influence material usage. But in the current industrial system a majority of the energy is still retrieved from incineration. For this reason, energy usage should still be taken into account when evaluating the circular value of a product.

The Level of Recycling is by Definition not Important to Resource Sustainability

The Circular Economy is often depicted by the various levels of recycling (from reuse to recycling) and indicating that reuse is better than recycling (figure 3–2). From a Circular Economy perspective, in which material preservation is important, this is a misleading premise. In general, the higher-level recycling loops use less energy and therefore less resources, however this is not the case for every process or material. In several cases, reuse would require a lot of energy due to transportation requirements or refitting requirements and thus a lower level loop would be much more efficient. In the end it does not matter in what way material and its quality are preserved, as long as it is done. Taking into account the energy usage instead of looking at the recycling level would result in a more complete evaluation of the circular value of a product or systems. Higher levels of recycling are, if implemented well, often cheaper than lower levels of recycling.

7.4. Addressing Practical Questions for Liander

The case study was used to further evaluate the developed decision aiding methodology SIDA, but at the same time, various questions could be addressed considering distribution transformers. Two main research questions were identified for the case study. However, due to the character of the decision aiding methodology definite answers to these questions cannot be given, only suggestions can be made. More detailed results on the case study can be found in chapter 6.9.

The 1970 Threshold is Currently a Defendable Threshold, but May be Changed over Time

Transformers manufactured before 1970 use relatively more energy than new transformers. This causes higher operational costs than younger transformers. But because their depreciation costs are written off their financial performance is neutral compared to current norm transformer. However, on most other elements these older transformers perform worse than this benchmark.

From a reliability point of view, old transformers do not underperform compared with newer transformers, but they do not match the current technical standards or capacity requirements anymore. In the locations where they still have a sufficient capacity, these transformers are good to be kept. Maintenance, sustainability and risk performance is all slightly underperforming to the norm. Concerning sustainability, they generally still comply with the current EU guidelines on ecodesign. But, within a couple of years they will fail these due to increased standards. Looking at other developments such as the growing number of PV panels, the transformers are expected to handle higher loads. This could cause these transformers to be too small concerning their rated load leading to an increase in failures.

Younger transformers of succeeding subpopulation perform a bit better in the assessment than the 1960-1970 population. Although the 1970-1980 population may fail the EU guidelines in a couple of years, its overall performance is less critical than the 1960 subpopulation. Therefore, it is concluded that the strategic threshold of 1970 is defendable to slowly phase out transformers manufactured before this year. Transformers manufactured after, may soon also qualify for phasing out if trends continue and similar assessments are made.

Bio Oil Transformers may be a Sustainable Alternative for New Investments

Various technologies can be chosen when investing in new distribution transformers. Comparing the aluminium, amorphous and bio-oil alternatives with the current standard argues mostly in favour of bio-oil. The aluminium distribution transformer does not differ much in advantages and disadvantages over the default norm transformer. The transformer with amorphous core has recently failed important load tests. Next to that there is not much known on the actual lifespan due to the expected fragility of the technology. This results in many disadvantages compared to the benchmark. The bio-oil has not been tested within Liander's grid, but based on experience of a German grid operator and rather a large number of reports and papers written on the topic many advantages are put forward. Next to that, the calculation on the circular value of the bio-oil distribution transformer shows that it achieves the goal set by Liander that 40% of the bought kilo's should be circular in 2020. The only drawback of implementing this option would be the additional type of oil that needs to be handled during maintenance. To tackle that, investment in logistics and administration will be required. In case the current mineral oil would be regenerated for reuse and not incinerated after its lifespan, it could compete with most of the advantages of bio-oil.

Investing in Energy Efficient Distribution Transformers Benefits the Circular Economy

A commonly discussed trade-off within the asset management of distribution transformers is the prolonging the life of old transformers or investing in more energy efficient transformers. This trade-off mainly depends on two factors: the current state of recycling of transformers and the type of energy that is used. In case of an abundance of renewable energy, keeping old transformers may be better from a circular economy perspective since no material will get lost. However, in case non-renewable energy is used the quality of recycling becomes an important factor to consider. In case of low recycling quality, high quality material will get lost through downgrading into low quality material. In case both the material and energy losses can be quantified such that they can be compared, an optimum could be calculated how long one should postpone replacement. Since distribution transformers can already achieve a high percentage of recycling and energy losses are compensated with non-renewables, it can be assumed that replacing old transformers for more efficient transformers benefits material preservation on the long run and hence the Circular Economy.

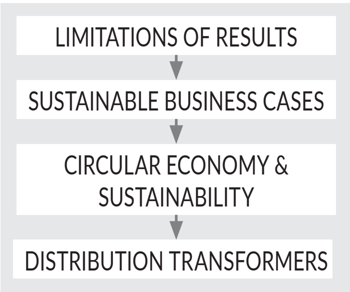
7.5. Conclusion

Accounting for environmental sustainability within the business case and within investment decisions supports the business to become more resilient against changing environments while creating the incentive to positively influence the environmental impact. These effects on their turn affect the financial and social impact of the business through increased competitive advantage, new business models and jobs.

To support the decision making process within investment decisions a decision aiding methodology can be used to help make the decision process less complex and more transparent. For asset investment decision within the energy infrastructure sector six main assessment criteria are suggested: Technical appraisal, Financial appraisal, Stakeholders, Environmental Sustainability, Strategic alignment and Risks valuation.

The research touched upon various topics through various forms of research. To put the results and conclusions in the right context and perspective, this chapter will reflect on them by discussing the limitations of the research results, various research decisions and assumptions made throughout the study. Next to that, possible alternatives or improvements will be addressed. First, the limitations of the research will be discussed after which the various topics of the research will be addressed.

8. Discussion



Outline Discussion Chapter

8.1. Limitations of the Research Results

The research aimed at developing an investment decision methodology that includes environmental sustainability. The research methodology used is Design Science Research, which allows for developing additional knowledge within the field as well as an artefact that can be used by practitioners. The limitations of this methodology have already been discussed in section 2.4, however, the research results are also subject to validity, reliability and generalisability limitations.

8.1.1. Validity

Concerning the research results, the question can be asked how valid they are. The validity within this study is mainly related to the scoping. For example, the environmental performance of the transformers has been based on first order circular value calculations. A more thorough overview would have been generated if a larger part of the supply chain had been included within the evaluation. Especially because mining of ores or energy demand for production of a distribution transformer may have a quite large impact on the overall performance of a decision alternative. Because it was not equally possible for all alternatives to determine the impact to the same level, it has been chosen to keep indirect impacts out of the scope. Liander is currently in the process of aligning their Circular Economy ambitions throughout its supply chain. This may help to base future investment decision on more complete information.

8.1.2. Reliability

The reliability of the research results considers how replicable they are in a future research. This differs for the literature research, the theoretical methodology and the case study. Each of these will be discussed.

Theoretical Reliability

The reliability of the study can be mainly tied to the data used within the study. From a theoretical point of view, there are some comments to be made concerning the reliability. First of all there is a lack of scientific literature on the Circular Economy paradigm considering the scope of this study: micro, asset management based, within the Netherlands. As noted before, most of the literature is based on Chinese scholars or on reports by commercial organisations. These organisations have a specific agenda with promoting the Circular Economy. To tackle this, a broad view on the Circular Economy has been used including the use of various related models.

Next to that, the theory on the business case and investment decisions is largely influenced by IT related papers. Specific literature on business cases within the electricity distribution sector is scarce. To overcome this, the literature review has been broadened to a more general infrastructure scope. This reduces the reliability on specific practices within this field.

Reliability of the Methodology Execution

The model has been evaluated in line with the Design Science Research methodology: using a case study and by evaluating the results and its application. However, a single demonstration of the model in a controlled case study does not benefit its reliability. If the model would be subjected to additional case studies, its replicability could be evaluated in support of the reliability. This would also benefit the consistency of the decision evaluation execution.

Reliability of the Case Study

The reliability of the case study on distribution transformers can be discussed based on the data that was used to evaluate the various alternatives of the transformer. Liander provided for most of the data used. However, some additional information had to be gathered or generated to apply the decision model. One of the alternatives that required extra data collection considered the bio-oil based transformer. For this, a combination between scholarly articles and data request for manufacturers was used. Especially the information returned from the manufacturers was, because of secrecy and competitiveness reasons, incomplete. Therefore, assumption or extrapolations had to be made.

8.1.3. Generalisability

The research was scoped to distribution transformers and the infrastructure sector using specific models and methodologies. But, can the results be generalised and extrapolated to other sectors?

Generalisability of the Scope

The main scoping is based upon Liander's position: (1) a company with a large distribution infrastructure in (2) the Netherlands. The sector scope (1) relates to companies with a large asset base that need to be reliable and long lasting. Asset manufacturers or companies in a total different sector, such as the fast moving consumer goods, may require completely different configuration and valuation of the business case elements. Secondly, (2) the company, being located in the Netherlands, is required to adapt to national and European legislation. Next to that, because of Liander's widespread infrastructure in a densely populated country, it is necessary to account for effects on other infrastructure, housing and other social and environmental aspects. These are more broad effects than simply accounting for environmental sustainability as requested by Liander. But it places the research topic in a specific area of application, and hence, how aspects like stakeholders are included within the decision model. Other regions, which are less densely populated or do not have a high density of infrastructural elements, may also require different characterisation and valuation of the important aspects within a business case.

The main models and literature used for this study are not restricted to this specific area of application. For example the FSSD model is much more on a strategic and general level and assumed to be globally applicable [151]. Since the SIDA model is customisable by the user through adjustment of the indicators and weighing, the model is potentially applicable to a wider range of sectors in which the six main constituents (financial, technological, stakeholder, strategy, sustainability and risk appraisal) are relevant business factors.

Generalisability of Theory Application

The implementation of the various theories such as the decision-making theory, business case methodologies and sustainability are based upon the scope as defined above. The decision making approach for this design problem was assumed to be positivist and composite of character. On that basis, the different constituents and structure of the SIDA model were determined. That means that the model is only applicable to similar design problems in which a positivist and composite approach is required.

Using the Circular Economy paradigm is very specific choice to base the environmental sustainability framework upon. As shown in the literature review there is not yet much consensus amongst scholars on the principles of the Circular Economy. Within this study, a combination of the various applicable approaches has been used. Even so, the framework resulted in three indicators (material usage, ecological footprint and environmental impact) that are expected to be applicable to other commodities.

Generalisability of the Model

Because the case study was about distribution transformers, which are relatively simple and robust assets with a low maintenance demand, some design criteria for the model were based on this asset type. For example the importance of understanding the differences between physical and functional characteristics of the asset. This resulted in a clear required distinction of physical, functional and operational technological appraisal within the model. Alternatively, in case the life cycle stages determine of the asset's technological impact, a distinction made these stages would be more beneficial. For example assets with a higher maintenance impact, shorter life time or heavy impact production and disposal due to toxic contents. A different approach may help to create different incentives for creating decision alternatives and finally result in a different decision.

8.2. Sustainable Business Cases

Including sustainability into the business case was one of the aims of this research. In chapter 3.3 the advantages and the need for more research on the sustainable business case were already discussed. Next to that, some extra discussion points should be addressed.

Sustainability Requires a Resilient Business Case

Environmental sustainability and social responsibility are elements of sustainability that do not change abruptly as they are related to many different factors that tend to move slowly. So, to enable a business to become environmental sustainable and social responsible, it is necessary that it can take actions and measure its impact over a long period. A prerequisite is therefore that the business remains viable over the long run and can withstand internal and external threats. To do so the business case should be resilient towards these threats through accounting for possible changes of the case. A certain level of flexibility within the business case would support necessary adjustments that may be required.

Silvius [98] and Trigeorgis [98, 102, 106] have suggested a way to include flexibility in the business case through financial accounting. This would be a good start to include this within the business case, but it can be argued that flexibility should also be accounted for in other elements of the business case, such as stakeholder appraisal or sustainability.

Risk valuation of these elements is not the same as flexibility. Flexibility should provide for possible adaptations that can be made within the business case while risk valuation is mere a valuation of the possibility that the business case may not turn out the way it was planned.

Trigeorgis suggests to make use of the game theory to implement this form of flexibility into the business case. However, this is an extensive and time-demanding method. As he suggests himself more research on this topic needs to be done [106], and with extending flexibility valuation to the other constituents of the business case future research should also focus on that.

Liander is currently implementing the TECK method (as discussed in section 5.1.1) to identify possible scenarios over the life cycle of an asset introducing a certain level of flexibility into the asset management. Integration of this method into the asset investment decision process could be an option to further include the necessary flexibility.

Business Flexibility requires Management of Competencies

One of the main elements influencing flexibility within the business case considers the organisations current capability to adjust to changes. In other words, what other actions, opportunities, business models, etc. can be adopted by the business with the current means to adjust to changes. These means are the people, their knowledge, the capital and all other resources that the business has direct access to.

To know what these means or competencies are, and how they can be capitalised, they should be identified and kept up to date. For products, some proposed tools could keep track of this data. The resource passport as researched on by Aimée [85] mainly considers the products and the materials. Especially so, because it is developed within the perspective of the Circular Economy. For a more thorough tracking of a company's potential competencies, the resource passport could be extended to account for the other means besides products and materials.

8.3. Circular Economy & Sustainability

Next to the sustainable business cases, a major part of the research considered the Circular Economy paradigm and its relation to sustainability. Various points of discussion were identified throughout the process. Unfortunately only a selection of the most relevant and interesting points will be discussed here.

Need for Coherency within Circular Economy

One of the most important findings considered the lack of consistency, especially amongst scholars, on what the Circular Economy actually refers to, or what its 'principles' actually are. As identified during the literature study, differences were especially to be found between scholars from different countries, the perspective of the subject (micro, meso or macro), or the background of the author (commercial, non-profit, academic). This leads to lousy claims based on the Circular Economy, a broad interpretation of what accounts as Circular Economy and hence a devaluation of the popularised term Circular Economy.

More consistency and agreement on the paradigm amongst scholars would benefit, especially if their scoping is to acknowledge when claims are made. Not only more research could benefit, but also a better cooperation, something that is, ironically, often propagated in reports on the Circular Economy.

Changing Trends within Sustainability

Within this study, the Circular Economy has been used as paradigm for sustainable business cases. This paradigm has gained attention in Europe since 2010 and focuses on material usage. However, an element of sustainability that still receives more attention is carbon emissions. Carbon emissions became a trend within sustainability about ten years ago when scientists started reporting on global warming. Before this, other trends have been a centralised discussion such as acid rain from pollution and ozone layer depletion caused by CFC's, and so on. Hence, there can be various trends identified considering environmental sustainability that last for a few years up to a decade. Focussing on a specific paradigm, which influences for long term planning, means that there is a big chance that during that period the attention may shift to new paradigms. It is therefore important not to follow a paradigm because it has gained attention, but to do this because its basic principles are relevant. For example for Liander, the assets that are invested upon outlive these sustainability trends. It must therefore not be the popularity of the Circular Economy paradigm, but the conviction that the motives of the Circular Economy, the scarcity of resources, are the reason for adopting it.

The developed SIDA model uses six constituents of which one assembles the environmental sustainability indicators. These indicators are based upon the Circular Economy paradigm as described in chapter 4. But the model gives room for adjustment of these indicators in case the perspective on environmental sustainability changes.

Product versus Service

A new business model that is commonly referred to in relation to the Circular Economy is making services from products. Examples are the sales of lumen instead of light bulbs [152], but more well-known is the library for renting books instead of selling them. Even though this model may have financial benefits and reduces costs while giving a better service to customers, there may also be some negative effects.

Once customers are not the owners of a product anymore, there is less incentive to feel responsible towards it. For certain products this may not be much of a problem such as light bulbs as people don't have the tendency to use them in such a way that they may damage or break easily. However, in other cases, for example books, the chances of quicker quality degradation are higher. For larger products, assets or spaces it may even become more problematic to the manufacturer who now rents the commodity. Renting may cause the customer to easily move to a competitor while the costs of the product investments have not yet been returned, it may cause economic deficits. A common example of this situation is the high vacancy of office spaces. There may be several reasons to this: the customer demands new standards within a relative short time period in relation to the office life time; a decrease in need for office space due to trends in flexible working; or the lack of financial resources.

A second negative effect of the service business model considers the trend of social platforms that focus on sharing products. This may in general have a positive effect on environmental sustainability because less products are necessary to fulfil the demands of the consumer. However, these platforms may create the negative incentive of buying new products such that it can be offered for "sharing". This is because a refund is given to the owner for sharing its product with others. In other words, the sharing principle may actually increase the demand for certain products. A recent example of this is Uber for which people start to buy new cars to offer a taxi service [153].

If a DNO like Liander would like to use product service systems instead of buying its own assets, there are some advantages that can be thought of. For example, the driving force of the asset price is its material contents. This can now be taken out of the investment costs in case the manufacturer stays owner. The manufacturer would also become more responsible of the maintenance of the assets. However, these changes would cause several issues.

First of all, the question is whether this does not infringe the legislative tasks that Liander is subjected to. Considering operation and maintenance of the grid, Liander wants to have a reliable grid and is willing to pay extra for that. The manufacturer may have the incentive to lower costs, which could be at the costs of availability and quality of the electricity service. Of course, one could try to overcome this through contracts, but to be able to transition to a business model both parties need to benefit.

Then there would also be problems that are more practical. For example, the expertise on maintenance that Liander has but manufactures generally lack. Hence, the expertise would need to be transferred and costs may not necessarily lower. Another practical issue is the financial capital that the manufacturers would need to become asset owners.

A possible solution for these issues, as well as the more general issues on product service systems may be overcome by implementing a form of shared ownership. Both parties may get the incentive to create a sustainable and effective product, use, and maintain it in a proper way. This form of cooperation would however require a high level of trust and stakeholder alignment.

Social Sustainability

Next to changing trends in environmental sustainability, social sustainability gains more attention in recent years. For example, the social impact of clothes fabrication in low-wage countries like Bangladesh has been in the spotlights. Next to that, in the electronics sector a company called FairPhone was initiated to focus on the social aspects of electronic devices by creating a positive social impact and using conflict-free materials. It may be likely that this trend of social impact will gain more attention in other sectors as well.

In relation to the Circular Economy, there are sometimes calls for developing new disruptive business models by people or organisations that promote the paradigm. Online applications that offer a service instead of products are often taken as example. These applications may cause negative social consequences because their disruptive models are often examples of solutions that bypass current welfare system such as minimum wages, pensions and other social securities. Hence a cost reduction is achieved, but at costs of the income and job security of people.

When developing such businesses these externalities should therefore also be acknowledged and accounted for. This does not necessarily need to be in the form of compensation as this may make the new business model financially unrealistic, but creating opportunities and giving answers to the problems that one's externalities cause is the least that could be done.

8.4. Distribution Transformers

Next to the theoretical points of discussion, the case study on distribution transformers also resulted in a couple points of discussion.

Energy Reliability Drawbacks

The state of the energy distribution grid in the Netherlands is highly reliable and the SAIDI is relatively low. DNO's in the Netherlands have a financial incentive to perform well because an independent watchdog, the ACM, judges them. The ACM can determine the fee DNOs may ask their consumers as well as financially sanction the DNOs in case of malperformance. These financial incentives do not only result in high reliability of the energy supply, but also reduce the space a DNO may need to test and implement new technologies.

With regards to the Circular Economy, and especially based on the preceding paradigms of Cradle to Cradle and Biomimicry, that promote diversification as an important method to achieve sustainability, the current financial incentive has pushed DNOs to a very uniform system. This uniformity makes the system reliable if demand and supply keep the same characteristics over time. However due to decentralisation of supply, for example through PV cells, the energy characteristics are starting to change. More diversified solutions for energy supply would therefore be welcomed, but due to the reliability requirements, DNOs are hesitant to test and implement these new solutions.

A possibility for reducing the characteristics of the energy supply is the use of peak shaving. This can be achieved through local energy storage. Local energy storage has, in addition to positive effects on the demand capacity, also the possibility to accommodate for power cuts caused by testing new technologies. Hence, reliability of energy supply does not need to be compromised while creating space for DNOs to test new technologies.

Accounting for Energy Losses

Distribution transformers have inherent energy losses that are compensated for by feeding extra energy into the system. This compensation is the responsibility of Liander. It results in additional operational costs to buy the energy as well as the costs of carbon emissions. Switching to renewable energy would avoid the costs for carbon emissions and have a positive effect on material usage. However, the amount of energy loss is not reduced and "scarce" renewable energy is used making it possibly more expensive to consumers. It would therefore be more responsible if the energy losses were not just compensated with renewable energy, but with energy that has been produced by Liander for this purpose. This creates an additional incentive to focus also on reduction of the energy losses, as it would make the investment in renewable energy financially more feasible. Unfortunately, legislation currently prevents Liander from producing its own energy as it has the sole task of distributing the energy and maintaining the grid.

9. Recommendations

Outline Recommendations Chapter

After the conclusions and points of discussions in the previous chapters, the thesis will end with the recommendations as a practical summary of the study. The recommendations are split into three parts, the theoretical recommendations considering the theory and developed model, the recommendations for Liander based upon the case study on distribution transformers and other observations during the internship, and finally the recommendations for governments.

9.1. Theoretical Recommendations

9.1.1. Circular Economy

1. More research needs to be done on the actual principles of the Circular Economy, and what elements can be seen as derivatives or externalities of implementing the Circular Economy, such as the social impact.
2. Next to this clarification, the differences between the Circular Economy on the various scales (micro, meso, and macro), differences between countries as well as industries, could use extra research. Preferably, this may be accompanied by case studies.
3. A need to measure the Circular Economic performance of a company or product was identified during the research. An initial proposal has been done during this study (The Concept of Circular Value, appendix F.3), but further improvements may be necessary and its efficacy should be tested.

9.1.2. Business Cases

4. Accounting for environmental sustainability, within the business case, is recommended to be done using a separate constituent instead of including it only within the financial case through capital accounting. For example as proposed within the SIDA model.
5. Accounting for flexibility within the business case is assumed to be beneficial for cases that have a relative long life span, for example for businesses like Liander that manage assets and an infrastructure for the long run. How this can be done requires more research, especially on the business case constituents other than the financial case. Next to the theoretical research, its implementation and practicality should be studied.
6. Even though touched upon, social sustainability has been kept on a superficial level within this study. As the need to account for social impact by businesses is growing more research on the topic is considered necessary. Social sustainability is perceived a complex topic just like environmental sustainability.

9.1.3. Investment Decision Methodology

7. The developed investment decision methodology has been tested within a single case study on a specific asset investment problem. Testing the methodology for different assets and different sectors may help to increase generalisability of the methodology and support further improvements.
8. The application of the investment decision methodology raised some questions on the exact evaluation methods. The evaluation method of using numerical or different scales is one of those. These issues are relatively minor and the preferred method should be determined by the decision makers before the decision making process is initiated.
9. Clarity on the exact characteristics of the indicators is necessary. For this study, a guiding manual is created (Appendix H), however for different fields of application this manual may need to be revised for compliancy.

9.2. Recommendations for Liander

9.2.1. Business Cases and Investment Decisions

1. Considering the business case and investment proposals of Liander, it is recommended to start accounting for sustainability not solely as carbon emission costs, but using ecological footprint, environmental impact and material usage.
2. For the financial case within the investment decisions, also the disposal or end of life costs and benefits should be included. This will create an incentive within the investment proposal to make the investment even more sustainable until after its lifetime within Liander.

9.2.2. Circularity

3. Liander should stay in close contact with the partners throughout its supply chain to gather the necessary information for more complete evaluations. Next to that, close cooperation with these stakeholders allows for better understanding, better alignment of each other's process, and support technological development.
4. CO2 emissions are counterproductive to achieve circularity in the sense that they occur due to burning (destruction) of materials, and accumulate in the air. Therefore reducing CO2 emissions is low hanging fruit. This can partially be achieved by either reducing energy losses, and completely through using renewable energy instead of an energy mix to compensate for the energy losses in the distribution transformer.

9.2.3. Distribution Transformers

5. Make asset investments for distribution transformers more resilient. This has three main reasons. The current investments on distribution transformers are made for approximately forty years. However, it is expected that in forty years there will have been big changes in technology, energy demand and infrastructure as well as resource availability. Technological changes such as distribution transformers based on solid-state technology, the energy transition that requires more active control systems to adjust the capacity of the transformer and possible lower quality of resources since scarcity caused the necessity of recycling. These changes may require adjusting the newly invested transformers to be prematurely replaced or phased out. Considering this by developing new end of life opportunities may help to prevent financial risks.
6. Create a resource passport [85] on the distribution transformers and other assets such that per asset (type) the material contents are known for future repurposing or recycling.
7. The current use of mineral oil in distribution transformers has a negative effect on environmental sustainability. That is mainly caused during the disposal of the old dirty oil, as it will be incinerated. Improvements can be made by regenerating the old oil such that it can be used again. A better solution would be to use biodegradable bio-oils which. The advantage of bio-oils is that they do not pose any environmental risks when they leak out of the transformer; secondly, many studies have shown that the paper in the distribution transformer will degrade slower and will also stay compostable after disposal. It must however be clear that the advantage of bio-oils on environmental level will only remain if they are not incinerated after use and are of non-competitive feedstock.

9.3. Recommendation for the Government

1. Allow DNOs to produce their own electricity to compensate their energy losses.
2. A more holistic approach to environmental sustainability is necessary. A CO2 emission focus is too narrow minded. Next to these emissions, material use and footprints could improve this.
3. Mandatory tenders undermine long-term collaborations that are desired for making the assets of Liander circular. Especially for assets that last for forty years, contracts with supply chain partners allow for appropriate optimisation. Therefore, supporting long-term collaborations would be advised.

10. References

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11. Appendices

Appendix A — Literature Research Framework

Table 11 – 1 Search queries and number of results for the topic of Circular Economy

Subject	Database	Query	Results
Circular Economy	Scopus	TITLE-ABS-KEY ("Circular Economy" AND (method OR indicator OR tool OR impact)) AND SUBJAREA (econ OR ener OR engi OR envi OR mate) AND DOCTYPE (ar OR ip OR bk OR bk OR bz OR cp) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p"))	93
	ScienceDirect	TITLE-ABS-KEY ("Circular Economy" AND (Method OR Indicator OR Tool OR Impact)) AND LIMIT-TO(contenttype, "1,2","Journal") [All Sources(Economics, Econometrics and Finance,Energy,Engineering,Environmental Science,Materials Science)]	28
	Google Scholar	"Circular Economy" Method OR Indicator OR Tool OR Impact [IN: Title words only, no books, citations]	48
Cradle to Cradle	Scopus	TITLE-ABS-KEY ("Cradle to Cradle" AND (method OR indicator OR tool OR impact)) AND SUBJAREA (econ OR ener OR engi OR envi OR mate) AND DOCTYPE (ar OR ip OR bk OR bk OR bz OR cp) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p"))	53
	ScienceDirect	TITLE-ABS-KEY ("Cradle to Cradle" AND (Method OR Indicator OR Tool OR Impact)) AND LIMIT-TO(contenttype, "1,2","Journal") [All Sources(Economics, Econometrics and Finance,Energy,Engineering,Environmental Science,Materials Science)]	14
	Google Scholar	"Cradle to Cradle" Method OR Indicator OR Tool OR Impact [IN: Title words only, no books, citations]	2
Biomimicry	Scopus	TITLE-ABS-KEY ("Biomimicry" AND (framework OR principles OR fundamentals) AND (method OR indicator OR tool OR impact)) AND SUBJAREA (econ OR ener OR engi OR envi OR mate) AND DOCTYPE (ar OR ip OR bk OR bk OR bz OR cp) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p"))	27
	ScienceDirect	TITLE-ABS-KEY ("Biomimicry" AND (Method OR Indicator OR Tool OR Impact)) AND LIMIT-TO(contenttype, "1,2","Journal"). [All Sources(Economics, Econometrics and Finance,Energy,Engineering,Environmental Science,Materials Science)]	15
	Google Scholar	"Biomimicry" Method OR Indicator OR Tool OR Impact [IN: Title words only, no books, citations]	5
Blue Economy	Scopus	TITLE-ABS-KEY ("Blue Economy" AND (method OR indicator OR tool OR impact)) AND SUBJAREA (econ OR ener OR engi OR envi OR mate) AND DOCTYPE (ar OR ip OR bk OR bk OR bz OR cp) AND (LIMIT-TO (LANGUAGE , "English"))	1
	ScienceDirect	TITLE-ABS-KEY ("Blue Economy" AND (Method OR Indicator OR Tool OR Impact)) [All Sources(Economics, Econometrics and Finance,Energy,Engineering,Environmental Science,Materials Science)]	3
	Google Scholar	"Blue Economy" Method OR Indicator OR Tool OR Impact [IN: Title words only, no books, citations]	2
Industrial Ecology	Scopus	TITLE-ABS-KEY("Industrial Ecology" AND (Framework OR Principles OR Fundamentals) AND (Method OR Indicator OR Tool OR Impact)) AND SUBJAREA(ENER OR ENGI OR ENVI OR MATE) AND DOCTYPE(AR OR IP OR BK OR BK OR BZ OR CP) AND (LIMIT-TO(EXACTKEYWORD,"Industrial ecology")) AND (LIMIT-TO(LANGUAGE,"English")) AND (LIMIT-TO(SRCTYPE,"j") OR LIMIT-TO(SRCTYPE,"p"))	154
	ScienceDirect	TITLE-ABS-KEY ("Industrial Ecology" AND (Framework OR Principles OR Fundamentals) AND (Method OR Indicator OR Tool OR Impact)) AND LIMIT-TO(contenttype, "1,2","Journal") [All Sources(Energy,Engineering,Environmental Science,Materials Science)]	38
	Google Scholar	"Industrial Ecology" Method OR Indicator OR Tool OR Impact [IN: Title words only, no books, citations]	16
Performance Economy	Scopus	TITLE-ABS-KEY ("Performance Economy" AND (method OR indicator OR tool OR impact)) AND SUBJAREA (econ OR ener OR engi OR envi OR mate) AND DOCTYPE (ar OR ip OR bk OR bk OR bz OR cp) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p"))	32
	ScienceDirect	TITLE-ABS-KEY ("Performance Economy" AND (Method OR Indicator OR Tool OR Impact)) AND LIMIT-TO(contenttype, "1,2","Journal").[All Sources(Business, Management and Accounting,Economics, Econometrics and Finance,Energy,Engineering,Environmental Science,Materials Science)].	1
	Google Scholar	"Performance Economy" Method OR Indicator OR Tool OR Impact [IN: Title words only, no books, citations]	1

Table 11 — 2 Search queries and number of results for the topic Investment Decisions

Subject	Database	Query	Results
Asset Investment	Scopus	TITLE-ABS-KEY ("Asset Investment" AND (sustainable OR sustainability) AND (infrastructure OR power OR energy OR it)) AND SUBJAREA (deci OR ener OR engi OR busi) AND DOCTYPE (ar OR ip OR bk OR bk OR bz OR cp) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p"))	6
	ScienceDirect	TITLE-ABS-KEY ("Asset Investment" AND (sustainable OR sustainability) AND (infrastructure OR power OR energy OR it)) [All Sources(Business, Management and Accounting,Decision Sciences,Energy,Engineering)]	1
	Google Scholar	"Asset Investment" Sustainable OR Sustainabilty OR Infrastructure OR Power OR Energy OR IT [IN: Title words only, no books, citations]	7
Business Case	Scopus	TITLE-ABS-KEY ("Business case" AND (sustainable OR sustainability) AND (infrastructure OR power OR energy OR it)) AND SUBJAREA (deci OR ener OR engi OR busi) AND DOCTYPE (ar OR ip OR bk OR bk OR bz OR cp) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p"))	120
	ScienceDirect	TITLE-ABS-KEY ("Business case" AND (sustainable OR sustainability) AND (infrastructure OR power OR energy OR it)) AND LIMIT-TO(contenttype, "1,2","Journal")	9
	Google Scholar	"Business Case" Sustainable OR Sustainabilty OR Infrastructure OR Power OR Energy OR IT [IN: Title words only, english, no books, citations]	144
Cost Benefit	Scopus	TITLE-ABS-KEY ("Cost Benefit" AND business AND (sustainable OR sustainability) AND (infrastructure OR power OR energy OR it)) AND SUBJAREA (deci OR ener OR engi OR busi) AND DOCTYPE (ar OR ip OR bk OR bk OR bz OR cp) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p"))	73
	ScienceDirect	TITLE-ABS-KEY ("Cost Benefit" AND (sustainable OR sustainability) AND (infrastructure OR power OR energy OR it)) AND LIMIT-TO(contenttype, "1,2","Journal")	54
	Google Scholar	"Cost Benefit" Sustainable OR Sustainabilty OR Infrastructure OR Power OR Energy OR IT [IN: Title words only, no books, no citations]	429
Investment Decision	Scopus	TITLE-ABS-KEY (("Investment decision" OR "Investment decisions") AND (sustainable OR sustainability) AND (infrastructure OR power OR energy OR it)) AND SUBJAREA (deci OR ener OR engi OR busi) AND DOCTYPE (ar OR ip OR bk OR bk OR bz OR cp) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p"))	97
	ScienceDirect	TITLE-ABS-KEY (("Investment Decision" OR "Investment Decisions") AND (sustainable OR sustainability) AND (infrastructure OR power OR energy OR it)) AND LIMIT-TO(contenttype, "1,2","Journal")	22
	Google Scholar	"Investment Decision" Sustainable OR Sustainabilty OR Infrastructure OR Power OR Energy OR IT [IN: Title words only, no books, citations]	117
		"Investment Decisions" Sustainable OR Sustainabilty OR Infrastructure OR Power OR Energy OR IT [IN: Title words only, no books, citations]	114

Table 11 — 3 Search queries and result for secondary literuature review on material flow methodologies

Subject	Database	Query	Results
Material Analysis	Scopus	TITLE-ABS-KEY (("Material balance" OR "Material flow analysis") AND (model OR method)) AND SUBJAREA (envi OR mate) AND DOCTYPE (ar OR ip OR bk OR bk OR bz OR cp) AND PUBYEAR < 2015 AND (LIMIT-TO (EXACTKEYWORD , "Material flow") OR LIMIT-TO (EXACTKEYWORD , "Material balance") OR LIMIT-TO (EXACTKEYWORD , "Flow analysis") OR LIMIT-TO (EXACTKEYWORD , "Life cycle")) AND (LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "MATE")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p"))	183
	ScienceDirect	TITLE-ABS-KEY (("Material balance" OR "Material flow analysis") AND (Model OR Method)) AND LIMIT-TO(topics, "material flow,material balance,flow analysis,life cycle") [All Sources(Environmental Science,Materials Science)]	45
	Google Scholar	("Material balance" OR "Material flow analysis") AND (Model OR Method) [IN: Title words only]	45

Appendix B — Historic Overview on the Circular Economy

Even though there is no single definition of the Circular Economy, references to the principles of the Circular Economy often include Industrial Ecology, the Performance Economy, Cradle to Cradle and several other ideas of scholars and organisations pursuing sustainability or seeking new business models. An historic perspective of these paradigms and ideas will give a more comprehensive view on the Circular Economy.

Figure 11 — 1 Earthrise - 1968. Photo taken by William A. Anders/NASA [154]

The Industrial Ecology paradigm took off in the 1960s [38], a decade that was highly influenced by the space exploration ambitions. The first images of Earth from space were taken in these years and are claimed to have influenced mankind's awareness of Earth's fragility [154]. It was also in this decade in which several books and reports supporting the idea of Industrial Ecology, referred to the Earth as a finite spaceship. For example, in 1966 Boulding wrote an essay titled "the Economics of the Coming Spaceship Earth" [155] and two years later architect Buckminster Fuller wrote a book called "Operating Manual for Spaceship Earth" [1]. Boulding mainly indicated in his essay that the economy should be looked at from a different perspective as the current economic system doesn't take into account the limited number of material resources. Fuller did not only describe the challenges like Boulding did, but also gave guidelines as how mankind should take care of the Earth such as by using only our daily energy income.

A decade later, in 1977, Stahel and Reday-Mulvey wrote a report to the Commission for the European Communities[1] called "The Potential for Substituting Manpower for Energy"[157]. In this report they reason that due to limited resources manpower will be favourable over machines since machines use energy generated from these limited resources. Besides, promoting manpower over machines helps to prevent emissions and create new jobs. They suggest setting this transition in motion by introducing recycling and reconditioning into the industry. This report is not so much based on the material efficiency but focuses more on energy efficiency, an important topic in the 1970s due to the energy crisis.

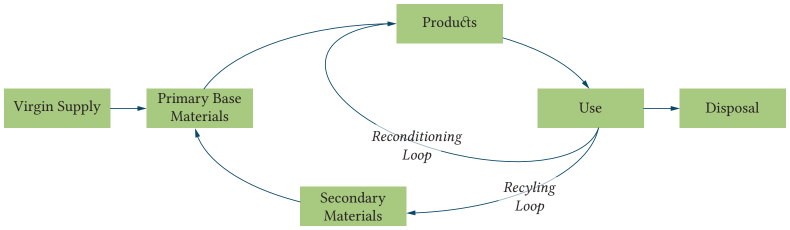


Figure 11 — 2 Stahel and Reday-Mulvey introduce reconditioning and recycling loops, replacing the traditional production-use-disposal pattern. [157]

Whether manpower should be substituted for energy in the future has become more debatable due to growing use of renewable energy resources which takes away one of the main reasons Stahel and Reday-Mulvey put forward as energy used by machines may become fully renewable and unlimited in the future. The socio-economic argument of job generation for their reconditioning and recycling system remains uncertain due to continuing trends of workweek reduction and automation of labour intensive jobs such as sorting out products or waste separation [158]. However, current projects like the Ex'tax project still aim to reduce the tax on labour and increase tax on resources, secondary in favour of job creation but mainly to promote resource efficiency and services instead of consumption of products [159].

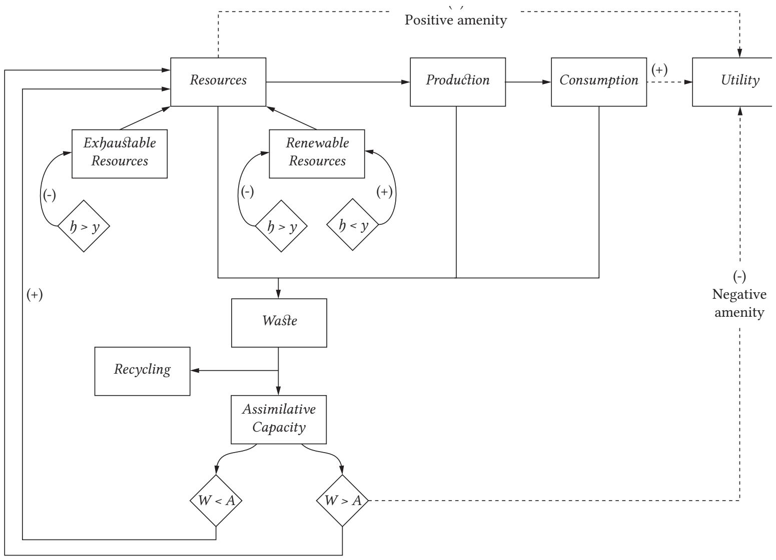


Figure 11 — 3 Circular Economy model as developed by Pearce and Turner [30]. The solid lines are flows of material and energy, the dashed lines are utility flows.

1. The European Communities was the predecessor of the European Union and existed from 1967 until 2002.

In the nineties the term Circular Economy was introduced by Pearce and Turner in their book "Economics of Natural Resources and the Environment". The Brundtland commission had written their report, "Our Common Future" on sustainable development just three years earlier [1] when Pearce and Turner [30, 160] developed the first fully closed circular model (figure 11–3). They based it on Boulding's conclusion that the Earth is the system boundary of our economy [155] with negligible amounts of matter exchanges across that system boundary [2]. The second law of thermodynamics also inspired Pearce and Turner in their fundamental premise by stating that the economy is a process that increases the entropy of materials.

Sustainable development is development that
meets the needs of the present
without compromising the ability of future generations
to meet their own needs.

Quote 11 – 1 Definition of sustainability by the Brundtland Commission [1].

It is striking that their model already includes a welfare factor (utility), being one of the first to identify and embed social aspects within the paradigm that do not cover just jobs. Their approach comes close to what the Brundtland commission identified as key concepts for sustainability in 1987 considering limitations of our Earth's resources and secondly the social impact or equity which, in be Pearce and Turners model would be the utility factor [1]. Pearce and Turner state that consumption and resource contribute to welfare, while too much waste (the waste exceeds the assimilative capacity of the environment) has a negative amenity and hence reduces welfare and limits future generations.

After the turn of the millennium, the Circular Economy gained attention in China especially due to the fact that China's economic growth has correlated to the amount of resources used. To avoid future problems of scarce materials, China wanted to decouple economic growth from their consumption and pollution [22] and hence move to a more sustainable economic structure [29]. Because of this China implemented a thorough set of regulations to make the Circular Economy a national strategy [161]. Their main focus of most of these regulations are to keep the materials flow in cycles as shown in figure 11–4 [21, 29, 36, 84]. Chinese scholars generally refer to this method as *3R*, being an abbreviation for implementing reduce, reuse and recycle [21, 36, 84] (figure 11–4).

China tries to implement this paradigm not just at product or company level but at several higher of the economy[29]. For example by developing eco-industrial parks and even eco-industrial networks on the regional level and with that including entire product, material and energy chains.

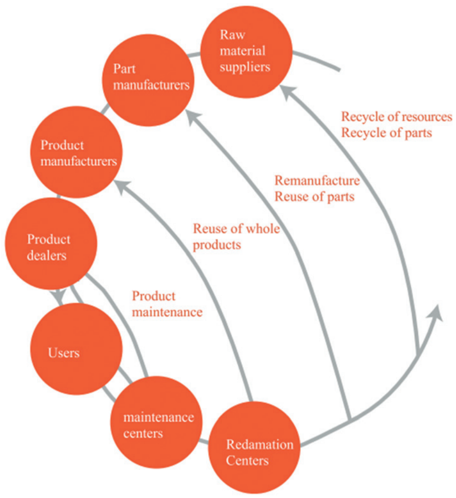


Figure 11 – 4 China's Circular Economy multi-cycling of materials based on 3R and including maintenance [22].

In the last few years the Circular Economy is gaining momentum in Europe. The reasoning to implement the Circular Economy is not always consistent, however it is often focused on financial benefits and job creation [19, 32, 34, 162–164]. These are supposed to be achieved through new business models that would push for waste reduction, resource efficiency and other environmental gains. The resource efficiency is supposed to have a direct effect on reducing costs while the new business models often encompass services throughout the life cycle of a product. These are supposed to create a more continuous income over the life cycle of the product spreading but increasing turn over as well as requiring more jobs to manage these new services.

2. The material exchange between the Earth and the universe is negligible, however, there is a large energy exchange from Sun to Earth and through radiation from Earth back into space.

Appendix C — Overview Circular Economy Indicator Sets

C.1. Overview of selected indicator systems

Author or method	Description	Scope	High level Indicators / drivers	Low level indicators
Bastein *et al.* [32]	Environmental impacts of increased circularity in metal and electrical sectors	Micro (product)	N/A	◦ CO_2 Emissions ◦ Use of Freshwater ◦ Land use (ecological footprint) ◦ Raw Material Equivalent
Circular Scorecard [81]	A method to score determine in which fields a product can be optimised	Micro (product/ project)	1. Energy	◦ Usage of renewable energy at point of service ◦ Usage of renewable energy across life cycle ◦ Generation of renewable energy ◦ Relative energy intensity ◦ Inefficient energy usage ◦ Applicability across other sectors
			2. Materials	◦ Usage of renewable materials at point of service ◦ Usage of renewable materials across life cycle ◦ Sustainable production renewable materials ◦ Encouraging usage of renewable materials ◦ Relative material footprint ◦ Percentage of diverted waste ◦ Long-term waste diversion potential ◦ Usage of cascading across industry ◦ Potential replicability quality matching ◦ Systematic impact reduction due to diverting waste streams
			3. Ecosystems	◦ Impacts on ecosystems and or species ◦ Potential in contributing to ecosystems ◦ Ecosystem disruption at global scale ◦ Species disruption at global scale ◦ Long-term consequences ecosystem and species impacts ◦ Contribute to ecosystem robustness, diversity and health at global scale
			4. Culture and Society	◦ Provide good and decent work ◦ Provide essential value to customers ◦ Health and safety impacts during production or delivery ◦ Health and safety impacts for customer ◦ Core business expansion potential ◦ Potential replicability project ◦ Encourage decent labour practices for society ◦ Provide essential value for society
			5. Value Generation	◦ Business model ◦ Raw material prices ◦ Costs of technology ◦ Economic returns for all stakeholders
Circularity Calculator (ema) [34]	Economic impact based on relative indicators of linear versus circular product, measured in dollars.	Meso (Industry)	N/A	◦ Material inputs ◦ Labour inputs ◦ Energy inputs ◦ Carbon emissions ◦ Balance of trade

Author or method	Description	Scope	High level Indicators / drivers	Low level indicators
Cradle to Cradle [82]	Product Standard 2013 for Cradle to Cradle certification.	Micro (product)	1. Renewable Energy and Carbon Management	◦ Quantifying purchased energy use and emissions ◦ Renewable energy and carbon management strategy ◦ Using renewable energy and addressing on-site emissions ◦ Embodied energy use ◦ Addressing embodied energy use with offsets or other projects
			2. Water stewardship	◦ Regulatory compliance for effluent ◦ Local and business-specific water issues ◦ Water stewardship intentions ◦ Water audit ◦ Characterizing and assessing product-related process chemicals in effluent ◦ Supply chain water issues and strategy ◦ Optimizing process-related chemicals in effluent ◦ Addressing supply chain water issues ◦ Drinking water quality
			3. Material Reutilisation	◦ Material reutilisation score ◦ Nutrient management strategy ◦ Nutrient cycling
			4. Material Health	◦ Generic material type and inputs subject to review ◦ Identifying appropriate metabolism(s) ◦ Determining absence of banned list chemicals ◦ Collection of material ingredient data ◦ Chemical hazard profiling & material assessment ◦ Determining percentage assessed ◦ Material optimisation strategy ◦ Determining absence of CMR substances ◦ Volatile organic compound (VOC) emissions testing ◦ Process chemicals
			5. Social Fairness	◦ Streamlined self-audit fundamental human rights ◦ Management procedures to address high risk issues and opportunities ◦ Full social responsibility self-audit ◦ Material-specific or issue-specific audit ◦ Supply chain social issues and impact strategy ◦ Innovative social project ◦ Facility level third party audit

Author or method	Description	Scope	High level Indicators / drivers	Low level indicators
CSR Performance Ladder [83]	Performance ladder measures the performance of a company on corporate social responsibility.	Micro (company)	1. Working conditions	◦ Employment ◦ Relation between employer and employee ◦ Health and safety ◦ Education ◦ Diversity and opportunities
			2. Human rights	◦ Strategy and management ◦ Prohibit discrimination ◦ Freedom of association ◦ Eliminate child labour ◦ Prevent forced and mandatory labour ◦ Security policy ◦ Rights of indigenous people
			3. Fair business	◦ Community ◦ Corruption ◦ Public policy ◦ Competition obstructive behaviour ◦ Compliance
			4. Consumer Affairs	◦ Health and safety consumers ◦ Labelling products and services ◦ Marketing and communication ◦ Privacy of customers ◦ Compliance
			5. Environment, resources, energy, emissions	◦ Resources ◦ Energy ◦ Water ◦ Biodiversity ◦ Emissions, wastewater and waste ◦ Products and services ◦ Compliance ◦ Transportation
			6. Involvement development society	◦ Direct generated and distributed economic value ◦ Contribute to local economy and entrepreneurship ◦ Contribute to economic system
Geng *et al.* [84]	Indicator system at macro level	Macro	1. Resource output rate	◦ Output of main mineral resource ◦ Output of energy
			2. Resource consumption rate	◦ Energy consumption per unit GDP ◦ Energy consumption per added industrial value ◦ Energy consumption of per unit product in key industrial sectors ◦ Water withdrawal per unit of GDP ◦ Water withdrawal per added industrial value ◦ Water consumption of per unit product in key industrial sectors ◦ Coefficient of irrigation water utilisation
			3. Integrated resource utilisation rate	◦ Recycling rate of industrial solid waste ◦ Industrial water reuse ratio ◦ Recycling rate of reclaimed municipal wastewater ◦ Safe treatment rate of domestic solid wastes ◦ Recycling rate of iron scrap ◦ Recycling rate or non-ferrous metal ◦ Recycling rate of waste paper ◦ Recycling rate of plastic ◦ Recycling rate of rubber
			4. Waste disposal and pollutant emission	◦ Total amount of industrial solid waste for final disposal ◦ Total amount of industrial wastewater discharge ◦ Total amount of SO_2 emission ◦ Total amount of COD discharge

Author or method	Description	Scope	High level Indicators / drivers	Low level indicators
Geng *et al.* [84]	Indicator system at meso level	Meso (industrial park)	1. Resource output rate	◦ Output of main mineral resource ◦ Output of energy ◦ Output of land ◦ Output of water resource
			2. Resource consumption rate	◦ Energy consumption per unit industrial production value ◦ Water consumption per unit industrial production value ◦ Energy consumption of per unit key product ◦ Water consumption of per unit key product
			3. Resource comprehensive utilisation rate	◦ Recycling rate of industrial solid waste ◦ Industrial water reuse ratio
			4. Waste disposal and pollutant emission	◦ Total amount of industrial solid waste for final disposal ◦ Total amount of industrial wastewater discharge
MEP indicator system [29]	Indicator system by the Chinese Ministry of Environmental protection	Meso	1. Economic development	◦ Industrial value added per capita ◦ Growth rate of industrial value added
			2. Material reduction and recycling	◦ Energy consumption per industrial value added ◦ Fresh water consumption per unit of industrial value added ◦ Industrial wastewater generation per unit of industrial value added ◦ Solid waste generation per unit of industrial value added ◦ Reuse ratio of industrial water ◦ Utilisation rate of industrial solid waste ◦ Reuse ratio of middle water
			3. Pollution control	◦ Chemical oxygen demand loading per unit of industrial value added ◦ SO2 emission per unit of industrial value added ◦ Disposal rate of dangerous solid waste ◦ Centrally provided treatment rate of domestic wastewater ◦ Safe treatment rate of domestic rubbish ◦ Waste collection system ◦ Centrally provided facilities for waste treatment and disposal ◦ Environmental management system
			4. Administration and management	◦ Extent of establishment of the information platform ◦ Environmental report release ◦ Extent of public satisfaction with local environmental quality ◦ Extent of public awareness degree with eco-industrial development
NDRC indicator system [29]	Indicator system by the Chinese National Development and Reform Commission	Meso (region)	1. Resource output rate	◦ Output rate of main mineral resources ◦ Output rate of land ◦ Output rate of energy ◦ Output rate of water
			2. Resource consumption	◦ Energy consumption per unit of production value ◦ Energy consumption per unit of production in the key industrial sector ◦ Water consumption per unit of production value ◦ Water consumption per unit of production in the key industrial sector
			3. Integrated resource utilisation	◦ Utilisation rate of industrial solid waste ◦ Reuse ratio of industrial water ◦ Recycling rate of industrial wastewater
			4. Reduction in waste generation	◦ Decreasing rate of industrial solid-waste generation ◦ Decreasing rate of industrial wastewater generation

Author or method	Description	Scope	High level Indicators / drivers	Low level indicators
Resource Passport , Damen, M.A., [85]	Method to keep track of all related product information across its life cycle.	Micro (product)	1. General Scarcity information	◦ Material scarcity in the short/ medium/ long term ◦ Price and supply security dependence of materials ◦ Current and future scarcity-related legislative requirements
			2. Mining information	◦ Mine site/ origin ◦ Mining data ◦ Local circumstances/ environment at the mine site
			3. Product information	◦ Physical structure of the product ◦ Material content and composition of products ◦ Material characteristics and properties ◦ Production processes used, plus specification per material ◦ Initial lifetime of the product ◦ Product adaptations during usage ◦ Life extending possibilities ◦ End-of-life possibilities of the product ◦ Disassembly information
			4. Company information	◦ Supply chain partners (including 2nd, 3rd, etc. tier) ◦ Position of scarcity on a strategic level within the company ◦ Market demand for products proactively addressing scarcity ◦ Product-related information of competitor products ◦ Guidelines for dealing with trade-offs resulting from substitution/ elimination of critical elements ◦ Where and how products are disposed of
			5. Technology information	◦ Best available mining technologies ◦ Best available material manufacturing technologies ◦ Best available production technologies ◦ Best available technologies for end-of-life systems
Schoolderman *et al.* **[19]**	KPI's for businesses, value creation. Economically driven	Micro	1. Short cycles (repair, reuse, recycle)	◦ Ratio of income of repaired products per total sold products ◦ Time required for repair or financial gain of repairing ◦ Ratio of reused components per total sold products ◦ Total refurbished or upgraded products per total sold products ◦ Percentage recycled material from own products ◦ Rest value of products after certain timespan
			2. Long cycles (life cycle, consecutive cycles)	◦ Ratio EBITA second hand sales per total EBITA ◦ Number of times a resource is used as input for production ◦ Technical lifespan
			3. Cascades	◦ Total financial value of sold by-products per total value sold products ◦ Turnover of innovative products from processing secondary products
			4. Pure heterogeneous cycles	◦ Degree of possible dissection of resources per product ◦ Volume toxic materials used during production ◦ Volume toxic materials incorporated in the product ◦ Ratio of leased assets per total sales

Author or method	Description	Scope	High level Indicators / drivers	Low level indicators
SWARD [57]	Criteria and indicator system for UK water industry	Micro	1. Economic criteria	◦ Capital costs ◦ Operational costs ◦ Maintenance costs ◦ Decommissioning costs ◦ Willingness to pay for the product, environmental benefits, safety, health, other attributes ◦ Percentage of household budget for lowest-income households ◦ Financial risk exposure for capital investment and other investments
			2. Environmental criteria	◦ Withdrawal of water resource ◦ River water quality ◦ Nutrients in water ◦ Land use ◦ Energy use for water supply ◦ Energy use for wastewater treatment ◦ Chemical use ◦ Material use (aggregates, plastics, metals) ◦ Water consumption ◦ Leakage rates ◦ Water reuse ◦ Wastewater production ◦ Impact on water ◦ Impact on land ◦ Sludge reuse ◦ Recovery of nutrients ◦ Quality of sludge ◦ Impact on air (CO_2, SO2, NO) ◦ Impact on biological diversity
			3. Social Criteria	◦ Availability of clean water ◦ Risk of infection ◦ Exposure to toxic compounds ◦ Acceptability to stakeholders ◦ Perceived health and safety impact ◦ Participation in sustainable behaviour ◦ Individual action ◦ Willingness to change behaviour ◦ Awareness of implications of behaviour ◦ Stakeholder information ◦ Social inclusion ◦ Voluntary activity ◦ Community spirit ◦ Access to watercourse
			4. Technical criteria	◦ Quality of supplied water ◦ Water quality complaints ◦ Compliance with consent conditions ◦ Effluent quality ◦ Raw water availability ◦ Water use restrictions ◦ Restriction or interruption complaints ◦ Mains water pressure ◦ Flooding from sewers ◦ Risk of failure ◦ Design life ◦ Flexibility of the system ◦ Ability to add to or remove from system

C.2. Categorised Indicators

Table 11 – 4 Categorised Indicators

Category	Indicator	Description
Material impact	See table 11–5	
Social Impact	◦ Culture and society [81] ◦ Social fairness [81] ◦ Working conditions [83] ◦ Human rights [83] ◦ Fair business [83] ◦ Consumer Affairs [83] ◦ Involvement development society [83]	The social impact of the process such as welfare, human health, equality and human rights.
Economic Impact	◦ Value generation [81] ◦ Labour inputs [34] ◦ Balance of trade [34] ◦ Economic development [29]	The impact of the process on economic performance of business, country and globally.
Energy Usage	◦ Energy [81] ◦ Energy inputs [34] ◦ Renewable energy and carbon management [82]	Energy usage by the process.
Ecosystems	◦ Ecosystems [81] ◦ Environment, resources, energy, emissions [83]	The impact on ecosystems.
Footprint	◦ Land use (ecological footprint) [32] ◦ Use of fresh water [32]	The impact on ecological resources that act as regenerative capacity and sink for our economy.
Emissions	◦ CO_2 emissions [33] ◦ Carbon emissions [34] ◦ Pollution control [29]	Emission output, leakage from economy to ecology.
Knowledge & Organisation	◦ Administration and management [29] ◦ Product information [85] ◦ Technology information [85] ◦ Company information [85] ◦ Material Health [82] ◦ General scarcity information [85] ◦ Mining information [85]	These are conditions for long term resource management [86].

Table 11 – 5 Sub categorisation (Table 11–4) of resource impact

Sub Category	Indicator	Description
Material Impact	◦ Water stewardship [83] ◦ Materials [81]	The impact of the material usage on the quality of materials.
Material Usage	◦ Raw Material Equivalent [32] ◦ Material inputs [34] ◦ Resource consumption rate [85] ◦ Integrated resource utilisation rate [85] ◦ Resource consumption [30] ◦ Integrate resource utilisation [30] ◦ Material reutilisation [83]	The input of materials into the process. Measurement of various sources and amount.
Production	◦ Resource output rate [30]	The production of materials and its efficiency.
Disposal	◦ Waste disposal and pollutant emission [85] ◦ Material reduction and recycling [30] ◦ Reduction in waste generation [30]	End of life handling of the materials.
Cycles	◦ Short cycles (repair, reuse, recycle) [20] ◦ Long cycles (life cycle, consecutive cycles) [20] ◦ Cascades [20] ◦ Pure heterogeneous cycles [20]	Implementation of the life cycle of materials and how they are valued.

Appendix D — Business Cases for Sustainability

D.1. Metrics for drivers for sustainable business case

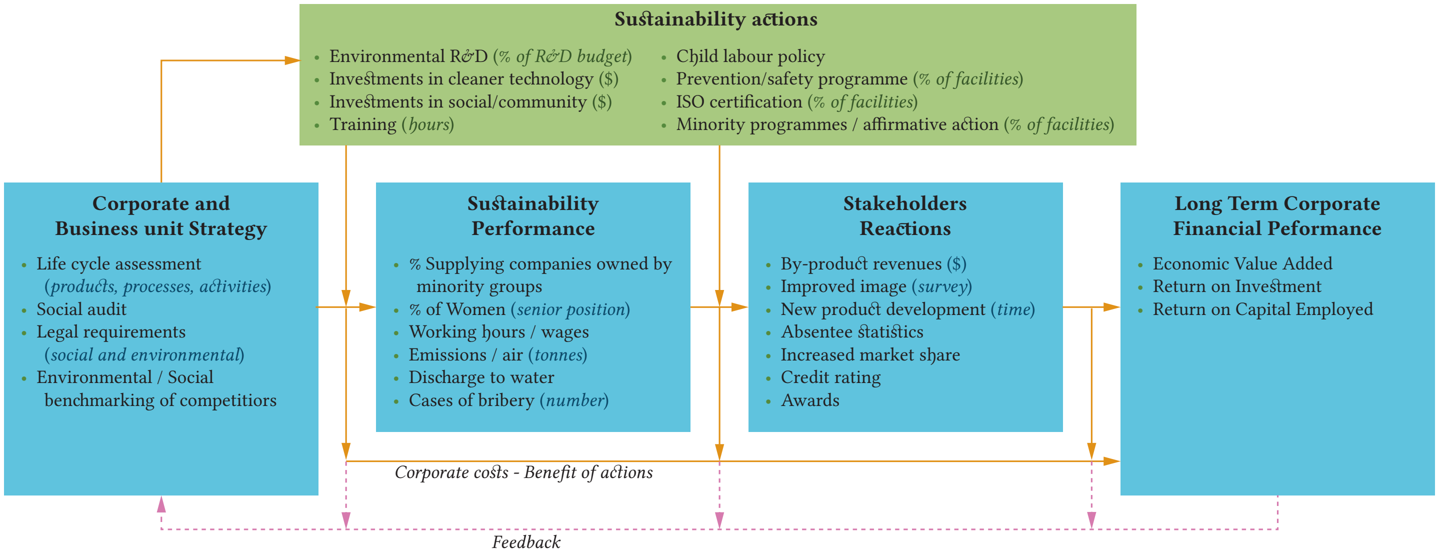


Figure 11 — 5 Metric of sustainability and financial drivers [71].

Appendix E — Circular Economy Approaches, Methods and Tools

There are various approaches, methods and tools related or developed in line with the Circular Economy. Often from a specific perspective. The most common approaches, methods and tools are discussed below.

E.1. Approaches

a) Industrial Ecology

Industrial Ecology is a paradigm that places industrial processes such as product design and manufacturing in context of ecology. However the ecological part can refer to two different aspects: the model of natural ecosystems that can be applied to industry or indicating the carrying capacity and ecological resilience of the environment that an industry has to take into account [38]. The first can be seen as an analogy for biological systems that is also used in Biomimicry, while the second looks more at the effects of a process like Cradle-to-Cradle does.

Industrial Ecology is a paradigm that can be applied to several levels of industry. There can be a focus on product design and manufacturing when looking at material and product life cycles. However there are also implementations of Industrial Ecology at sectorial or geographical level by integrating systems on these levels [165].

b) Cradle to Cradle

Cradle to Cradle was set-up by Michael Braungart and William McDonough to counter the cradle-to-grave model in which materials are taken, consumed and disposed without thinking about future uses of these materials [40, 166]. Their paradigm has defined several principles such as 'waste equals food' and 'celebrate diversity'. One of their main ideas that have been perpetuated by the Ellen MacArthur Foundation is the separation between biological and technical materials. The biggest criticism on the Cradle-to-Cradle paradigm is that they assume that there is an unlimited amount of renewable energy available necessary for reverse logistics to close the loop. However, at the current development of renewable energy production it is not feasible to make this assumption yet.

c) Biomimicry

Biomimicry uses nature as example: its aim is to try to mimic concepts and solutions to problems that can be found in biological systems. Next to using principles as inspiration and as model, Biomimicry also uses nature a measurement for sustainability [42]. Biomimicry is often used as inspiration for functionality and structure in product design at the molecular scale to macro scale.

d) Blue Economy

Gunther Pauli developed the idea of the Blue Economy. In his book [41] he gives many examples of current practices and possibilities in which materials are cascaded. Waste or other material output of a business can be used as input for another business. This creates new cash flows, jobs and social capital [167]. An common example is the use of coffee waste to grow mushrooms. For example RotterZwam, a company that collects coffee waste from bars and restaurants in Rotterdam, the Netherlands and grows its mushrooms in an abandoned swimming pool [168].

e) Waste Hierarchy

A common principle being discussed in literature is the triple-R or 3R principle. It is an abbreviation for *reduce*, *reuse* and *recycle* and represents the waste hierarchy as introduced by Chinese scholars [29, 84, 161, 162, 169] around the millennium change to reduce the amount of waste produced. However, the waste hierarchy was already introduced as Lansink's Ladder in 1979 [35] in the Netherlands and consisted of five elements. The Ellen Mac Arthur Foundation has extended the 3R principle and Lansink's ladder in their view on the Circular Economy by embedding it into the technosphere [34, 35] (see figure 3–2). Even though the waste hierarchy principle stays the same more R's are sometimes added. Figure 11–3 shows a more comprehensive list of the waste hierarchy.

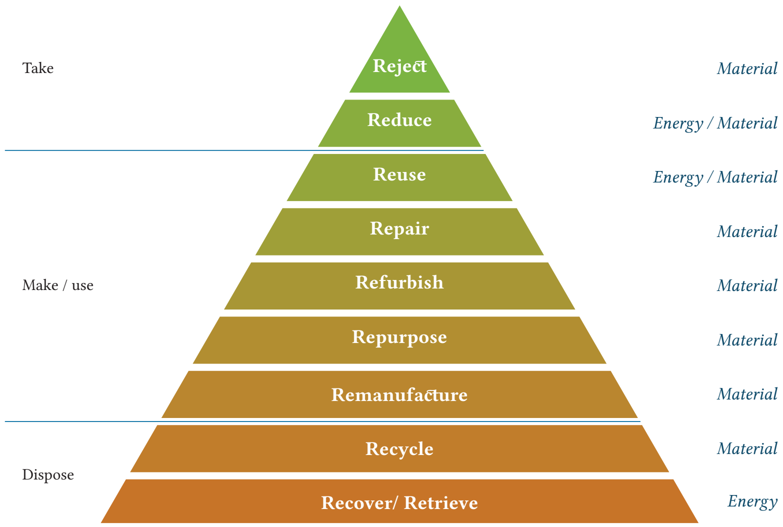


Figure 11 — 6 Example of the waste hierarchy with eight elements. Elements can be omitted or extra elements, such as repeat and rethink, can be added. Cascading is sometimes also added.

Figure 11–6 indicates which product life stages are applicable to the different R's. For example, rejection and reduction would be done before even buying or developing a new product, repurposing could already be done during its first usage by adding extra functions to the product, reusing or repairing would extend the usage life for a next iteration. Recycling and recovering would only be done at the very end of the life cycle.

In the end, it depends on the application which R's are useful and which not. As a starting point, however a comprehensive list of R's might help in discovering all options and chances for increasing product effectiveness.

Since the number of R's within this waste hierarchy is not static and various scholars refer to it as 3R, 6R or 7R, this study generalises it by naming it xR.

Table 11 – 6 Waste hierarchy definition by the European Union Waste Directive [170]

Hierarchy	Definition
Prevention	Measures taken to reduce the quantity of waste
Reuse	Using a product or component again for the same purpose for which it was conceived
Recycling	Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. This does not include energy
Other recovery	This is any other form of recovery that does not include recycling. This is an undefined list, but includes for example energy recovery.
Disposal	Any operation which is not recovery even when there is a secondary of substance or energy reclamation.

f) Performance Economy

The Performance Economy introduced by Stahel [43] or the Leasing Society by Merkies [171] are similar economic paradigms that give a different view on ownership versus functionality. These paradigms, also often called Sharing Economy reason that the use of a function or getting a certain performance is more important than owning a product. By means of selling a performance, leasing a product or sharing your goods with others, costs can be spread over more people and other economic incentives are supposed to be triggered.

For example Philips who is experimenting with a pay-per-lux model instead of selling light bulbs [152]. By selling the performance of light in terms of lux, the consumer does not have to worry anymore about side issues such as heat dissipation and sustainability. Phillips now has the incentive to provide light that uses as little energy as possible and making their bulbs last as long as possible.

E.2. Common principles

Next to the several approaches that are a basis for the Circular Economy paradigm, there is still the question of how to guide actions towards a more circular economy. With this question comes the necessity for a method to measure the Circular Economy.

Several methods and tools have been developed to help processes such as manufacturing and waste management move into the right direction. The tools are often based on principles or premises that are commonly used in relation to the Circular Economy [19, 21, 28, 32, 34, 163, 164, 172]:

» Avoid virgin material usage
» Apply the 3R method
» Build resilience through diversity
» Rely on renewable energy sources
» Think in systems
» Waste equals food
» Keep bio- and technosphere separated
» Increase resource effectiveness
» Increase lifespan
» Bio-based approach
» Product Service System

If one had to categorise them they can actually be applied to different stages of a product life cycle where they will have impact as table 11–7 shows. Some of these premises have a limited scope, considering only a part of their life cycle or from gate to gate. Others encompass their entire life cycle, from cradle to grave or even from cradle to cradle. This has as consequence that certain principles should not be applied without others to achieve a comprehensive implementation of the Circular Economy.

Table 11 – 7 Circular Economy principles per product lifecycle stage. The design phase is omitted as that is where all principles should be included. Some principles can be applied throughout all lifecycle stages such as system thinking.

Manufacturing	Use	Dispose
◦ Avoid virgin material usage ◦ Rely on renewable energy source ◦ Increase resource effectiveness ◦ Bio-based approach ◦ Think in systems ◦ Apply 3R method	◦ Increase lifespan ◦ Build resilience through diversity ◦ Think in systems ◦ Product Service System ◦ Think in systems ◦ Apply 3R method	◦ Waste equals food ◦ Bio-based approach ◦ Think in systems ◦ Apply 3R method

E.3. Indicators

Eco-Efficiency

In 1992 eco-efficiency was introduced for the first time as a new business concept. It aims to measure the efficiency of economic activity on the ecological resources [173], or in terms of the Brundtland definition, to meet the needs of the present [1].

$$\text{Eco-efficiency} = \frac{\text{Product or service value}}{\text{Environmental impact}}$$

(11.1) Equation 11–1 Formula for Eco-efficency as defined by the OECD [173].

Effects method

A model currently developed by the University of Utrecht is based on the waste hierarchy. They define the impact reduction as a percentage calculated as a ratio of the circular percentage of a new product in in relation to the current standard product [174]. Assumed is that the R-level influences the measure for circularity.

$$I_{reduction} = \left(1 - \frac{P_{circular}}{P_{standard}}\right) \cdot 100\%$$

(11.2) Impact reduction of a product based on the percentage of circular material in in a product in relation to a standard product [174]. The circularity of the circular product is influenced by the level of the waste hierarchy.

To calculate the circularity of the product an adapted form of a Material Flow Analysis is used. The analysis indicates how much material is processed by which R-level.

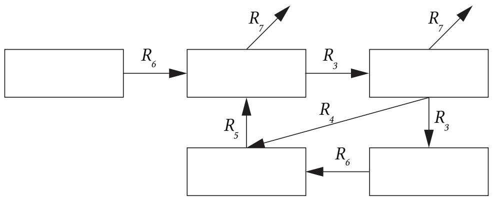


Figure 11 – 7 MFA of a product indicating R-levels. For the impact calculation the percentage for each R in the MFA is used.

The circularity value determined with this method is a relative number that only indicates the improvement of one product over another product. Determining the scope and system boundaries is essential in calculating a number that can be used for comparison. It may therefore pose the same issues as LCA's in which results from various studies cannot be compared objectively.

Avoiding Virgin Material

The amount of virgin material required for a product is a way to determine the impact on scarce materials. Equation 11–3 will give the amount of materials used for the products per timespan. In a linear system of take-make-dispose this equation would be valid.

$$R = \left(\frac{N_p \cdot m}{t}\right)$$

(11.3) Yearly amount of resources required in a linear system [64].
R = resources, Np = number of products, m = mass, t = age of products in years.

However, in a circular system waste material is being used as a new resource reducing the need for virgin materials. Equation 11–4 takes into account the percentage of recycled materials in the product.

$$R_{virgin} = \left(\frac{N_p \cdot m \cdot (1 - r)}{t}\right)$$

(11.4) Yearly required virgin material in a circular system [64].
With r = percentage of waste hierarchy element.

This equation could give a very biased view on one's achievement. An impact on virgin materials may not be bad per se. By using renewable materials and disposing of them again in a responsible way may even be a way to keep a certain eco-system or metabolism function. Avoiding the use of these renewable resources may therefore disrupt the ecosystem. Hence, a simple measurement of avoided virgin resources may be too simple as a measurement for circular performance.

Reuse Potential

The Reuse Potential (RP) is a developed by Park and Chertow as a quantitative tool to make up for lack of tools to support waste reuse and recycling efforts [95]. It is a method that has an economic base and indicates a material to be reuse potent once the reuse technique used has a greater revenue than cost. The total RP value is the ratio of materials of a product for which this is true relative to the total amount of materials in a product.

$$RP = \frac{}{\sum_i^n \frac{m_i}{m_i}}, \text{ for } c_i - r_i > 0$$

(11.5) Reuse Potential. In which mi is a portion of the mass that has a specific reuse achievement and r is the reuse revenue and c the reuse costs of that specific mass.

The possible externalities due to a lack of efficiency or effectiveness of the techniques used are not taken into the measurement of the RP. There is no incentive to choose for the most circular option over the most financially beneficial option because it does not change the RP. It could be argued that this should not pose any problem if the economic system is set-up in such a way that all external costs of a process are accounted for by its financial costs.

Reutilisation Score

The Reutilisation Score (equation 11–6) is used by the Cradle to Cradle certification [82]. It takes into account the materials of which the current product is constructed and the end-of-life of that same product. It does this by a by a weighted measurement of the percentage of product that is still recycle of compostable after use and the amount of rapidly renewable content used in the fabrication of the content.

$$RS = \left(\frac{\left(\begin{array}{c} \textit{\% of the product considered} \\ \textit{recyclable or compostable} \end{array} \cdot 2 \right) + \left(\begin{array}{c} \textit{\% of recycled or rapidly renewable} \\ \textit{content in the product} \end{array} \right)}{3} \right) \cdot 100$$

(11.6) Equation 11–6: Reutilisation Score [82]

The advantage of the Reutilisation score over the *Reuse Potential* or *Avoiding virgin materials* is that it takes into account both production and disposal instead of either of the two. However the reutilisation score is weighted: the disposal part (how much of the product is considered recyclable) is twice as important as from what materials the product is made of. This choice in weighting is a valuation that can be debated upon as there is no scientific premise why this choice was made.

Comprehensive Reutilisation Rate

There are two different approaches for the Comprehensive Reutilization Rate (CCR) [91]. They are different from the Reutilisation score because they are ratios of the comprehensive reutilisation in relation to either the direct material input (DMI) or the total material generation (TG) of the entire system. The Reutilisation score only looks at the product itself.

The basis of the CCR is the Comprehensive Reutilisation (CR) and represents the total amount of reutilised resources in the economic system. It is computed as the sum of all reutilised, recycled and reused materials within the economy.

$$CR = RU + RC + RE$$

(11.7) The Comprehensive Reutilisation (CR) refers to the total amount of reutilised resources in the economic system [91]. RU = is material that is reutilised within economic activities (industry and agriculture) , RC = is the amount of recycled consumption, RE = is amount of recycled waste without physical or chemical process.

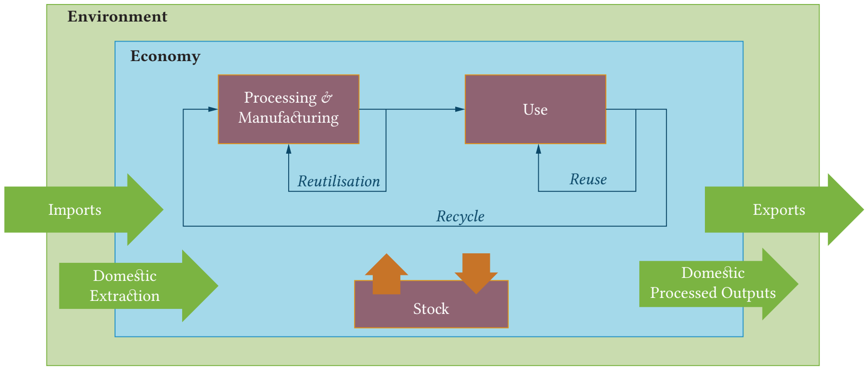


Figure 11 — 8 system scope for the comprehensive reutilisation rate [91].

The comprehensive reutilisation rate knows two different definitions. The first one is based on the premise that more reused materials will lead to less usage of non-renewable resources. The second comprehensive reutilisation rate is based on the perspective from total waste generation.

$$CRR_1 = \frac{CR}{DMI + CR}$$

(11.8) First definition of the Comprehensive Reutilisation Rate based on the premise that more reuse will lead to less use of virgin material. This is the comprehensive reutilisation (equation 11–7) divided by the sum of the DMI (direct material input) plus the comprehensive reutilisation. The DMI are all the virgin materials coming into the economy.

$$CRR_2 = \frac{CR}{TG}$$

(11.9) Second definition of the comprehensive reutilisation rate. It is the comprehensive reutilisation (CR) divided by the total waste generation during production and final use (TG).

The advantage of the CCR is that it tries to rate the reutilisation performance in relation to the bigger system and hence indicates the impact it has. However it does not show the how well the product or system itself is performing: how much of the product is being reused or not.

Resource and material Productivity

Resource productivity is one of the indicators in the Japanese material flow indicator system [84, 175]. Both of these indicators can be used to determine whether economic growth is decoupled from resource requirements or material use. The resource productivity is the ratio of the Gross Domestic Product (GDP) to Total Material Requirement (TMR) and the material productivity is the ratio of GDP to Direct Material Input (DMI) [176]. These indicators are focussed on a macro level (for countries and continents).

$$Resource\ Productivity = \frac{GDP}{TMR} \tag{11.10}$$

(11.10) Equation 11–10: Resource productivity.

$$Material\ Productivity = \frac{GDP}{DMI} \tag{11.11}$$

(11.11) Equation 11–11: Material productivity.

E.4. Tools

Material Flow Analyses

Material flow analyses are a tool to quantify flow of materials and energy through the economy, a specific sector or a company. It is based upon material mass balance. These analyses are often visualised in Sankey diagrams. These tools help to get a better understanding of where possible impacts are.

ABC-x method

The ABC-x method is like the reutilisation score used by the Cradle to Cradle product certification to measure and indicate the material health by categorising the used materials from optimal to intolerable [82]. Materials categorised as A are the most optimal materials used, B materials are largely okay but could be improved, C materials have moderately problematic properties and X materials are highly problematic. Besides these classifications, there is also an undefined and banned category. The undefined (or grey) category covers materials that are not fully known, the banned (or black) category are banned for use in any Cradle-to-Cradle certified products.

This tool is a comprehensive tool that requires the full ingredient list of the materials used and assesses them on risk towards human and environmental health as well as for recyclability/biological degradability. However, this tool is very subjective as how to rate certain materials.

Resource Passport

Resource passports have been proposed as a tool to keep track of the material contents and other related information of a product across its life cycle. This passport helps to give a better insight in the exact capital and allow for determining end-of-life opportunities in advance. Damen developed a comprehensive form of a resource passport in favour of the Circular Economy [85].

Circular Scorecard

The circular scan is developed by the Circle Economy organisation [81]. It is meant to identify possible areas in which a company can improve itself or its product in favour of the Circular Economy. It considers energy use, material use, ecosystem impact, culture & society and value generation.

CSR Performance Ladder

The Corporate Social Responsible Performance Ladder is developed by the Foundation Sustained Responsibility [83, 177, 178]. It is a certification system from Dutch origin to determine the sustainability performance of companies. On a higher level, it looks not only at the company but also at the performance towards chain responsibility.

Triple Top Line

Tool to find opportunities and innovative solutions to create extra value of product already in the design phase [68]. Instead of looking for trade-offs and so forth the least bad option as the Triple Bottom Line propagates, the Triple Top Line aims in designing and developing new opportunities that support ecology, equity and economy. This way it tries to find a solution with a positive impact on all three fields.

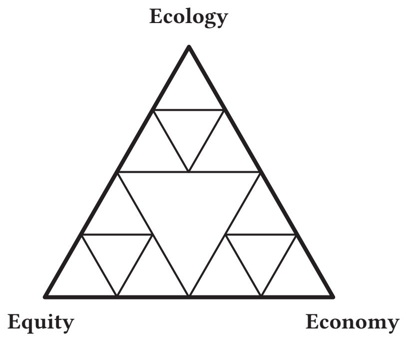


Figure 11 — 9 Figure 11–9 Triple Top Line design triangle

LiDS wheel (Life Cycle Design Strategy)

The Life Cycle Design Strategy wheel is a design methodology that is used in the Design for Environment strategy [179]. Essential is that the designer is involved in the entire life cycle. The wheel is a roadmap for recursive adjustments to the design in favour of the environment. After each step it should be evaluated whether the design still meets the requirements, but also whether new opportunities may arise. If necessary one may go through the wheel several times.

Appendix F — A Fundamental Framework for Circular Economy

The investment decision model as developed in this thesis will have a great focus on sustainability and the circular economy component. This component will be based on a fundamental approach towards the circular principle. Literature will be used to evaluate the conclusions from this approach.

Important to note is that the Circular Economy component will focus on sustainability considering material and energy use. Other elements that are often included in the paradigm of Circular Economy, such as business models, economic incentives or social elements will not be part of the theoretical framework. However, they will be accounted for in other constituents of the conceptual investment decision model as discussed in chapter 5.

F.1. Premises of the Fundamental Principle

The following main premises are important for the line of thought for the final framework. The premises are partially based upon literature and further developed throughout this research. The following premises are identified and explained afterwards:

» Interaction between open and closed systems
» Closed systems are scarce or accumulative
» Material exchange between ecosphere and economy
» Demand for specific materials changes over time
» Conversions as fundamental element of metabolisms

Interaction Between Open and Closed Systems

As Boulding already describes in 1966 in his essay, we can define open and closed systems [155]. Closed systems are very rare and hard to know since by definition a genuinely closed system would have no information in or outflow and thus cannot be perceived. However, there are two closed systems scoped around the Earth that humans are part of.

The first is a natural material system. It can be argued to be a closed system with nearly negligible in and outflow of material across the boundaries of the Earth. That we know this closed is because we ourselves are open subsystems of this material cycle. In fact all material based systems on Earth are open and together they form a closed system.

The second closed system is man-made. Our monetary system can be argued to be a theoretical closed system[1]. The amount of money, and hence the available value, is fixed. The theory of supply and demand uses principle and argues that the value of goods will drop when the supply increases. Specifically, the same amount of money is distributed over more goods making per good less money available.

Other systems that we are subsystems of can be considered to be open when taking the Earth as our scope. The energy system has an inflow of energy from the sun and an outflow through radiation. Information systems are also open, we can create new information ourselves, gather information from our surroundings.

Closed Systems are Scarce or Accumulative

A closed system is by definition a system that has no in *and* out flow of the element that it considers. This means that this element is a limited resource within that system. Depending on the scarcity in relation to the demand as well as the dependency of the system one might manage this element more or less accurately.

However, within the closed system the element can still be transformed into a different element that is on its turn is able to cross the borders of that system. This would be a way to create or get rid of the element in the system. If transformation in both directions is possible one could again argue that the system is actually open. But if the element can only be created or destroyed the element would either be limited and scarce or accumulate and be excessive.

The amount of material exchange across the border of the Earth is so little that it can be considered a closed system. We can also assume that there will be no large amounts of material brought onto Earth in the near future and thus the Earth is limited and scarce. However we have created several industrial processes that transform large amounts of material into energy and other materials such as exhausts. The energy is not bound by the Earth, but the exhausts are. The rate at which the exhausts are turned back into other materials such as biomass is lower than at which it is produced, hence accumulating in the system.

Material Exchange between Ecosphere and Economy

The next premise considers the exchange of material between the environment (the complete ecosphere) and the economy (economic sphere) (see figure 11–10). Within both spheres materials are "metabolized". One can state that there is an exchange between materials between the ecosphere and the economic sphere. For simplicity reasons it can be argued that material will either have a certain ecological value or an economic value and once materials have entered the economic sphere they have left the ecosphere and vice versa.

1. Basic economic laws such as supply and demand, inflation and deflation, etc. are based on the fact that there is a limited amount of money in the economy. However central banks do inject money sometimes to manipulate inflation or demand.

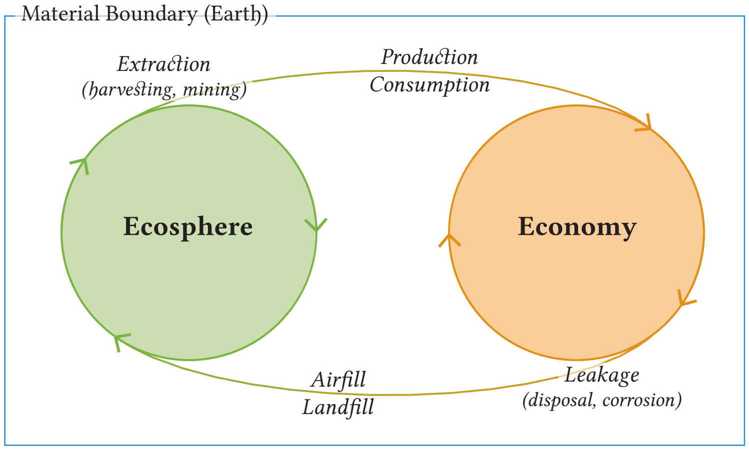


Figure 11 — 10 Material exhange between nature and the real economy. In nature the material has a certain ecological value. The value is taken out of nature and translated into economic value.

Note that this model is based on our current economic practices and can clearly be illustrated by the following examples. In these examples social value is not discussed as it is a secondary effect considering materials.

While crops are growing in the field they have a certain ecological value or footprint: they take nutrients from the Earth, they respire and form a habitat for insects and other animals. Before harvest they only have a *future* economic value. After harvesting the crops will get an economic value based on the current supply and demand. By using the same farmland each year over again, the same ecological system, and with that its value, is regenerated for a certain timespan.

Peat consists of old decomposed leaves that have built up over thousands of years. It functions as a complex ecosystem of plants and animals and acts as a water reservoir as well as a carbon reservoir. It has therefore a great ecological value. However to grow flowers on our balcony we extract this peat for its great nutritional value to form fertile soil. The fertile soil packed in plastic bags has now an economic value only. After the flowers have bloomed they are generally thrown away, they have no economic value anymore, and with that the ecological value is also thrown away.

Interacootions

It can be concluded from this premise that taking away value from the environment brings a certain responsibility to compensate for that value and the environmentally harmful effects that may occur. On the other hand if no harmful effects are present and hence no ecological loss, it can be argued on environmental basis that there is no problem for extracting materials from the environment. Economically it may however be a problem due to scarcity induced price changes.

Secondly keeping materials in the real economy is a good way to avoid further extraction from the environment, however, one is also not giving any value back to the environment. Theoretically recycling may therefore be not always the best ecological choice but giving back to the environment and extracting new may be favourable. A trade-off can be distinguished in keeping materials inside the economy out of economic reasons or out of ecological reasons.

Demand for Specific Materials Changes Over Time

The materials that are used in the environment are on the short term not varying much. However over the long term a rise or decline in species has changed the demand for certain materials. In the more recent history mankind has increase the rate in which specific materials are demanded greatly. At the beginning of the industrial revolution it was mainly iron, steel and coal. When the power grid started to grow copper became more important. Then plastics made demand for oil rise and since a few decennia there is a growing need for rare earth metals.

The fact that this demand for materials changes over time forcing material to stay in the economy is in conflict with this development. Recycling of material is therefore only useful if the future value of that materials stays the same in the economy.

Conversions as Fundamental Element of Metabolisms

All actions happening in open and closed systems can be dissected into single and simplified steps. These actions are in general a conversion in which energy and material is converted into another form or state of energy and material (figure 11–11). In this process the entropic value will change as the material output is of greater or lesser disorder.

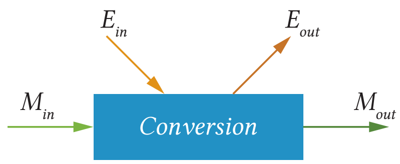


Figure 11 — 11 Model of fundamental conversion

The material that goes into the conversion process can in the process either be consumed and transformed into something else or used and possibly with a little degradation come out in the same state. The transformed material can be transformed into both material and energy.

Even though Einstein directly related energy to mass there has not been a method developed to turn energy back into material. Energy can however be stored in materials using processes like photosynthesis or photovoltaics. Energy is therefore used in these conversions and either stored or transformed into another form of energy.

Types of Conversions

Generally all conversion contain in greater or lesser extent the four elements as depicted in figure 11–11: energy inflow, energy outflow, material inflow and material outflow. Some conversions use energy and materials to create a new physical product, other conversions focus on energy production. Hence, the following conversions can be identified:

» Physically dynamic: change of matter through transformation into different material, product or energy. For example manufacturing, assembly and recycling.
» Physically static: change of energy while conserving the state of the material used. For example energy production in solar panels or the use phase of a product.

Conversions are often on a scale between dynamic and static. In static conversions material is not transformed physically but it may age and degrade slowly.

Chain of conversions

When taking a real world example such as the life cycle of a distribution transformer, many conversions can be distinguished depending on the level of detail. For example one can look at manufacturing, usage and disposal. But these high level conversions can be dissected into lower level conversions such as refinery, moulding, assembly, transportation, etc. All these conversions are part of bigger systems that can be described as chains of conversions that may branch off and join again. For transportation one would need a truck, a road and fuel each having their own chain that at one point come together.

For simplicity reasons the chain of conversions is modelled to a single chain as depicted in figure 11–12.

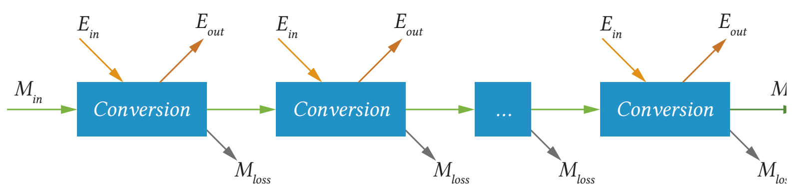


Figure 11 — 12 Chain of material conversions. In every step material is passed on to the next, energy is required and there will be some loss of material.

When determining the impact on materials and energy theoretically this would equal the sum of all conversions. However, a system with more conversions does not necessarily have a higher impact. It depends very much on the nature of the conversions: material and energy efficiency as well as the time span of a conversion.

Assuming that the ideal conversion with a 100 percent energy and material efficiency, meaning no waste or energy output, it can be argued that reducing the amount of conversion steps is generally beneficial for material conservation. A way to reduce the amount of steps would be prolonging the life span of a product such that fewer products are necessary.

Higher order chains

When evaluating a chain it is generally easy to look at the primary chain, the first order. The suppliers and consumers within that chain are usually well known as well as their behaviour and processes so that a proper analysis can be made. However, in each of the conversion steps in the chain there will be other, secondary, chains involved (figure 11–13). Common secondary chains are the energy chains that provide the energy for the conversion. These higher order chains may have a large impact on material or energy consumption and should therefore be part of the analysis. However, at a certain order the impact that can still be accounted for the primary chain may become negligible. This point at which a certain order chain may be neglected should be clearly defined and well known when an analysis is done.

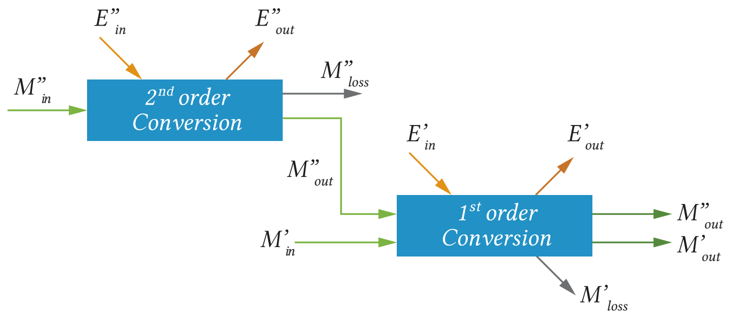


Figure 11 — 13 Higher order chains should be accounted for in the analysis.

Determining Indicators for Measuring the Circular Economy

The premises as presented in the previous section will be the starting point for determining which indicators are the top level criteria for the Circular Economy from a resource-based perspective. These primary indicators will be introduced together with their subindicators that could aid the assessment of the Circular Economy. Also possible alternative subindicators are suggested in case the initial subindicators are not applicable.

F.2. Main Indicators for the Circular Economy

By combining the second and third premise (accumulation and scarcity in the ecological and economic loop) it can be deduced that scarcity should be prevented as long as the material is valuable in the circle from which it is extracted. On the other hand, accumulation should be prevented as long as the material is not valuable in the circle it is entering or generated in. For both it should be noted that direct and indirect consequences in the long run should be taken into account.

With the reasoning that the total material cycle is closed, just prevention of accumulation and prevention of scarcity is not enough as it does not account for preventing materials to be destroyed. So before looking at scarcity or accumulation the total materials reserve should be preserved.

Concluding, the following three high level indicators can be identified:

1. Preservation of materials
2. Prevent accumulation of materials
3. Prevent scarcity of valuable materials

These three primary indicators are still rather ambiguous. To have a more specific definition of these three indicators, several lower level indicators are identified to support them.

Preservation of materials

Preservation of materials indicates the actual material loss due to destruction or burning of the material. Therefore the inverse of the weight of material loss is the main measurement for preservation of materials. Important to consider is the rate at which the material loss occurs. A way to easily estimate this is by looking at the life span of the product. A longer life span will generally require fewer replacements and thus also less manufacturing and disposal conversions. Assuming that at each conversion material is lost a longer life span will thus preserve more material than a shorter life span.

a. Material loss (in kg)
b. Life span (years)

Alternatives
The following methods can also be looked at to support the preservation of materials:

a. Use instead of consume (non-renewable) materials
b. Reduce the number of conversions
c. Renewable energy usage

Prevent Accumulation of Materials

Excessive material in the economy or ecosystem will accumulate. Accumulation often disrupts other processes due to inhibition. For example, excessive CO_2 in the atmosphere inhibits the process of heat leaving the Earth again. Accumulation can thus cause negative externalities in its own system but also in other systems. It is therefore important to prevent this from happening. Initially the supply of the material should not excess the demand and the assimilative capacity of the system.

Secondly, the reuse potential or recycling potential is a factor that helps to measure if the material can keep its value to the system if it has a potential reuse. Diversification is a way to prevent excess material by diversifying the type of output of the conversion or the location where the output is emitted.

a. Reusability / Recyclability (%)
b. Diversification

Alternatives
Some methods that could also help to prevent accumulation consider the reduction of irresponsible emissions. Examples are:

a. Reduce carbon-footprint
b. Reduce the down cycling
c. Reduce toxic materials

Prevent Scarcity of Materials

A lack of materials can also cause negative externalities. These effects can occur in the system where the material is extracted from or even trickle down to other systems that also rely on enough materials in that system. Secondly it can also backfire to the system where the material is initially extracted for through price volatilities, power shifts because of differences in ownership, etc.

A way to avoid these effects from occurring is to prevent extraction of scarce materials. First of all increasing the efficiency of the conversion would reduce the amount of materials needed that enter the conversion to get the same output. Secondly, the conversion could be adjusted such that the output materials can be reused or recycled without the need for new virgin materials.

a. Increase efficiency of conversion
b. Reuse / Recycle (xR)

Alternatives
Prevention of scarcity can also be achieved by reducing the impact on a single resource through increasing the life span of the resource or look at alternative resources or alternative locations from where the resource is extracted. A third method do reduce the impact on scarcity is by sharing resources with other systems.

a. Increase life span
b. Increase diversification
c. Sharing resources

F.3. Measuring Circular Value

The previously defined indicators can help to develop a method to measure the Circular Economy, or the circular value of a product. There are several options that could be measured with regards to the Circular Economy and thus what circular value or circularity could be defined as:

» How circular a product or product chain is,
» The added value of a product or service to a achieve the Circular Economy,
» How circular the current economy is,
» The added value of a product in a circular system compared to one in linear system.

During the research several parties mentioned the need to measure the performance of a single product or product chain with regards to the Circular Economy. This is therefore the focus of the circular value indicator that has been developed. The main indicators of the Circular Economy as defined in the previous section will be used as premise for the formula:

1. Preservation of materials
2. Prevent accumulation of materials
3. Prevent scarcity of valuable materials

The Concept of Circular Value

The circular value can be expressed as a measure that indicates the circular impact of a process. The impact would be the amount of materials that is preserved in the process of conversions. These materials should not cause scarcity or accumulate afterwards.

In theory, the circular impact of a process can be negative, neutral or even positive. A negative circular impact would be a process that does not contribute fully to the circular flow of resources. For example if resources are not preserved, materials accumulate or scarcity is created. A neutral impact would mean that no materials are being lost, no scarcity is created and no accumulation occurs. A positive impact would mean that, even though material cannot be created the process does reduce scarcity or accumulation.

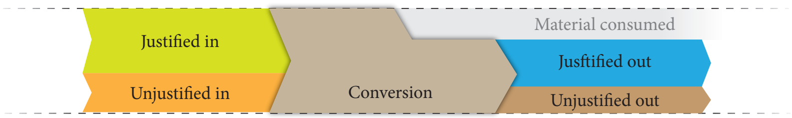


Figure 11 – 14 Model for measuring circular value of a conversion based on the materials coming in and out of the conversion.

The total amount of materials coming in with the scarce materials subtracted could be generalised as resourceful materials coming in, while the accumulating materials subtracted from the total amount of materials could be the resourceful materials flowing out (figure 11–14). In an ideal situation the total number of responsible materials coming in equals the total number materials used and equals the total responsible materials coming out of the conversion.

To translate the circular value into a formula the ratio of responsible incoming resources is multiplied with the ratio of responsible outgoing resources. Both ratios are in relation to the total amount of materials being used. Due to the multiplication, the total value accounts for the preservation of materials over the entire conversion. A general formula for circular value (C) could be defined:

$$C = \frac{m_{resp_{in}}}{m_{tot_{in}}} \cdot \frac{m_{resp_{out}}}{m_{tot_{in}}}$$

(11.12) Equation 11–12: Conceptual computation of the circular value ratio.

The following result ranges can be defined for this ratio equation 11–12:

» C < 1: A circular value below 1 indicates a partially but negative result on the Circular Economy.
» C = 1: A circular value that equals 1 indicates a neutral result on the Circular Economy.
» C > 1: A circular value above 1 indicates a positive, regenerative result on the Circular Economy.

These ratios could theoretically be put in perspective of the entire Circular Economy performance, and in case the ratio of the product is higher than the overall economy, it may still negative but it does help to contribute in making the overall economy a bit more circular.

Resourceful Inflow of Materials

The definition of the responsible incoming materials can be defined as the percentage of responsible materials in relation to the total number of materials. However defining what responsible materials are is more difficult than defining what irresponsible materials are. Therefore, the total percentage of irresponsible materials will be used to calculate this. The total amount of irresponsible materials is defined as the amount of non-recycled materials that are from a scarce resource. The level of scarcity is valued as well because in theory all materials are scarce.

The scarcity of materials (S) can be measured as the reserve-to-production ratio (R/P) in relation to a predefined time span in which one wants to measure scarcity (equation 11–13). A suggested time span (t) is one thousand years.

$$S = 1 - \frac{R/P}{t}$$

(11.13) Equation 11–13: Calculation of scarcity as the ratio of reserve to production ratio over time.

Since the amount of irresponsible materials depends on the type of material the function should be the sum of each material. The total mass of the responsible incoming materials would then be defined as the summation of the responsibility of each individual material as shown in the following equation.

$$m_{resp_{in}} = \sum_n m_{in_n} \left(r_n + (1 - r_n)(1 - S_n) \right)$$

(11.14) Calculation of resourceful materials that are flowing into the process. It is defined as the amount of materials that are of recycled origin or from non-scarce origin.

The rn is the percentage recycled content of material n entering the system. This can be specified by the recycled content rate (RC) as defined by Graedal *et al.* [117, 180]. A sectorial average can be used as well in case the data are not available, for example based on the UNEP International Resource Panel [117]. The Sn is that same material's scarcity ratio as defined in equation 11–13 and is only accounted for if there is virgin material use (1-r_n).

Resourceful Outflow of Materials

The responsibility factor of the outgoing materials is defined as the percentage of materials coming out that has a responsible future use. This should be related to the total amount of materials coming in to account for possible material losses in the system. The future use of the materials can be separately defined as the percentage of materials that will be reused or recycled. However part of what will be reused or recycled may accumulate in the future. Therefore the percentage of materials that will accumulate should be subtracted. Since this is a percentage of the total reuse percentage this is defined by the last part of equation . The first part this equation is the ratio of the total mass of outgoing materials in relation to the total amount of incoming materials in kilograms:

$$m_{resp_{out}} = \sum_n m_{out_n}\, r_{pot_n}\,(1 - A_n)$$

(11.15) Equation 11–15: Calculation of scarcity as the ratio of reerve to production ratio over time.

The potential recycling rate, rpot, can be a general percentage for the entire sector as found in reports of the UNEP International Resource Panel for example [180].

The accumulative factor An indicates how much of the recycled material will finally accumulate due to downgrading. For many compounds and polymers this is currently the case.

Overall Function for Circular Value

Combining equation , and results in an overall function for circular value:

$$C = \frac{\sum_n m_{in_n}\left(r_n + (1 - \mathrm{r}_n)(1 - S_n)\right) \times \sum_{out} m_{out_n}\, r_{pot_n}\left(1 - A_n\right)}{m_{tot_{in}}{}^2}$$

(11.16) Equation 11–16: Calculation of scarcity as the ratio of reserve to production ratio over time.

It is important to note that this equation does not include a time factor. For an ideal world situation this should not be necessary since materials should be preserved and managed responsibly infinitely. However it can be argued that in the current economic and technological context this is not yet feasible. Also, as suggested in the previous section, life span extension is a way to support the preservation of materials for a longer period of time. For this reason the circular value per year (Ct) is the suggested unit to overcome the current shortcomings. Since the circular value itself is a ratio that that should approach a limit at 1 on the very long run, the circular value per year formula should account for this.

For circular values that are below one, should be closer to one if this value accounts for a longer period, indeed if the relatively bad performance is only over a thousand years this would still be much more preferable if the same performance is just for one year. It is the opposite for positive circular value. A positive circular value on the short term is much more valuable than if the same circular value is spread out over thousand years.

$$C_t = \frac{C - 1}{t^w} + 1$$

(11.17) Equation 11–17: Calculation of scarcity as the ratio of reserve to production ratio over time.

A possible weight factor (w) can be set to indicate how much influence the time span has, and hence how quickly a positive circular value depreciates and a negative circular value appraises. Generally if a weight factor is set at 1 the circular values approach 1 already after 100 years. It would be a political choice to change this weight, however it would be suggested to set the weight between 0.25 and 0.5 as the time appraisal would then cause the circular value to reach 1 after around a thousand years.

Level of Recycling Can be Omitted

A common proposition within the Circular Economy is that a higher recycling level (xR) is better than a lower level: "it is better to reuse than to recycle". However this proposition is a rule of thumb for indicating which level of recycling uses less energy, which is generally easier to accomplish and which creates the largest financial benefit. The calculation of the circular value takes into account the energy as will be explained in the next paragraph. The other two reasons to follow this proposition are not within the scope of the proposed equation. Therefore the level of recycling is of no importance within the calculation of the Circular Value.

The Factor of Energy Use

Energy use is taken into account in the proposed equation in the form of energy carrying materials. In case the energy carriers are only used to transfer the energy this would mean that there is no loss in the mass of materials used during the conversion. However in case materials are burnt for the required energy of the conversion these materials should be accounted for in the analysis. So in general all materials that are used in the conversion, including the energy carriers that were transformed into usable energy should be used within the calculation.

Note that the proposed measurement of circular value only looks at material loops and does not account for environmental impact such as global warming that may be caused by burning fossil fuels. What is accounted for is the amount of CO_2 produced that is not being reused and may accumulate.

Appendix G — List of Design Criteria

Table 11 – 8 List of Design Criteria

Level	Design Criteria	Type	Focus on
Conceptual	Adaptable to other asset types (scope flexibility)	Contextual	scope
	Applicable to Dutch/European scope	Contextual	scope
	Applicable to electricity distribution infrastructure sector	Contextual	scope
	Applicable to micro level (asset related)	Contextual	scope
	Require sound theoretical background	Contextual	theory
	Use Circular Economy as basis	Contextual	theory
	Asset management perspective	Contextual	scope
	Based upon decision making theory	Contextual	theory
	Avoid Bonini paradox in decision making	Functional	constituent
	Avoid complexity of sustainability	Functional	theory
	Include environmental sustainability as a separate aspect	Functional	constituent
	Need for appropriate metrics	Functional	theory
	Use a composite decision making approach in a positivist application	Functional	constituent
Operational	Account for CO_2 emissions	Functional	indicator
	Aligned with RAMS methodology	Functional	indicator
	Applicable tool to show trade-offs	Functional	tool
	Create transparency in decision making process	Functional	tool
	Differentiate between functional and physical requirements	Functional	indicator
	Include financial case	Functional	constituent
	Practical for decision makers	Functional	tool
	Support a positive economic benefit	Functional	indicator
	Support flexibility appraisal in investment decision	Functional	indicator
	Support more efficient material usage	Functional	indicator
	Support reduction of energy usage	Functional	indicator
	Support reduction of material usage	Functional	indicator
	Take risk assessment into account	Functional	constituent
	Take stakeholders into account	Functional	constituent
	Use Material Usage, Ecological Footprint and Environmental Impact as indicator for the environmental sustainability constituent.	Functional	indicator

Appendix H — Manual for Sustainable Investment Decision Aiding Model

This manual contains guiding questions and tools that support the usage of the developed investment decision methodology, SIDA. These guidelines focus on the execution process of a multicriteria analysis being the operational form of the investment decision model for sustainability. It includes the contextual phases required for the entire decision making process. These phases are based upon the SWARD methodology [47] and decision making theory [46]. The guiding questions of the investment decision model for each of the indicators and metrics can be found under point 0 below.

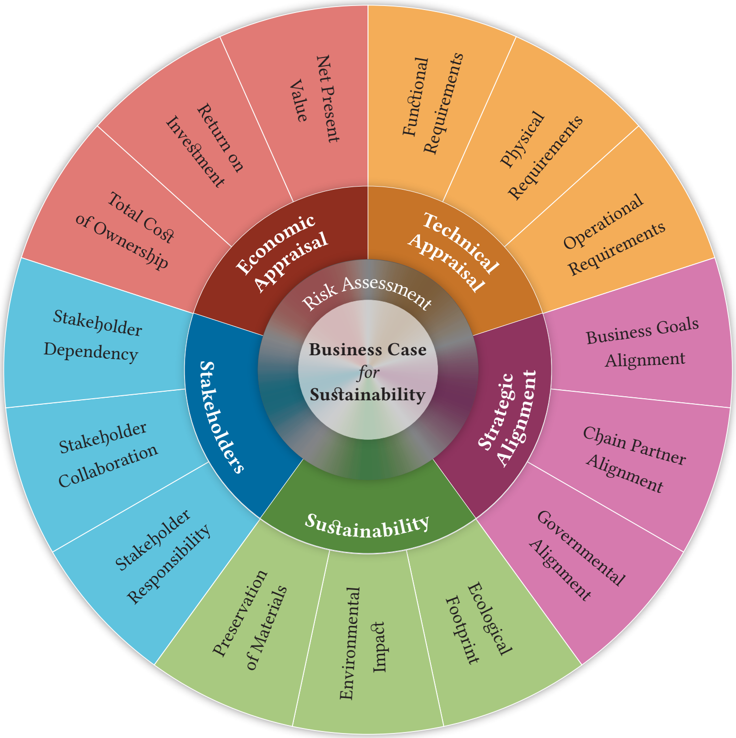


Figure 11 — 15 Investment Decision Model for a Business case for Sustainability.

Figure 11–15 Investment Decision Model for a Business case for Sustainability. is a representation of the various indicators of the investment decision model. The aim of this model is not to determine the best option, but guide and support the process in determining it. In the end, the best possible option should be chosen by the decision maker and they should be able to argue their choice. This model may help to substantiate their argument.

Initially, all indicators within this model are presented equally, however different weights may be appointed by the decision makers during the process. For a fair evaluation the weight should be known beforehand.

The following seven points guide the entire decision process:

Definition of Investment Decision Problem and Objectives

To be able to evaluate various options and make a decision, the actual investment decision problem and its objectives should be known. This helps to align the expectations of all stakeholders involved as well as making each step of the process more effective. Investment decision problems may be of various states. For example a more preliminary state to evaluate the current asset base and see whether replacement of a current subpopulation may be useful, or evaluation different concepts or technologies to guide the direction of follow up investment decisions. A final state investment decision problem will focus on actual, clearly defined products or assets as found through market research or offered by tenders. The objectives of the Investment decision problem link with its status.

Selection of relevant indicators

Just like the decision objectives, the indicators that will be used to evaluate the various options against should be determined at the start of the process. This allows for effective generation of alternatives, effective data collection, but also to enable a fair playing field for the decision making process. This is especially important when large tenders are considered within the decision. The indicators are basically the rules of the game, and hence should not be changed during the process anymore. Not only does it make the process fair, it also make the process more transparent.

Determining the right indicators may seem difficult at first. Therefore the investment decision methodology as shown in figure 11–15 has been developed. These have been developed within the scope of the energy distribution infrastructure. Hence, values such as technological reliance, risk reduction and sustainability are important factors. Each of the five indicators are proposed to be equally valued, with on top of each indicators a risk evaluation is made. The indicators are:

» Economic Appraisal
» Technological Appraisal
» Stakeholder Alignment
» Strategic Alignment
» Environmental Sustainability

Economic Appraisal

Economic appraisal considers the economic feasibility of the alternative for the business. Common metrics can be used to evaluate this indicator such as Net Present Values, Return of Investment and Total Cost of Ownership. Generally, the current practices within the business should suffice.

Technological Appraisal

Technology may be an important factor when choosing a certain alternative. The technological appraisal considers the functionality of the product, the operations such as maintenance as well as the physical character of the product.

Stakeholder Alignment

The stakeholders may have a large influence on the effectiveness of an alternative. This may be because of dependencies considering manufacturing or development, but could also be about the acceptability of the product. The stakeholder indicator is mainly valued on a personal level.

Strategic Alignment

The strategic alignment is an indicators that values the strategic directions of organisations such as the business itself as well as governmental institutions. These organisations may have long-term goals but are also able to make radical changes in policy. These can have great effect of the effectiveness or acceptability of the alternative.

Environmental Sustainability

Sustainability is a factor that increases attention throughout society. This has been pushed by environmental concerns such as global warming, extinction of habitats or increased scarcity of materials. These elements can affect the long-term sustainability of the alternative itself.

Risk Evaluation

Risk evaluation is the odd one out in this list as it is not a stand-alone indicator, but regards the risks of each of the aforementioned indicators. The risk considers the chance and the effect of a certain event from happening. Many companies translate the risk into a financial number, and can hence determine what is acceptable or not.

Generation of Alternatives

After definition of the problem, the various alternate scenarios need to be identified. These scenarios should satisfy the objectives of the decision problem. The various scenarios can be different options for a component, a design or even a conceptual idea. However, the different scenarios need to be properly defined such that they account for different scopes to solve the decision problem. Defining the options can be done in various ways. To benefit the decision making process the number of alternatives should be limited. Therefore, in case of many possibilities, it is advised to either have a quick pre-selection by reducing the alternatives to those that are considered feasible and suitable considering the decision problem. To allow the decision aiding tool result in distinct differences a number of 3 to 5 alternatives is ideal. It is important that one of the options represents the current situation. Comparing the other alternatives will then show on what fronts their might be a positive or negative change. If wanted, a fixed number of alternatives can be set beforehand.

Data collection

To gather the data to base evaluation process on, for each indicator several metrics can be used to get an overall performance of that indicator. The metrics as presented in the model in figure 11–15 will be used here. Several elements will be named or questions will be asked to guide the data collection process. It is a balance between the available time and the level of detail on how much information should be gathered in this phase. It may be good to try to achieve a certain level of certainty. This could be set beforehand.

Economic indicator

Generally, what is the financial sustainability of the alternative over its entire life cycle? Externalities are more often accounted for in the financial evaluation.

Net Present Value

What is the current net present value of the alternative, and what is its sensitivity to discounting. It is important to include the end of life costs and benefits. This creates a present responsibility on how this process should be taken care of and will therefore not burden possible future investments.

Return on Investment

How efficient is the investment? The Return on Investment (ROI) measures this by taking the ratio of costs and benefit of the investment. What is included in the benefits and costs should be clearly defined. From the perspective of the SIDA model it is suggested that all costs and benefits over the entire life-cycle within the company's domain (from gate-to-gate) are considered. It therefore also considers energy costs during usage and disposal costs at the end of life.

Total Cost of Ownership

The total costs of ownership considers all direct and indirect costs of the investment. For example, costs that need to be made to adjust environment, develop and install dedicated infrastructure and costs for externalities should be included. In the case of distribution transformers, this may be the costs for CO_2 emissions for example.

Risk Appreciations

The risk of financial evaluation is mainly influenced by the uncertainty in economic forecasts. It should be known what the financial risks are and whether these can be deferred by expulsion or making different use of the alternative during it life span.

Technical Appraisal

The technical appraisal can be evaluated on different domains. Here are the functional, physical and operational requirements discussed.

Functional Requirements

The functional requirements are requirements considering the performance. These are generally dynamic output of the investment considering capacities and loads. For example production, transformation, heating, etc. If the investment delivers also other performance that is not required, this performance should be valued accordingly. However, the delivered versus the required performance is suggested to be leading within this indicator.

Physical Requirements

The physical requirements consider the required conditions in which the investment will be placed, used and operated. These conditions can consider for example availability of space and climate conditions.

Operational Requirements

The operational requirement are about the usage or operation of the investment. For example ease of use, accessibility, maintainability and other aspects that make sure that the investment can properly be operated.

Risk Appreciations

The risks of the technical appraisal can for example be based on the chance that the requirements may change due to changing markets or legislation. How resilient are the technical aspects of the indicator

Stakeholder Alignment

The stakeholders consider all the parties involved throughout the supply chain and life cycle of the investment. These can be internal and external parties, suppliers and users, or even legislators.

Stakeholder Dependency

Dependency on the stakeholder is generally seen as positive. Many beneficial systems (in economy as well as in the ecology) are highly complex due to the large amount of parties involved that depend on each other. However, dependency may become less positive if the dependency becomes critical in case there is no replacement available. This means that if there are only a few potential stakeholders that can fulfil a certain function that is critical to the process, the stakeholder dependency may be valued as negative.

Stakeholder Collaboration

In line with the stakeholder dependency, collaboration with stakeholders is positive. This enables exchange of ideas, wishes and allows for better adjustment to changes as well as enabling development throughout the supply chain.

Stakeholder Responsibility

As organisation, one is also responsible to its stakeholders. Be it in the form of job security towards employees, human health towards consumers or living up to agreements with partners. These responsibilities are inherent. However, in case the investment causes a large impact to the wellbeing of that stakeholder, be it positive or negative, the responsibility is large and the stakeholder may be very dependent on you. This is something that can generally be better reduced to allow for easier change of course. So in general a lower responsibility is considered positive towards the assessment.

Risk Appreciations

The risks considering stakeholders can arise from their volatility.

Strategic Alignment

The strategic alignment considers whether the investment is in line with the chosen strategy of oneself, the market and the market regulator (the government).

Business Goals Alignment

Does the investment fit within the company's portfolio. But also, does it fit within the companies vision for growth and development. Next to that, the alignment with shareholders may also be accounted for within this indicator.

Chain Partner Alignment

Does the investment follow the market trends and the path that chain partners have chosen as well. This indicator is close to the stakeholder dependency. While that indicator is more on operational level, this one considers the longer-term plans and visions of the chain partner.

Governmental Alignment

The national and regional governments are important to be aligned with to avoid future problems. In case the investment is aligned it foresees gradual changes of legislation based on trends that are expected to continue or grow.

Risk Appreciations

The risks of strategic alignment consider the possibility of new strategies to come or the volatility of current strategies, and how resilient the investment is against such changes.

Environmental Sustainability

Environmental sustainability has been the focal constituent of the research that led to the SIDA model. It is based upon the Circular Economy paradigm and resulted in three indicators.

Preservation of Materials

The preservation of materials considers the use of resourceful materials, which are of recycled or non-scarce virgin origin. This means that they do not increase the scarcity of materials in the ecosphere or economy. Next to that the outflowing materials should be resourceful as well in the sense that they should not accumulate in either nature or the economy. Instead they should have a clear potential use in either of the two spheres.

Ecological Footprint

The ecological footprint considers the use of regenerative and assimilative capacity of the Earth. Either through reduction in these spaces or by using them as sink. For example, the use of land, forests or water, such that ecosystems cannot make use of that space anymore is part of this indicator.

Environmental Impact

The environmental impact considers the externalities of the process that cannot easily be accounted for or translated into ecological footprint usage. For example the production of CO_2 or heat are understood as impacts that affect the nature, but they are difficult to quantify in how much of the assimilative or regenerative capacity they take up. This indicator is therefore of a more qualitative character.

Risk Appreciations

The risks can be found within possible changes of the process requiring different input of materials or causing other outputs than what initially was determined. These can be internal changes, but also changes in the supply chain that the investment in still responsible for.

Multicriteria analysis

The Sustainable Investment Decision Aiding methodology suggests to use a multicriteria decision analysis tool (MCDA) to assess and compare the various scenarios. There are various MCDA tools available, however, they are generally a simple table in which the scenario's can be scored on the various assessment criteria. In the case of the SIDA methodology those criteria are the 6 constituents: financial, technical, stakeholder, sustainability, strategic and risk. The decision makers should decide beforehand on some rules how the analysis is done. Some of those elements are:

» Which scoring method will be used (numerical or not, the scale)?
» How should the information be translated into scores?
» Are certain criteria more important than others (weighing)?
» Are there certain veto-thresholds?
» How should additional information be depicted in the assessment (for example uncertainties, or specific argument)?

The collected data should be translated into scores. It is important that arguments and reasoning are clear and added to the scores to back-up the assessment.

Selection of preferred option

After assessment the chosen MCDA tool should aid the decision makers in making a judgement. They can do this with the previously described tools, such as applying threshold or critical values, ordering and sorting the scores and possibly assigning weights to scores.

It is suggested that the decision is not made solely on a mathematical exercise, but that the final decision is based on arguments. These can based upon identified trade-offs, secondary information that was provided within the analysis.

Implementation phase

After the decision has been made, the decision should be implemented. This means that in case of investment decisions the investment may be made and implemented. During the implementation it is wise to monitor the progress and whether the investment lives up to the assessment. This can help to improve the process towards the organisation and possibly adjust certain forms of assessment or selection methods.

Appendix I — Contextual Background on Distribution Transformers

To create a thorough understanding of the case study and the problems that lead to the reason for this case study some background information on the electricity grid and the distribution transformers is necessary. This paragraph will discuss the general outline of the electricity grid, the technical background and performance of the distribution transformer and introduce the problem definition of the case study.

The energy grid as operated by Liander consists of a transmission and distribution grid. The transmission grid is a regional grid operated between 10V-50kV and powered by the regional energy producers and the national grid operator. The distribution grid consists of a high voltage (3kV-20kV) and low voltage (400V) and distributes the energy within the residential neighbourhoods. Distribution transformers are the link between the high and low side within the distribution grid and provide for the necessary voltage step.

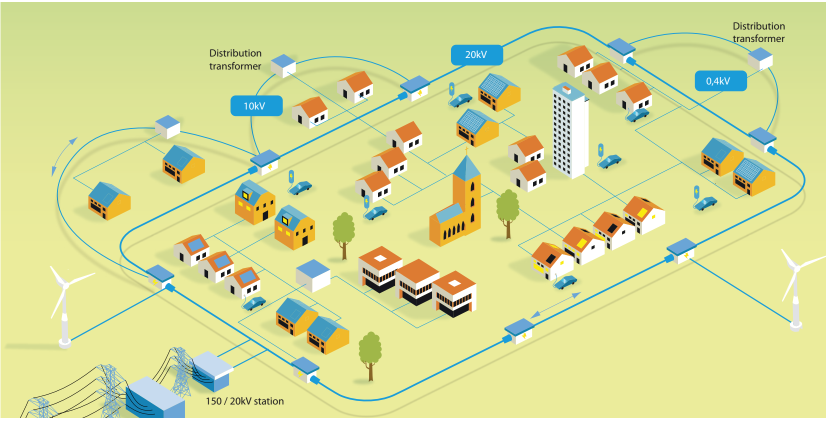


Figure 11 – 16 The electricity distribution grid.

In Europe, distribution transformers are mainly used for the electricity grid to supply households (56%). Another large application sector is the industry which account for around 41% and the remaining 3% is used within the transport sector, especially for railways [181]. Within the distribution grid nearly all transformers are of the oil-immersed type due to the higher reliability and a longer lifespan.

I.1. Technical Background of Distribution Transformers

The most common distribution transformers used in Europe and operated by Liander are oil-immersed three-phase ground mounted transformers. They are generally shipped in rated loads ranging from 100kVA to 2,500 kVA costing on average €10,000. Due to the finely meshed distribution grid there were approximately 74,900 distribution transformers in 2008 in the Netherlands which is about 2% of the total EU-27 population [181]. Liander operated around 29,500 distribution transformers in that same year [111].

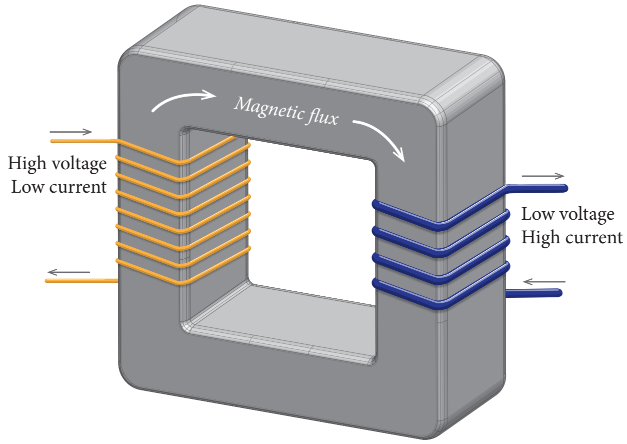


Figure 11 – 17 Principle of power transformation from high voltage to low voltage.

Physical Principle of Transforming Energy

Transformers are built around the physical principle of electromagnetic induction. A copper coil will induce a magnetic flux in a metal core which on its turn will induce a new current in a secondary coil. The number of windings in each coil determines the ratio and hence the voltage step as illustrated in figure 11–17.

Coils

Since the distribution grid in the Netherlands is based on a three phase alternating current, each of the phases require a transformation and therefore their dedicated coils. Figure 11–18 Common oil-immersed distribution transformer cut view. shows a typical transformer from the inside. Three coils can be seen, they are the high voltage windings. Concentric to the inside of these windings are the low voltage windings. The coils are often made from copper or aluminium wire or plating because of their conductivity characteristics. To prevent short circuits insulation is added in between the windings in the form of oil-immersed kraft paper. For the dry-type transformers the entire winding is casted in resin and therefore acts as insulator.

1. The rated load is the designed capacity or the electrical size of a transformer, measured in kVA.

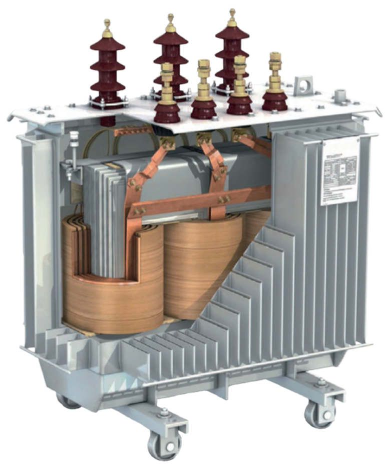


Figure 11 – 18 Common oil-immersed distribution transformer cut view.

Core

The coils are mounted around the iron core of the transformer. The core is the interface between the currents in the coils. It transfers through a magnetic flux the electric current from one coil to the other. To do this efficiently the core material needs to have a high magnetic permeability to establish a low magnetic reluctance. Common materials are iron and carbon steel. Another material that recently gains attention for production of transformer cores is Metglas, an amorphous (non-crystalline) metal alloy of which the patents recently expired [182]. Metglas has a magnetic permeability that is five times larger than 99.95% pure iron and will therefore have much lower energy losses [183, 184] (also see Efficiency of a Distribution Transformer).

Insulation

The transformer needs insulation to prevent short circuiting between and within the coils. Also flash-over between the coil and the housing or other components should be prevented. In oil-immersed transformers the oil insulates all bare components. To get the oil in between the windings of the coil kraft paper is embedded that soaks up the oil. It is therefore important that the paper is free of moist or other impurities that prevent the oil from being absorbed and homogenously distributed.

Cooling

The cooling of the transformer is important as loads cause heat production due to energy losses. This heat needs to be dissipated away to prevent thermal stresses in the transformer that cause aging and premature breakdowns. There are various ways of cooling, several substances can be used such as air or oil and these can cool the transformer passively and actively. In the general oil-immersed transformers the oil acts as insulation and coolant and is passively cooling the transformer. The oil on its turn can release its heat to the enclosure.

Enclosure

Commonly steel tanks are used as enclosure. They give structural support, prevent contamination and leakage. To prevent leakage the tanks are completely sealed. However to counteract the expansion of the oil due to temperature variation, the tank either needs an oil conservator as buffer or the structure needs to be flexible enough such that it can expand with the oil. To get rid of the excessive heat the tank often contains radiators to increase the surface area for heat to dissipate away.

I.2. Efficiency of a Distribution Transformer

The energy efficiency of a transformer is very important when deciding which transformers to buy. This is because the energy losses over the entire life span of a transformer may cost the same as the initial investment costs. Generally distribution transformers that contain more or higher quality metal tend to be more efficient. However, increased mass will on its turn increase the investment costs.

Theoretically more efficient transformers do not have to be more efficient in practice. It depends very much on how they are operated and the loads to which they are exposed to during their life. Figure 11–19 shows the relationship between the efficiency and the load that the transformer is exposed to. Generally, the transformer is most efficient at the point where the load losses and the no-load losses are equal. This tends to be at a load between 40-50% of its rated size [181].

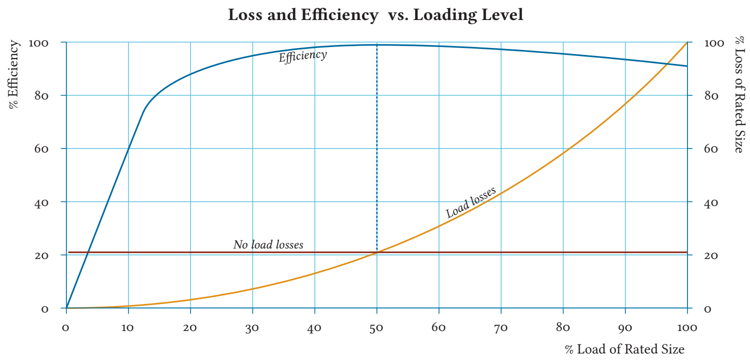


Figure 11 – 19 Losses and efficiency versus rated load of distribution transformers [181].
The load and no-load losses are indicative on this chart and describe their general function as load changes.

No-load Losses

No-load losses (also iron or core losses), are losses that occur in core of the transformer. These can be described as the initial losses that occur to magnetise the core and induce the magnetic flux. These losses are caused by two phenomena: eddy current losses and hysteresis losses. Eddy currents are a fundamental principle of the induced flux. The flux causes eddy currents to occur which on its turn act against the flux causing a constant variation in flux density. If the eddy currents can be streamlined more orderly in the core this would reduce their resistive force.

The hysteresis losses are caused by the alternating current of the energy grid. This causes the magnetic dipoles of the core to constantly change sides heating up the molecules.

Load Losses

Load losses (also copper or coil losses) are losses that occur within the windings of the transformer. They exist due to resistance in the copper wire and plating. As clearly illustrated in figure 11–19, the load losses depend on the load the transformer is exposed to. For this reason the load losses are the losses that can be influenced during operation.

When looking at the historical loss developments of the distribution transformers (figure 11–20) it can be seen that the no-load losses have decreased by two thirds over the past seventy years while the load losses have barely decreased over the past. These development have taken place within the context of a distribution transformer that technically and from a physics point of view barely changed. In that light the trend that figure 11–20 shows indicates that there might not be a lot of reduction in energy losses within the current applied technology. Further reduction should therefore be looked for in new technologies.

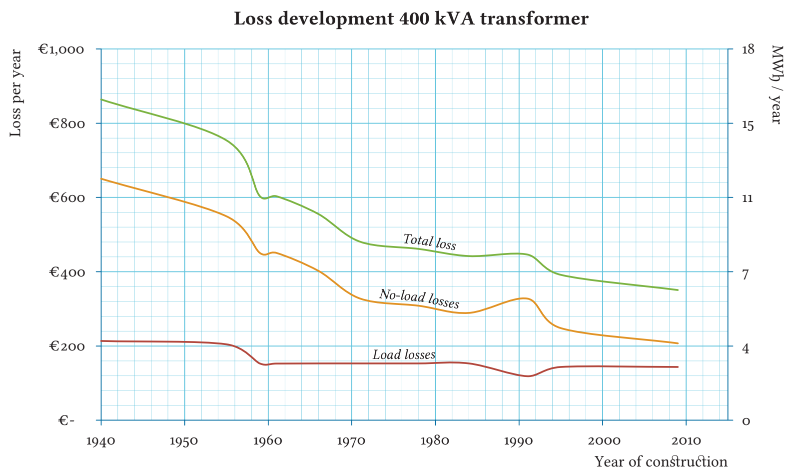


Figure 11 – 20 Historical energy loss development of 400kVA distribution transformer population operated by Liander [114]. The losses are measured at the average maximum load which is nominally at 55% of the rated load.

Within the current TCO model the no-load losses are capitalised in twofold: the actual energy losses and the indirect CO_2 emissions that have to be accounted for because of the required energy to compensate for these losses.

I.3. Technical Aging Process of a Distribution Transformer

Generally, distribution transformers are very reliable and lasts for several decades. Their failure rate over the transformer's lifetime is well described by the bathtub curve (figure 11–21). Right after installation of the transformer there is a higher chance of failures due to production, transport or install errors. The number of failures quickly decreases (figure 11–21-A) During operation there are few breakdowns that are time independent (figure 11–21-B) and these are generally caused by external factors such as operator errors, lightning or animals causing short circuits or eating away components. The end-of-life of a transformer is greatly dependent on insulation aging (figure 11–21-C) caused by degradation, and as the bathtub curve indicates there is certain threshold (point c in figure 11–21) at which the chances of breakdown start to increase [144].

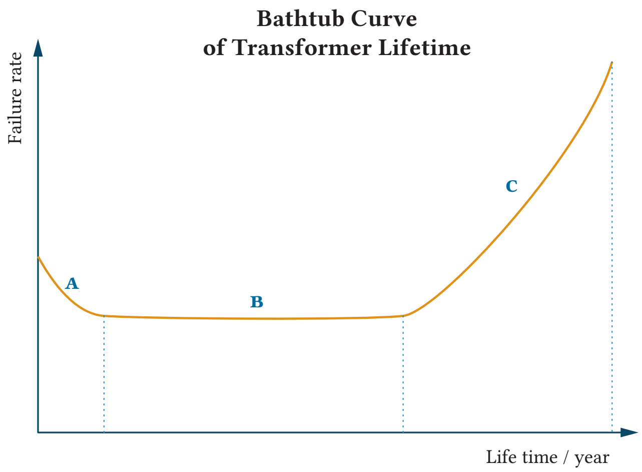


Figure 11 – 21 Bathtub curve illustrating three life cycle phases (installation, use or maintaining, and phasing out) of a distribution transformer [144].

This increased failure rate can mainly be accounted for by the aging insulation within the transformer. The deterioration of the insulation is greatly influenced by thermal stresses that occur due to high and variable loads or contamination due to moist or sludge [112]. The loads can cause hotspots in the windings resulting in local heating of the oil and paper hence increasing the deterioration rate. And in case the heat cannot dissipate away enough, the oil might eventually evaporate allowing short circuiting of the transformer [144]. Also other components are influenced by thermal aging stresses as well as mechanical and electrical. However, the resulting failure mechanisms such as leakage or overvoltage occur far less than insulation deterioration and can be credited to design or operation errors as well as uncontrollable externalities.

Extending the lifespan of a transformer can be achieved by reducing the rate at which the insulation ages or completely renew the oil to reduce the amount of sludge and hence get the electric strength of the oil back to the required levels.

Within Liander the replacement criteria for old transformers are quality and risk-prevention driven. There are yearly only a few transformers that fail mostly due to production and install error or oil-leakage [112]. Most transformers are replaced because of functional aging. For example the rated load is not sufficient anymore or the transformer does not comply with the newly introduced grid voltage levels. In case the transformer is still good enough to be reused at a different site in the grid, the transformers will return to the stock (33%) instead of being disposed of (66%). Guidelines have been set up within Liander to determine the transformer's life cycle status mainly based on Thermal Maximum Indication (TMI) inspections as depicted in figure 11–23. These TMIs indicate what the maximum temperature has been within the transformer and related to that the maximum load that the transformer has handled.

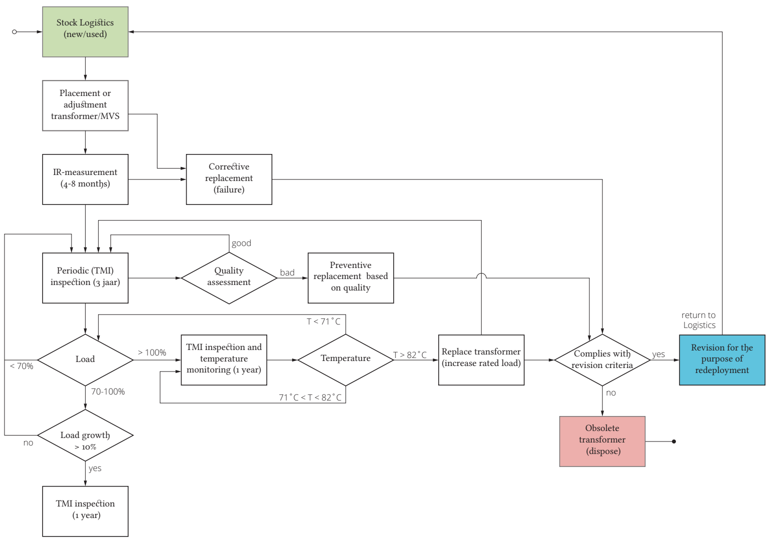


Figure 11 — 22 Life cycle guidelines for individual distribution transformer at Liander (adapted from Levensloopplan Distributie Transformatoren [112]).

I.4. Distribution Transformers Operated by Liander

Liander operates around a third of the distribution grid in the Netherlands. It has around 33,000 distribution transformers operating within this grid to enable a high quality, reliable and safe power supply. Most of the transformers within its network are oil-immersed transformers. Due to the historical development of the energy grid and the grid operators that Liander inherited, the grid contains transformers from 1920 till now and manufactured by many different suppliers. Since 1997 Liander started to install norm transformers: a standard for transformers developed by the various grid operators in the Netherlands. The last revision of the norm has been in 2009. This type is being used as benchmark within the case study.

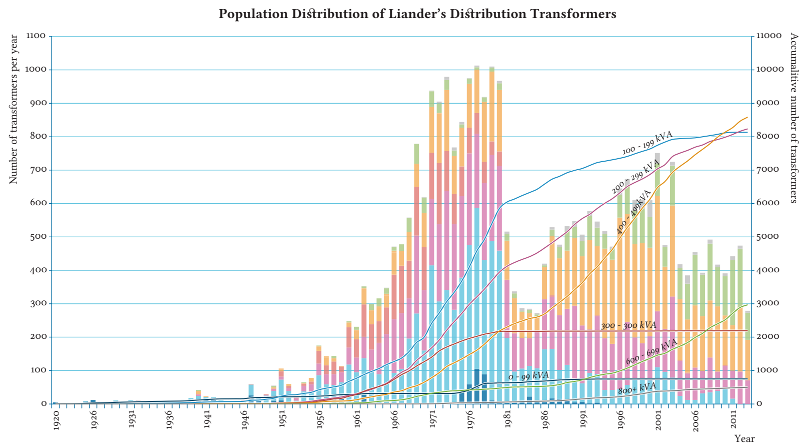


Figure 11 — 23 Current install base of distribution transformers broken down per capacity.

Liander currently operates its transformers such that the average maximum nominal load of the transformers is at 55% of its rated load. The rated loads of the transformers are increasing over recent years from a period where most transformers were at a load of 100kVA in 1976 to the recent years in which most transformers were of the 400kVA or even 630kVA type (figure 11–23). This is a clear indication that the demand and supply on the energy grid is increasing and it is expected that this trend will continue.

I.5. Developments within the Distribution Transformer Market

The current energy transition towards a more decentralised electricity production has several impacts on the grid and its distribution transformers [112, 185, 186]. Continuous currents that used to flow from a centralised power plant to the households are now changing to a bidirectional flow due to local electricity production from for example photovoltaic (PV) cells and wind turbines. Besides the bidirectional flow, the load variation is increasing as well. The centralised power plants are very stable and continuous in production; however PV cells and windmills are dependent on the weather that may change minute by minute. Next to the variation in production, there is also an increase in demand due to further electrification of homes and cars.

The older population of the current install base is not designed to handle the increased variation in load nor the bidirectional flow. This influences the quality (stability) of the energy supply to the homes and causes an increased rate of aging of the transformer. The fact that the current install base can last for several decades cannot simply be extrapolated to the future in case the transformers are not adjusted to handle the requirements that a decentralised energy grid imposes.

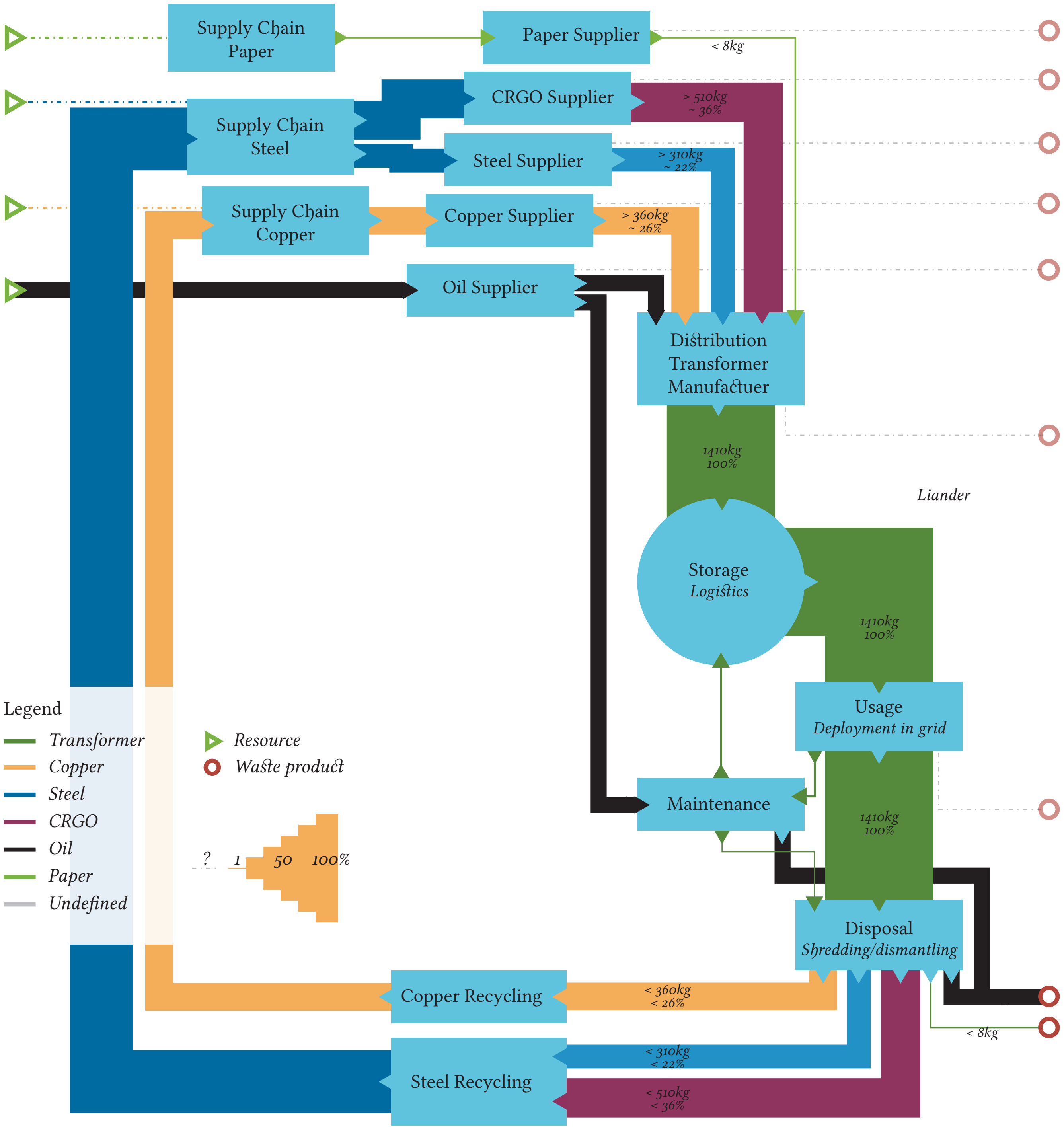
Appendix J — Data Collection

J.1. Material contents Norm 2009 distribution transformer

Table 11 – 9 Material contents of a transformer mass and percentage. Based on contract with a transformer supplier and internal research.

Material / kg	Power / kVA																	
	100		160		250		400		630		1000		1600		2000		2500	
10kV																		
Copper	143.5	22%	195.0	25%	266.0	25%	360.5	26%	531.5	27%	722.0	26%	1034.0	28%	1135.5	26%	1337.5	25%
Iron core (CRGO)	212.0	33%	272.0	35%	363.0	34%	510.0	36%	679.0	35%	837.0	31%	1172.0	32%	1469.0	33%	1667.0	31%
Oil	120.0	19%	120.0	15%	165.0	16%	210.0	15%	295.0	15%	445.0	16%	575.0	15%	655.0	15%	845.0	16%
Tank		0%		0%		0%	310.0	22%		0%		0%		0%		0%		0%
Paper		0%		0%		0%	8.0	1%		0%		0%		0%		0%		0%
Other	169.5	26%	193.0	25%	261.0	25%	11.5	1%	429.5	22%	726.0	27%	939.0	25%	1165.5	26%	1530.5	28%
Total	**645.0**	**100%**	**780.0**	**100%**	**1055.0**	**100%**	**1410.0**	**100%**	**1935.0**	**100%**	**2730.0**	**100%**	**3720.0**	**100%**	**4425.0**	**100%**	**5380.0**	**100%**
20Kv																		
Copper	145.5	21%	181.0	20%	282.0	25%	382.5	25%	521.5	26%	738.0	26%	945.0	24%	1088.5	24%	1218.5	22%
Iron core (CRGO)	244.0	35%	348.0	39%	400.0	35%	566.0	37%	734.0	36%	919.0	33%	1292.0	33%	1531.0	34%	1849.0	34%
Oil	135.0	19%	155.0	17%	205.0	18%	265.0	17%	330.0	16%	480.0	17%	675.0	17%	725.0	16%	905.0	17%
Other	175.5	25%	206.0	23%	263.0	23%	336.5	22%	449.5	22%	683.0	24%	988.0	25%	1215.5	27%	1492.5	27%
Total	**700.0**	**100%**	**890.0**	**100%**	**1150.0**	**100%**	**1550.0**	**100%**	**2035.0**	**100%**	**2820.0**	**100%**	**3900.0**	**100%**	**4560.0**	**100%**	**5465.0**	**100%**

J.2. Material Flow Analysis Norm 2009 distribution transformer



J.3. Circular Values of Transformers

Table 11 – 10 Circular value for the benchmark Norm 2009 transformer, with time span factor = 1000, recycling rates and reserve/production rates are retrieved from [14, 117].

MATERIAL	IN FLOW					OUT FLOW				RESPONSIBLE RATIO		RESULT
Part	Mass in		Recycled	R/P	M_{scarce}	Mass out		Recyclable	M_{acc}	In	Out	Circular value
	kg	%	%	year	%	kg	%	%	%	kg	kg	
Copper	360.5	26%	30%	32	97%	360.5	26%	53%	1%	116.23	189.15	0.274
Core (CRGO)	510.0	36%	52%	60	94%	510.0	36%	90%	1%	279.89	454.41	
Mineral oil	210.0	15%	0%	37	96%	210.0	15%	99%	100%	7.77	0.00	
Tank	310.0	22%	52%	60	94%	310.0	22%	90%	1%	170.13	276.21	
Paper	8.0	1%	10%	1000	0%	8.0	1%	99%	100%	8.00	0.00	
Other	11.5	1%	50%	500	50%	11.5	1%	50%	50%	8.63	2.88	
Total	**1410.0**	**100%**				**1410.0**	**100%**			**590.64**	**922.65**	

Table 11 – 11 Circular value calculation for aluminium transformer, with time span factor = 1000, recycling rates and reserve/production rates are retrieved from [14, 117].

MATERIAL	IN FLOW					OUT FLOW				RESPONSIBLE RATIO		RESULT
Part	Mass in		Recycled	R/P	M_{scarce}	Mass out		Recyclable	M_{acc}	In	Out	Circular value
	kg	%	%	year	%	kg	%	%	%	kg	kg	
Aluminium	270.4	17%	36%	80	92%	270.4	17%	49%	1%	111.18	131.16	0.2776
Core (CRGO)	612.0	38%	52%	60	94%	612.0	38%	90%	1%	335.87	545.29	
Mineral oil	304.5	19%	0%	37	96%	304.5	19%	99%	100%	11.27	0.00	
Tank	390.0	24%	52%	60	94%	390.0	24%	90%	1%	214.03	347.49	
Paper	8.0	1%	10%	1000	0%	8.0	1%	99%	100%	8.00	0.00	
Other	11.5	1%	50%	500	50%	11.5	1%	50%	50%	8.63	2.88	
Total	**1596.4**	**100%**				**1596.4**	**100%**			**688.97**	**1026.82**	

Table 11 — 12 Circular value calculation for amorphous transformer, with time span factor = 1000, recycling rates and reserve/production rates are retrieved from [14, 117].

MATERIAL	IN FLOW					OUT FLOW				RESPONSIBLE RATIO		RESULT
Part	Mass in		Recycled	R/P	M_{scarce}	Mass out		Recyclable	M_{acc}	In	Out	Circular value
	kg	%	%	year	%	kg	%	%	%	kg	kg	
Copper	360.5	26%	30%	32	97%	360.5	26%	53%	1%	116.23	189.15	0.2653
Core (Amorphous)	510.0	36%	52%	60	94%	510.0	36%	85%	2%	279.89	424.83	
Mineral oil	210.0	15%	0%	37	96%	210.0	15%	99%	100%	7.77	0.00	
Tank	310.0	22%	52%	60	94%	310.0	22%	90%	1%	170.13	276.21	
Paper	8.0	1%	10%	1000	0%	8.0	1%	99%	100%	8.00	0.00	
Other	11.5	1%	50%	500	50%	11.5	1%	50%	50%	8.63	2.88	
Total	**1410.0**	**100%**				**1410.00**	**100%**			**590.64**	**893.07**	

Table 11 — 13 Circular value calculation for bio-based oil transformer, with time span factor = 1000, recycling rates and reserve/production rates are retrieved from [14, 117].

MATERIAL	IN FLOW					OUT FLOW				RESPONSIBLE RATIO		RESULT
Part	Mass in		Recycled	R/P	M_{scarce}	Mass out		Recyclable	M_{acc}	In	Out	Circular value
	kg	%	%	year	%	kg	%	%	%	kg	kg	
Copper	360.5	26%	30%	32	97%	360.5	26%	53%	1%	116.2252	189.15	0.454
Core (CRGO)	510.0	36%	52%	60	94%	510.0	36%	90%	1%	279.89	454.41	
Bio-based oil	210.0	15%	0%	1000	0%	210.0	15%	99%	0%	210.00	207.90	
Tank	310.0	22%	52%	60	94%	310.0	22%	90%	1%	170.13	276.21	
Paper	8.0	1%	10%	1000	0%	8.0	1%	90%	0%	8.00	7.20	
Other	11.5	1%	50%	500	50%	11.5	1%	50%	50%	8.63	2.88	
Total	**1410.0**	**100%**				**1410.00**	**100%**			**792.87**	**1137.75**	

Appendix K — Case Study Assessments

K.1. Install Base Assessment

Per constituent, the assessments will be explained for three populations that are part of the current install base. Overall the 1960 population scores negative on most indicators, the 1970 population scores significantly better but still negative, while the 1985 is close to the benchmark Norm 2009 transformer.

Technical Aspects

The technical appraisal is especially for the older transformers worse than the Norm 2009 due to larger differentiation in transformer types, oils, components etc. This makes maintenance more difficult. Physically they are still okay as their failure rate is very low and does not seem to directly related to transformer age. Considering the functional requirements, older transformers are more limited due to the general low capacity (rated size) they have. Especially the 1960 population has still quite some transformers that are too small for current distribution grids.

Table 11 — 14 Technical aspect assessment install base

	1960	1970	1985
Technical aspects			
Functional requirements	-1	0	0
Physical requirements	0	0	0
Operational requirements	-1	-1	-1

Economic Appraisal

The main influencing factors on the assessment of the older sub populations in relation to the benchmark is that they have higher energy losses than the Norm 2009. This results in higher operational costs per unit time to compensate for the extra energy required and carbon emissions. This is especially the case for 1960 transformers that have nearly twice the amount of energy losses than current transformers. The longer these transformers are in the grid the more they costs. These costs are especially relevant for the total cost of ownership that only accounts for the costs. Considering the Return on Investment, the oldest transformers have already been written off and are therefore cheaper per year than newer assets for which a lifetime of 40 years is estimated and used within this calculation.

Table 11 — 15 Economic appraisal assessment install base

	1960	1970	1985
Economic appraisal			
Net present value	0	0	0
Return on investment	1	0	0
Total cost of ownership	-1	-1	0

Stakeholder Appraisal

The stakeholder appraisal is more or less the same as the Norm 2009 for all sub-populations. This is because the stakeholders involved are the same. Except of the oldest population there are some transformers still installed from manufacturers that do not exists anymore. This makes possible revision more difficult in case the exact specifications are not known for these transformers. Hence, the dependency for some of the transformers in this population is critical and thus negative.

Table 11 — 16 Stakeholder appraisal assessment install base

	1960	1970	1985
Stakeholder appraisal			
Stakeholder dependency	-1	0	0
Stakeholder collaboration	0	0	0
Stakeholder responsibility	0	0	0

Sustainability

In general, the sustainability of all transformers are scored negatively in comparison with the Norm 2009. This is because of their higher energy losses compensated by a general energy mix that account for most of the material usage, environmental impact and ecological footprint. The use phase of transformers is estimated to account for most of the energy and material usage in case the energy from a non-renewable source. A second factor is that older transformer have a higher level of degradation and hence score slightly worse on sustainability than newer transformers as their recyclability is somewhat less. The 1985 population scores the same as the Norm 2009 on preservation of material because its energy losses are not as large as the other subpopulations and its recyclability is expected to be nearly equal. However, for production and recycling there is still an impact on the environment as well as a substantial ecological footprint.

Table 11 — 17 Sustainability assessment install base

	1960	1970	1985
Sustainability			
Preservation of materials	-1	-1	0
Environmental impact	-1	-1	-1
Ecological footprint	-1	-1	-1

Strategic Alignment

Considering strategic alignment, the old population of 1960-1970 still complies with the current standards within EU legislation on ecodesign for new transformers, but as these standards increase over time, they will soon fail them. However, this subpopulation already fails the company's own standard of the 1970 threshold. The 1970-1980 subpopulation also complies with the current EU standards for new transformers, but alike the 1960 population, will soon also fail those.

Table 11 — 18 Strategic alignment assessment install base

	1960	1970	1985
Strategic Alignment			
Business goals alignment	-1	0	0
Chain partners alignment	0	0	0
Governmental alignment	-1	-1	0

Risk Assessment

The risks of the 1960 population are estimated to be a bit higher than the others due to the larger variation in transformers. This makes acting adequately on changes within this population more difficult. Also due to static performance of transformers the risk that they may not comply with new legislation or sustainability insights are higher. The 1970 population also scores a bit negative on the stakeholder risks for the same reasons as the 1960 population.

Table 11 — 19 Risk assessment install base

	1960	1970	1985
Risks			
Technical risks	-1	0	0
Economic risks	-1	0	0
Stakeholder risks	-1	-1	0
Sustainability risk	-1	0	0
Strategic risks	-1	0	0

K.2. Material Alternatives

The different material alternatives that were assessed consider aluminium for the coils of the transformer, amorphous material for the core and bio-oil for the coolant and insulation function.

Technical Aspects

The technical appraisal is overall negative for the amorphous core because of the recent tests that were carried out. Further development could change this situation. Also because of the brittleness of the amorphous transformer, transportation and installation should be done very carefully as it may damage the transformer. This causes the operational assessment to score very low as this characteristic may also make revision of the transformer in a workshop more challenging.

The aluminium and bio-oil alternatives score slightly higher than the amorphous transformer. The bio-oil will not need additional preventive measures against leaking, as mineral oil needs and therefore the physical requirements are better than the Norm 2009.

Table 11 — 20 Technical aspect assessment material alternatives

	Aluminium	Amorphous	Bio-oil
Technical aspects			
Functional requirements	1	0	0
Physical requirements	0	-1	1
Operational requirements	0	-2	0

Economic Appraisal

The financial appraisal is especially for the amorphous transformer positive. Even though the higher investment costs, the TCO is lower due to the lower energy losses, which are double counted through energy compensation, and costs for carbon emissions. This is only slightly positive, and not appraised in the ROI, because of uncertainty considering additional investments to prevent noise nuisance.

Table 11 — 21 Economic appraisal assessment material alternatives

	Aluminium	Amorphous	Bio-oil
Economic appraisal			
Net present value	0	0	0
Return on investment	0	0	0
Total cost of ownership	0	1	1

Stakeholder Appraisal

The stakeholder appraisal is for the amorphous transformer is currently assessed negative in comparison with the benchmark. This is because there are only a few manufactures of this material causing a critical dependency. Next to that, stakeholder responsibility is also assessed lower because of the increased noise production. This means that Liander would have additional responsibilities towards citizens to overcome this problem.

Both aluminium and bio-oil score slightly higher than the benchmark because of ready availability of these alternatives and material. For bio-oil, the social impact within stakeholder responsibility is estimated positive due to a safer product. In case it would leak oil there is no harm done to the environment or groundwater.

Table 11 — 22 Stakeholder appraisal assessment material alternatives

	Aluminium	Amorphous	Bio-oil
Stakeholder appraisal			
Stakeholder dependency	0	-2	0
Stakeholder collaboration	1	0	1
Stakeholder responsibility	0	-1	1

Sustainability

The sustainability scores are generally positive. For the amorphous core, the circular value is slightly under that of the benchmark. But when including the energy usage during production and use, the amorphous core is assumed to score much better.

The bio-oil also scores better than the current benchmark as result of the decreased degradation of oil and paper. As well as the increased recyclability and hence the preservation of materials.

For aluminium, there is a slight increase in sustainability based on the circular value that indicates the positive use of less scarce aluminium over the scarcer copper of the Norm 2009. Even though recycling of aluminium is estimated to be a little harder.

Table 11 — 23 Sustainability assessment material alternatives

	Aluminium	Amorphous	Bio-oil
Sustainability			
Preservation of materials	1	1	2
Environmental impact	0	1	0
Ecological footprint	0	0	0

Strategic Alignment

The strategic alignment of the three alternatives all score slightly positive, except for the amorphous on chain partner alignment. This is because current suppliers to Liander are not ready to fulfil the wished amorphous transformer that passes all requirements. For the other indicators, the business strategy and governmental strategy are in line with these alternatives because of legislation targets and cost reduction.

Table 11 — 24 Strategic alignment assessment material alternatives

	Aluminium	Amorphous	Bio-oil
Strategic Alignment			
Business goals alignment	1	1	0
Chain partners alignment	0	-1	0
Governmental alignment	1	1	1

Risk Assessment

The risks of these transformers are generally positive as they move ahead of possible problems in the market or changes in sustainability perspectives and legislation. Only the amorphous transformer has a negative assessment on economic risks due to the uncertainty of its return on investment.

Table 11 — 25 Risk assessment material alternatives

	Aluminium	Amorphous	Bio-oil
Risks			
Technical risks	0	0	1
Economic risks	0	-1	0
Stakeholder risks	0	0	0
Sustainability risk	1	2	2
Strategic risks	0	0	1

K.3. Non-Product Related Alternatives

The non-product related alternative consider parallel placement of transformers at a single location; creating buffers in the distribution grid, in this case through the use of electric cars; and buying renewable energy to compensate for the energy losses in the grid. As these three scenarios are not competing and could be used in simultaneously, they should not be compared other than to the benchmark.

Technical Aspects

The technical aspects considering the parallel placement and installing the buffers is important since it will increase the number of assets in the grid. The carbon neutral alternative has no positive or negative assessment here, as it is a non-technical alternative.

The functional requirements are both positive in relation to the benchmark since these solutions contribute to a better energy quality and possible less SAIDI. Physically, the parallel placement of transformers is assessed neutral because it is only possible on places where there is enough room for adding an extra transformer. Adding buffers to the grid will physically require more room to be able to connect the buffers. Also more material is needed while for placing the transformers in parallel old transformers may be used as a way of extending their life span.

Operational performance is for both the parallel and buffer alternative positively assessed as it allows for better maintenance of the grid as well as optimised energy distribution throughout the distribution grid.

Table 11 — 26 Technical aspect assessment non-product related alternatives

	Parallel	Buffers	CO_2 neutral
Technical aspects			
Functional requirements	1	1	0
Physical requirements	0	-1	0
Operational requirements	2	2	0

Economic Appraisal

For the parallel scenario, the economic appraisal is generally positive. Costs will not change much as transformers from current pool will be used, but the benefits increase due to load-balancing and slight increase in SAIDI.

For the second scenario on buffers, additional infrastructure may be necessary, but the use of already available buffers limits the necessary investments. The need for replacing transformers for new ones with a larger capacity is not needed anymore and thus large investment costs are deferred. The total costs are therefore smaller.

The carbon neutral alternative is also economically positive, even though the costs for renewable energy are higher. The reduction can be found in the avoidance of carbon emissions. The return on investment on transformers is therefore higher as the costs reduce.

Table 11 — 27 Economic appraisal assessment non-product related alternatives

	Parallel	Buffers	CO_2 neutral
Economic appraisal			
Net present value	1	0	1
Return on investment	1	1	1
Total cost of ownership	0	1	0

Stakeholder Appraisal

The stakeholder appraisal considers the impact of the alternative on dependency, the collaboration and the responsibility towards the stakeholder. For the first alternative of placing the transformers in parallel the different stakeholder impacts do not change since the same asset is still being used.

For investing in buffers, the impact on the stakeholder dependency increases because the availability of buffers depends on the EVs or other possible privately owned buffers that are connected to the grid. The collaboration is however positive as this is an inherent need in this scenario, allowing for further optimisation and development of the system. on the other hand the responsibility is assessed negative because using buffers such as the batteries of EVs creates a responsibility towards the availability of the battery towards its primary system. The battery needs to be charged when it is necessary and every charging-discharging cycle batteries age.

Finally, the carbon neutral alternative is highly dependent on the availability of this form of energy generated by third parties. There is no increase or decrease in collaboration for this alternative and hence is assessed neutrally. The responsibility is also assessed neutral; however it is positively and negatively affected. The responsibility towards stakeholders in reducing CO_2 emissions is positive. However, buying large quantities of carbon neutral energy reduces the amount available on the market for consumers and small businesses that do not have the opportunity for generation of their own green energy.

Table 11 — 28 Stakeholder appraisal assessment non-product related alternatives

	Parallel	Buffers	CO_2 neutral
Stakeholder appraisal			
Stakeholder dependency	0	-1	-2
Stakeholder collaboration	0	1	0
Stakeholder responsibility	0	-1	0

Sustainability

The three alternatives are all positively assessed on their sustainability impact. The parallel placement reduces the energy losses within the transformers as the load is divided over two transformers. Besides the reduction of energy losses, the transformers will also last longer due to lower temperatures. Both effects are positive of all three indicators when considering the entire life cycle.

The buffers will aid in peak shaving of energy demand. This helps to reduce the amount of energy that needs to be produced from non-renewable sources to suffice the demand throughout the day. This effect has large impact on reduction of non-renewable energy and thus material preservation, environmental impact and ecological footprint.

Considering the investment in CO_2 neutral energy compensation, there are large benefits from this considering sustainability. Besides that, there are no large quantities of materials lost for energy production, there is also less mining necessary as the harvesters of renewable sources (windmills, water turbines, etc.) can largely be made from recycled materials. Next to that, if chosen well, they may have much less, or even a positive impact on the environment.

Table 11 — 29 Sustainability assessment non-product related alternatives

	Parallel	Buffers	CO_2 neutral
Sustainability			
Preservation of materials	1	1	2
Environmental impact	1	1	2
Ecological footprint	1	1	2

Strategic Alignment

Parallel placement of transformers is not directly in line with Liander's business goals, nor with chain partners. However, it may be in line with the government due to reduction of carbon emissions. For the same reason the buffers and the carbon neutral alternatives are in line with the government as they achieve reduction in carbon emissions as well. Next to that, the buffer scenario makes the energy grid more resilient and increases service. This is also in line with the business goals. The CO_2 neutral has more reduction of carbon emissions than the parallel scenario and is therefore also scored positively for the business goals alignment.

Table 11 — 30 Strategic alignment assessment non-product related alternatives

	Parallel	Buffers	CO_2 neutral
Strategic Alignment			
Business goals alignment	0	1	1
Chain partners alignment	0	0	0
Governmental alignment	1	1	1

Risk Assessment

Considering parallel placement, all of the constituents have a general positive influence on the safety and security, and therefore creates windows of opportunities for testing and innovations. This opportunity is explicitly valued within this assessment.

For the buffer scenario, the risks are high for the technical and stakeholders constituents as external factors such as new technologies or economic incentives may likely change the technical performance or stakeholder behaviour.

Considering carbon neutral, the risk assessment is generally assessed positive. Less sustainable resources are removed moving Liander ahead of various economic and strategic trends that may later be enforced by governments.

Table 11 — 31 Risk assessment non-product related alternatives

	Parallel	Buffers	CO_2 neutral
Risks			
Technical risks	1	-1	0
Economic risks	1	1	-1
Stakeholder risks	0	-1	-1
Sustainability risk	1	0	1
Strategic risks	0	1	1

Appendix L — List of Analysed Documents Concerning Investment Decisions

Below is a list of documents that were analysed to determine the practice and structure of investment decision proposals within Liander. These have been used in concordance with information retrieved from experts on the subject.

Template and Manuals

Template Investeringsvoorstel
17-02-2012, Liander - TEMPLATE Investeringsvoorstel.docx

Template projectvoorstel v2.0
Template projectvoorstel v2.0.docx

Instructie Investeringsproces Netinvesteringen
22-03-2012, Intructie investeringsproces Netinvesteringen PIB 22-3-12.pptx

Handleiding PIB/TRC process
10-02-210, 20120210 Handleiding PIB TRC proces v1 0.ppt

Besluitvormingsdocument TRC
24-02-2014, Besluitvormingsdocument TRC 2 1 dd 20140224.docx

Project & Investment Proposals

Vervanging schakelinstallaties te RS Leuven en SS Harderwijk Lorentz
22-9-2011, 20140306_Bijlage_4.1.4b_IV_Leuven.pdf

Aansluiten A1 industrieterrein Deventer
4-11-2013, 20140108_Bijlage_4.1.2b_IV_A__industrieterrein_Deventer[1].pdf

Ede het nieuwe landgoed Opgedrongen verlegging van kabels en algemene voedingspunten.
20-02-2014, 20140306_Bijlage_4.1.1b_IV_Ede.pdf

Windpark Wagendorp
01-03-2014, 20140306_Bijlage_4.1.2b_IV_Windpark_Wagendorp.pdf

Ombouw OS Zorgvlied deel 2
24-04-2014, 20140424_IVOmbouwZorgvliedDeel2.pdf

20kV op onderstation Anklaar
12-06-2014, 20140612_Bijlage_4.1.7b_Investeringsvoorstel__Anklaar.pdf

Appendix M — Meetings and Consultations

The following lists most important meetings and consultations that form the basis of the action research of this study:

M.1. Single or Occasional meetings

Aurubis (Zuthpen)
Copper recycling

B. Braam (Liander)
On oil regeneration

Circular Booštcamp (Amsterdam)
On Circular Economy for infrastructural sector (energy grid and railways)

P. van Engelen (Liander)
On Investment decisions

Get Connected Café on Circular Economy (the Hague)
Local and regional governments, several and experts Tom Bastein (TNO), Erik Wuestman (Circular Economy)
Network meeting on best practices

K. Heida (Liander)
Various meetings on distribution transformers, assessment and evaluation.

Interface flooring (Scherpenzeel)
On FSSD framework and Circular Economy

Kivi meeting Circular businessmodels (the Hague)
By E. Wuestman
Lecture on Circular Business models

Management Team Liander Asset Management Policy & Standardisation (Liander)
On the assessment method

A. Medema (Liander)
On procurement, material knowledge

W. Molenaar (Liander)
On waste management at Liander and distribu tion transformer recycling

B. Peppelman (Liander)
On Risk matrix and investment decisions

Pothuizen Recycling
with B. van Maris, K. Heida
On Waste handling of transformers

SITA Plastic Recycling (Rotterdam)
W. Mur, W. Molenaar
Excursion for Liander to SITA on the Plastic Heroes

W. Vermuelen, Witjes and D. Reike (University of Utrecht)
On Circular Economy and Impact method

WCM Summer School (Breda)
On Asset management, distribution transform ers and sustainability

H. van Zandvoort (Liander)
On material flow and transformer procurement

E-mail Contact

ABB Bio
G. Kockelkorn
On distribution transformer and developments

Circle Economy
A. van der Plas
On Circular Scorecard

IEO trafo
On distribution transformers

MI Materials
J. Caldeira, R. Martin
on Midel bio oil

Smit Trafo
A. Verhart
On distribution transformer and developments

M.2. Regular meetings

Operationeel Team Circulair inkopen (weekly)
D. Hermans, K. Eising, H. de Vries, L. Verweij, L. van Genugten, N. van den Steen

Kernteam Circulair Inkopen (monthly)
Members from various departments within Liander

Circular Economy Labs (bi-monthly)
Organised by Utrecht Sustainability Institute