DTU Civil Engineering
Department of Civil Engineering

Study and analysis of the transition towards a circular economy in the construction sector.

Business models, indicators and assessment methods. Covering a case study for the economic evaluation as a design parameter in collaboration with Arkitema.

MASTER THESIS

Pablo Villaizan - s212207

Study and analysis of the transition towards a circular economy in the construction sector.
Business models, indicators and assessment methods. Including a case study for the economic evaluation as a design parameter in collaboration with Arkitema.

Master Thesis
July, 2022

By
Pablo Villaizan

Cover photo: Vibeke Hempler, 2012
Published by: DTU, Department of Civil Engineering, Brovej, Building 118, 2800 Kgs. Lyngby Denmark
www.byg.dtu.dk

Approval

This thesis has been prepared in the period from 1 February to 22 July at the Department of Civil Engineering, Technical University of Denmark, DTU, in partial fulfilment for the Master's degree under the supervision of Lotte Bjerregaard (DTU-Byg) and in collaboration with Arkitema Architects.

Pablo Villaizan - s212207

PABLO|
VILLAIZAN|MARIN

Firmado digitalmente por
PABLO|VILLAIZAN|MARIN
Fecha: 2022.09.12
10:51:41 +02'00'

Signature

22/07/2022

Date

Abstract

This project aims to research and analyse the literature behind the circular economy, its concepts, enablers and its application in the construction industry, with a focus on business models and methods of evaluation and measurement.

Secondly, by applying some of the concepts reviewed in the literature and testing the adaptability of the LCC method and the LCCbyg tool, it tries to assess the feasibility in the design stage of implementing circular business models, in a case of re-use of roof tiles developed in Gadehavegård, Denmark. In order to evaluate a business model suitable for circular economy in the building industry.

The results suggest that, under current conditions, it is possible to achieve economic sustainability by applying circular business models, a necessary factor to encourage change and the adoption of these concepts in organisations. Indeed, it is also noted that this will be enhanced in the coming years by the incoming enablers being generated in the industry, which could help make the necessary final move to adopt circular models on a regular basis.

Finally, the study has also allowed observing the support of using conceptual frameworks and archetypes of strategies for the generation of ideas and conceptualisation of models; while it has also made it possible to identify the usefulness of assessment methods such as LCC and tools like LCCbyg for decision-making in the design phases and their adaptability to circular models.

Acknowledgements

I would wish to give special thanks to my supervisor, Lotte Bjerregaard Jensen, for the opportunity to do this thesis and to go deeper into this field, and for the support and guidance provided during the whole process.

I would also like to extensively and personally thank Signe Bang Korsnes, Sisse Rüss and Marianne Mark Lindhardt of Arkitema Architects for their accessibility for collaboration, support, resolution of doubts, facilities and the information and time given to the case.

In the same sense, I wanted to express my gratitude to Maria Saridaki for her great predisposition, attention and the documentation provided to compare data.

I would further like to mention Anders Sørensen of Enemærke & Petersen a/s and Thomas Sinding of J.Jensen for their first-hand information and quick response.

Pablo Villaizan,
Author of this thesis.

Contents

1 INTRODUCTION

Globally, the world is facing a series of problems that are calling into question our current economic models. Now, more than ever, we need solutions and new proposals to address them [1]:

1. **Climate change:** The current and past generations of energy production and consumption is causing global climate change [2] [3].

2. **Population growth and Urbanisation:** The global population is projected to grow to 8.6 billion people by 2030, and 11.2 billion by 2100 [4].
This is expected to lead to a huge growth in urbanisation and urban areas. This will have a major impact on energy-intensive material consumption, reduced air quality and increased water pollution downstream.

3. **Raising energy use:** Nowadays, it takes nature 18 months to produce what we consume globally in 12 months. Globally, the growth in energy consumption is increasing[1]. This is due to multiple factors triggered by development, population growth and the need to cover different (and increasing) needs in different parts of the world. In addition, dependence on fossil fuels is still very high (appendix A.2.1). It is true that in the case of Denmark, measures are being taken to reduce dependence on fossil fuels to the maximum and to become a country based on clean energy consumption, among other things:

   (a) Stop oil and gas extraction by 2050, with a greater push for renewables.

   (b) Abandoning the use of natural gas in half of the households that use it by 2028 at the latest, and stopping using it completely by 2030.

   (c) To become an exporter of renewable energy to the rest of the continent by 2030.

   These measures will achieve almost 100% renewable generation by 2030 and aim to increase the share of green energy in the energy mix and gradually increase the share of renewable energy to 100% in the energy and transport sectors by 2050. It is true that these measures will reduce many negative impacts from the use of fossil fuels, but this does not indicate a more responsible consumption and a decrease in energy consumption. Higher consumption means higher costs for materials, resources and space, in addition to the impact on the environment, even if they come from clean sources. Renewable energies, including wind, solar, biomass and hydropower, also have environmental impacts, such as the impact on land use of wind power installations and solar photovoltaic systems, bird deaths from wind turbines, concentrating solar thermal units that require water for cooling, and the flooding of land for hydroelectric dams [5]. So the problem cannot be reduced to changing the type of energy consumed, but the focus must also be on reduction and responsible consumption.

4. **Increase demand of water:** The current water consumption scenario will result in demand far exceeding the existing water supply in the coming decades. The main

[1]Exceptionally, this past year has seen a drop in energy consumption mainly due to the recession experienced during the pandemic (appendix A.2.1), from which certain lessons can be learned that will help in the near future, but even so, the general trend is upwards, which continues to keep energy growth in focus.

drivers of demand are urbanization, population growth, and increased demand from industry and energy[1].

5. **Economic growth and increase of material usage:** Economic growth, seen by many economists as a positive and essential point for the growth of the global economy (now at risk of slowing down due to various circumstances such as the COVID outbreaks, and problems in the supply chain with strong impacts on inflation), can also be a major cause for concern. Among other things because of the increase in material consumption and emissions, the limitation of natural resources and the increase in demand that this entails [1].

6. **Solid waste:** By 2050 global waste is expected to increase by 3.4 billion tonnes. The highest-income countries are expected to generate the most waste, accounting for 34% of the total [1].

7. **Air pollution and greenhouse gas emissions:** Derived from the other factors discussed above and the strong emissions that still prevail globally. In this point, Denmark reaffirms its intention to reduce greenhouse gas emissions by 70% by 2030 without compromising its profit and welfare states.

8. **Infrastructure expansion:** With the expected global population growth of around 26% by 2050 and the growth of urban areas, there will be a projected growth in demand for infrastructure. This creates a challenge as to how to achieve them in such a way that the impact on the environment is, in all respects, as low as possible.

As we have seen, Denmark is indeed taking steps to confront some of the main problems, but there are still many issues that need to be addressed and many others that still need to undergo major changes to meet the targets set.

Within all of the above, the construction sector is not only one of the main actors responsible for the negative trends presented, but due to the high impact of the sector, it is one of the industries with the greatest potential for change.

Therefore, the sustainable development of both the economy as a whole and, in this specific case, the building sector, will be a key point for the future of our society and the environment around us.

The current way of understanding the economy and the current models and processes are based on linear models, where the consumption of natural resources is exploited in an unconsidered way for the generation of products. After their useful life, these products are discarded as waste. This linear approach is one of the main drivers of the negative impact on the earth and socio-economic systems. Therefore the abandonment of these models for more efficient ones is essential for the shift towards sustainability.

To this end, the circular economy and the adoption of this model in the different sectors, and in this case in the construction sector, can represent a key strategy for partially solving some of the main problems we face in achieving sustainable development.

1.1 Problem Statement

In this project, the aim has been to:

- Research the literature behind the circular economy, its concepts and its application in the construction industry.
  - Reviewing the key concepts, and presenting an analysis of the main stages and key enablers.
  - Focusing on the circular economy business models, indicators and assessment methods suitable for a circular framework.
    - In terms of business models, different conceptual frameworks, strategies (by making a classification) and other methodologies are presented and reviewed.
    - In terms of the indicators and evaluation methods, this are presented in a classified form and two new indicators LS(E)IR and EENS are proposed.
- Apply different circular economy business strategies and an assessment method highlighted by the study, in a case study on the re-use of roof tiles in Denmark, to evaluate various business models from the economic dimension in the design phase.

2 METHOD

Note in first place the fact that the results of the project will be presented in two main parts:

1. **Results part 1 (”Results 1”):** The first part presents the results of the analysis and study of the literature. It is divided into three main blocks for better classification, analysis and presentation of the results.
2. **Results part 2 (”Results 2”):** Part two presents the results of the case study carried out with the company Arkitema, where the economic viability of different circular business models at the product level is analysed.

2.1 Literature Study (”Results 1”)

For the elaboration of the study and analysis of the literature, different sources have been used to gather information for the project. These include:

- Academic publications, mainly extracted from tools such as ”Web of Science”, ”DTU findit” and ”Scopus” or ”Google Academic”.
- Governmental resources, at national and international level.
- Standards and guidance
- Known sources, of books or articles that were already available.
- Grey literature, including research reports, articles, specific projects, statistics, etc.

After compiling all the information, all is read, filtered, and selected, to carry out the analysis set out in the project. In the process, research continues, and new information is sought without limiting itself to the bibliography found and analysed in the first instance.

After a first reading and analysis of the information, it was decided to present the results of the literature review (”Results 1”) in the following three main blocks, for better differentiation and understanding:

- ”Transition To a Circular Economy in the Building Sector”
- ”Business Models”
- ”Assessment and Measurement as Design Parameters”

Once this decision has been taken, the final analysis is carried out with the results on the literature as presented in the final project.

2.2 Case Study (”Results 2”)

Based on the findings and results from the literature review, it is decided to approach a case study to continue the research and to test some of the tools or models analysed during the first part of the study.

On this basis, conversations are held with different companies for the selection of the case. Finally, Arkitema proposed a case study for the economic viability of various proposals applied to the roofs of Gadehavegård, specifically to the roof tiles.

This proposal allows to address different points that may be relevant, such as the following:

- The actual usefulness of at least some of the tools for developing and conceptualising business models studied or proposed.
- The adaptability of some of the evaluated evaluation systems to circular models and their actual capacity to advise decision-making in the design process.
- The feasibility of applying circular business models in the industry.

It is therefore decided to conduct this proposal.

With this case in hand, and before visiting the company, a pre-study of the area and the project is carried out. Different ideas are put forward that will later be contrasted with Arkitema. In addition, based on the literature study, the assessment model to be used (LCC) is chosen.

Afterwards, several visits are made to Arkitema, where the case information is collected, the proposals and business models to be finally evaluated are discussed, and all the necessary doubts are resolved.

In this process, the tool for developing the LCC assessment is selected. The use of Excel (with the advantage of knowing the tool) is assessed against other semi-automatic tools. Excel is discarded as there are currently sufficiently advanced tools available to avoid having to create the model on a spreadsheet.
Finally, with the information gathered on the available tools, it was decided to use the LLCbyg software [6], which stands out for its great possibilities and options, ease of use and fast learning, much more powerful than other tools thanks to its functionalities, as well as being the most widely used in Denmark.

After its selection, the software operation and use are studied more deeply by carrying out tests without impact on the case.

The economic evaluation is carried out with the information gathered from Arkitema, the model and the selected tool.

In the process of assessment, it has become necessary to gather more information from different sources such as Arkitema itself [1], demolition companies J.Jensen and Enemærke & Petersen, and digital documentation.

With this, the primary evaluation is carried out following the assumptions agreed with Arkitema, detailed in the project. Some other scenarios are also assessed with minor feasible variations on the initial assumptions, and the results of these scenarios are also presented and analysed in the results.

Maria Saridaki, a professional with extensive knowledge of economic sustainability assessment of circular models using LCC in the building sector, is contacted to contrast the assessments made.

[1] The images of the neighbourhood, sketches and drawings of the project are provided by ”Arkitema Architects”.

3 RESULTS 1.A - TRANSITION TO A CIRCULAR ECONOMY IN THE BUILDING SECTOR

This section will provide and overview and analysis of the findings done about circular economy in building sector. It also proposes strategies for implementing the CE in the different phases of the sector and analyses the main drivers that will make this economic model more viable and profitable in the coming years.

On the other hand, this chapter serves as a basis for a better understanding of the different business models and evaluation methods presented in (chapter 4 and chapter 5) to address and correctly analyse them.

Finally, this study will facilitate the understanding and practical framework in which the Gadehavegård case study (chapter 6) will be placed and developed. It will also provide the strategies to consider for developing the business models for the case. Lastly, it will recognise the future potential of the results obtained, and the possible change of parameters on them when new disruptors come into play.

3.1 Key Concepts

The main purpose of this section is firstly to present definitions, understandings and relationships between the concepts that will be mentioned throughout this document: Sustainability, Sustainable Development and Circular Economy (CE). This was necessary due to the still lack of a clear consensus and linkage between these terms throughout the literature.

Secondly, it will explore the current situation and the main challenges in the construction sector and how the EC can intervene and play an important role in this sector.

3.1.1 Sustainability and Sustainable Development

Faced with the problems encountered in our context, the concepts of sustainability and sustainable development acquire great relevance as they are essential elements in tackling the great challenges facing today's society, both, in the economy as a whole, and in the specific case of the construction sector.

According to the Bruntland Commission Report (1987), this being one of the first definitions developed, it described sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." [7].

Nowadays, it can be said that sustainability is a paradigm for thinking about the future in which environmental, social and economic considerations are balanced in the pursuit of a better quality of life. The difference between sustainable development and sustainability is that sustainability is often seen as a long-term goal, whereas sustainable development refers to the many processes and pathways to achieve it [8].

As it can be seen, the essence of the idea remains the same but has been developed and improved over time.

Today, the idea that sustainability is made up of three main pillars, also referred to as the ”Triple Bottom Line” (TBL) perspective, is widespread:

1. Environmental sustainability
2. Economical sustainability
3. Social sustainability

However, some organisations or researchers add some more dimensions to these three main and commonly accepted ones. UNESCO [8] adds the dimension of cultural sustainability, adding that these four dimensions are interlinked and not separate. This would be interesting to take into account in the building sector in the future and, by giving it this relevance along with the rest, it can be taken into account when dealing with different projects[1].

Having commented on the discussion of the dimensions to be taken into account to conceptualise sustainability, and being able to affirm the three non-excludable dimensions of this concept, it is necessary to determine the interaction between them and how the understanding of this interaction is also evolving in recent years.

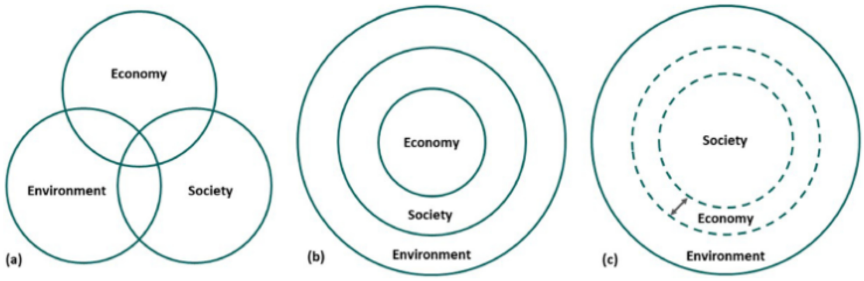


Figure 3.1: Evolution in the practical interrelationship between the three main dimensions of the sustainability concept [9].

As seen in the figure, traditionally, the sustainability perspective understands that the three pillars of sustainable development are considered to be of equal importance (a), the commonly accepted perspective at the theoretical level and found in most publications.

It is interesting to note that the concept has developed in such a way that, at a practical and business level, the interaction between the three dimensions is closer to (c), where the economy is considered as a tool to organise resources to maintain and enhance social well-being, environmental quality, and economic prosperity, so it is interesting to look at this graphical interpretation to better understand the natural interaction between the three dimensions.

A clear example of this can be seen in companies with sustainable objectives, where they seek to have a positive impact on society and the environment, but always without losing sight of economic viability. This is the tool that sets the limits because if the company is not economically sustainable, it will not be able to continue its activity and have an impact in any way.

[1]For this study, the three main pillars of sustainable development proposed by the TBL perspective will be taken into account, as they are the most repeated and accepted in the sector.

3.1.2 Circular Economy - CE

The concept of circular economy has been gaining weight and relevance when it comes to achieving many of the objectives established to fulfil sustainable development.

The advantages of reconciling and integrating sustainable development into the circular economy are becoming increasingly clear, as it is a strategy with great potential for the sustainable development [9].

Nowadays, great deal of effort is being put into conceptualising the circular economy at different levels.

However, as has been observed throughout the literature and after the brief analysis done in one of the following sections (section 3.1.2.4), comment that, at a conceptual level it has been seen a need to establish a better understanding of CE and CE's strategies and principles. Although there are general definitions that enables to get the concept, there is a need to be more specific and seek a clear and formed consensus; otherwise, this will lead to misunderstandings [9].

3.1.2.1 *Definition and Main Objective*

Within the literature, there are a large number of definitions of a circular economy, each with different nuances. Based on a review of the literature trying to find a precise definition of what CE is broadly from an organisational perspective, Omar Alhawari [10] Concludes that "CE is the set of organisational planning processes to create, deliver component products, and materials at their maximum utility to customers and society through the effective and efficient use of ecosystem, economy and product cycles, closing the loops of all related resource flows".

From this project, it is understood that the circular economy is an economical model that may be focused on and seek environmental sustainability through the application of organisational strategies that in turn aim to maintain or improve the economic sustainability of the business, without losing sight of the social aspects. To achieve this objective, it is based on the concept of circularity, in which, ideally, each process follows a closed cycle that allows the recovery of the maximum of the means involved without them being discarded or expelled out of the system[2]. In this regard, the circular economy tries simultaneously to contribute to both regeneration and restoration of the environment.

If sustainability, in each of its dimensions, is neither integrated into the implementation of circular economy practices nor present in circular economy research, it risks losing the momentum of a strategy with enormous potential for sustainable development. Circular economy advocates must prioritise the integration of sustainability throughout the design, implementation and management of the circular economy [9]. Hence, circular economy implementation strategies must always keep the ultimate goal of sustainability impact in order not to lose perspective and not disconnect both concepts.

3.1.2.2 *Decoupling Concept*

In addition to the main objective attributed to CE of pursuing sustainability, another of the most critical aspects of this model, is that the circular economy may also seek to decouple economic growth from resource use and associated environmental impacts.

The basis of decoupling is that economic output increases or are maintained simultaneously as resource use rates are reduced and environmental impacts are slowed down to reduce them over time.

[2] In this way, the circular economy aims to maintain the value of the materials used as high and long as possible, as one of its main strategies.

Absolute decoupling is when the environmental variable is stable or decreases while the economic variable increases. Relative decoupling is when the ecological variable increases slower than the financial variable.

There are two main decoupling modes [1]:

- **Impact decoupling:** Seeks to increase economic activity while reducing negative environmental impacts from pressures such as pollution, carbon emissions or the destruction of biodiversity.
- **Resource decoupling or "dematerialization":** Involves reducing the rate at which natural resources are used per unit of economic output o o the decrease over time of the mass of materials used in final products.

3.1.2.3 *Achieving Sustainability with CE*

To cover the TBL perspective, it will be necessary to focus on the organisational activities of the CE. These actions take place in the context of infrastructure development and stakeholder relations to achieve material efficiency by reducing ecological impacts and decoupling. In essence, CE is a set of practices aimed at keeping products in use for as long as possible, even after the end of their useful life [10].

These actions will follow different principles [3] with the need to prioritise the highest impact actions, working under an economy that is circular by design. This requires profound changes in production, consumption, waste management, collaboration, and coordination to visualise its implementation.

3.1.2.4 *CE today and the way forward*

Currently, the circular economy is at a stage of development where it has not yet managed to cover the TBL perspective, which typifies sustainable development. However, the interest of all social agents in advancing in this aspect is growing.

The following is a discussion of the current state of the circular economy, in each of the three traditionally accepted dimensions

- **Environmental dimension:** So far, the circular economy has arguably focused on reducing negative environmental impacts. Still, it must shift its focus to preserving (zero impact) natural capital and enhancing it (net environmental gains), where possible.

  Further development and research are needed to determine the actual net environmental gains that can be achieved and to what extent this may be realistic. Some research areas have shown that some forms of natural capital can be regenerated. Still, many ecosystem changes are considered irreversible and restoring ecosystems and the natural capital within them to the same state as before may not be possible or preferable given the course of the environment [11]. It is also unclear whether the quality of life can be ensured while regenerating the environment and what is the real potential of circular economy and role that it can play in these regeneration processes [9]. Technological development will often not have the capacity to make up for the errors and consumption generated, and it is impossible to rely on this as a trump card, playing down the importance of decision-making and trying to make up for the impacts with technology.

[3] Many authors group into the 9R's (In order of priority: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recovery), or in strategies

All this must be taken into account in the circular economy. It may be necessary to reduce the effects at the root, which is discussed in other models such as the de-growth theory.

- **Economical dimension:** It can be observed both on a theoretical and practical level (already being applied in the market), there are different narratives and models at the economic status for the pursuit of sustainability or sustainable development.

  The circular economy points out that there is a need to change the perspective from economics as a means of generating money to economics as a means of managing resources to protect the environment and develop social welfare.

  To this end, and for adopting circular models in the market, the hidden benefits of the CE in each sector and the business opportunities that this generates must be shown and pointed out. Looking less for short-term results and focus more on long-term effects. Finding business models that work in the market that can be extrapolated and exported, and searching for collaborations between agents that enable new models.

  The circular economy is based on achieving an economically viable model that reduces consumption and negative impacts on the natural and social environment. Therefore, the economic aspect is the cornerstone of the circular economy when it comes to determining its capacity to replace the current economic model (linear economy) and it is capacity to convince market agents to adopt these practices (model of deception of the current economy).

  However, there are several dangers and problems within the economic dimension and its role in circular economy models as falling into the search for short-term results that measure their performance with general indices and indicators or decoupling problem [9].

  There are also other narratives from which the circular economy can draw. As Green Growth[4] or others[5]. It is also true that many authors are highly sceptical about the possibility of sufficient decoupling and state that the assumption that decoupling will allow economic growth to continue without an increase in environmental pressures seems highly compromised and quite unrealistic. Given the unlikelihood of sufficient decoupling, there is a demand for fundamental research on alternative ”post-green growth” economic models, especially in Western countries. The implication is that the imaginary potential for infinite economic growth, as theorised half a century ago, must finally be left behind to transform our society into a sustainable outcome. Becoming growth agnostic may be the next step while recognising that economic prosperity is a boundary condition for sustainable development. Indeed, in a sustainable circular economy, the purpose of the economy has changed from being a money-making machine to organising resources to maintain or improve social welfare and environmental quality [9].

- **Social dimension:** On a societal level, there is still a long way to go as it is still underrepresented in circular economy research, focusing mainly on environmental impact and economic viability.

[4]Aims for sustainable development through the relative and absolute decoupling and reconciliation of economic growth with environmental protection through technological progress [9].

[5]Other narratives question the need and capacity for economic growth or the use of economic growth as an index and measure of financial health, or the ability of long-term technological progress to achieve environmental protection while pursuing economic growth is called into question.

Indeed, reducing waste generation and natural resource extraction (among other effects sought by sustainable development) is already considered to benefit society and have a significant positive impact. Yet, some researchers comment that empirical evidence rarely substantiates these claims [12], it should also assess and focus on the actual effects of this benefit, such as how they are distributed and the impact levels.

On the other hand, when the analysis of social benefits is considered and not subject to the indirect impact of the environmental benefits achieved, it tends to focus only on the potential for employment generation. Other factors such as justice, welfare, social equity, power relations in value chains, users and citizens, labour exploitation, consumer rights and functions, and resource distribution are often not considered, nor are there any tools to assess them [9].

This makes it clear that in trying to move towards a more sustainable circular economy, the preservation and improvement of social and individual well-being must be integrated. Inspiration can be sought from other disciplines, such as socio-ecological economics and degrowth economics [9].

3.1.3 The Building Sector

The building sector accounts for around 40% of final energy consumption in the European Union [13], it is therefore of great importance and impact.

The sector currently has a significant impact on waste generation; in Denmark, it accounts for 35% of the total, being expected to continue growing. Forecasts suggest that 60% of the building stock in 2050 has not yet been built. This will further increase the amount of resources consumed and waste generated if current practices continue and these ratios are not reduced [14].

It is also one of the sectors with the highest consumption of raw materials, as well as being one of the largest producers of waste and the main responsible for greenhouse gas (GHG) emissions. All this, together with the accelerated development of many cities and the need to renew the building stock in many others, leads to large inflows and outflows of waste that must be managed appropriately [15].

As can be seen, this industry is currently still a sector based on linear economics, with a take-make-consume-dispose pattern [1], where inputs are new materials (raw construction materials are mined and excavated), and building components are manufactured and subsequently used in buildings and outputs are primarily understood as construction waste.

This way of thinking does not allow value to be created in the process, as well as being a model that cannot be supported and sustained in the long term. Current information only reaffirm the idea of the need for change and abandonment of the linear production practices used until now.

It is therefore essential to seek for solutions to these problems that will not only mitigate consumption and reduce waste production but also turn the current concept and business models rooted in the sector upside down to allow for sustainable development that does not compromise future generations.

In this way, the need to move towards a more circular and sustainable economy is growing. The different social agents are becoming aware of this, and the changes taking place on a legislative, business and social level can be seen.

3.1.4 CE in the Building Sector

CE can play an essential role in the construction sector. There is a real opportunity to address the problems and challenges of this sector by applying circular models.

The shift towards a more circular economy has and will have far-reaching implications for both business and society. This shift is a source of dilemmas, opportunities and challenges that must be addressed [16].

To do so, it is first necessary to clarify and define how the circular economy comes into play in a more concrete and specific way in the building sector.

3.1.4.1 *Levels of application*

It should be noted that there are different system levels to which the models can be applied or on which circular economy practices can be focused from a construction point of view; this also stands as one of the main ways of categorising and classifying models and methods, as will be seen below.

From a city perspective in can be stated that:

1. **Macro Level:** Is the level of the neighbourhood or group of buildings, taking into account all the other factors that this implies, the urban level, for example, the streets, buildings, transport and everything that makes up that area.
2. **Meso Level:** Is the building level or groups within the building, such as a facade as a whole or a complete roof, including structure and layers.
3. **Micro Level:** Is the level of materials, products and components.

From a country or regional perspective, it can be stated that the "Macro" level represents the regional or city level. In contrast, the "Meso" level accounts for the neighbourhoods or a group of buildings and "Micro" level represent the building level (or group within the building), leaving the components, materials and product level as a kind of "Nano" level. It is also described in this way in large part of the literature.

Must be said that although there is no agreement on the designation, there is agreement on the different existing levels.

In order to avoid confusion and in the absence of a clear consensus, both divisions being understandable and sensible, and having already set them out at this point, reference will be made in the remainder of the study to levels of:

1. **Region** (Macro)
2. **City** (Macro)
3. **neighbourhood or area** (Macro)
4. **Building** (Meso)
5. **Groups within the building** (Meso)
6. **Products, components and materials** (Micro)

However, the designation recommended in this study in the event of wishing to refer to the different categories has been marked in brackets.

If appropriate, the subdivision of the last level into two, product and components on the one hand and materials on the other, could be considered.

3.1.4.2 *Stages*

Within these identified stages [6], some have more potential for change towards circular economies, such as "Design", "End-of-life" or "Supply Chain" (which will be analysed below for their power of change (section 3.2), or "Use" where it can be also implemented circular solutions and business models (chapter 4)[7].

The rest, will be left out of this analysis as they have less potential on circular models. In these stages, such as production, distribution and construction, impact reduction strategies are applied by reducing consumption and emissions, trying to optimise them, making them more sustainable and efficient and promoting proximity and consumption reduction strategies.

3.1.4.3 *Drivers for the transition and Economic Potential*

This transition of the sector towards circular economy models can take place in three different ways:

- **Legislatively:** Legislation forces the sector to take action and make changes toward circular economies.
- **New players:** New companies enter the scene challenging the market with new circular proposals.
- **Transition from existing companies:** The existing firms anticipate the other two possible circumstances and adapt and make the transition before they are forced to do so by external agents.

As can already be seen in the sector, change is occurring through a combination of the three possibilities.

Companies' room for manoeuvre will be determined by how quickly they make the transition and how well prepared they are for stricter legislation and new types of competitors [14].

It should also be noted that the shift towards a circular economy could have a great economic potential in the Building Sector [17][8].

3.1.4.4 *New Trends*

Several emerging trends and likely scenarios in the construction industry are expected to significantly influence the potential open to circularity in construction as a different business area.

Three of the most relevant trends in the building sector are presented below:

- **Digitalization** For the past few years, digitalisation has been a global trend. For the tools and data side of the industry, a number of key changes are foreseen. Building Information Modelling (BIM), Big Data and the Internet of Things (IoT) are expected to have a substantial influence in the short term.
- **Prefabrication and semi-prefabrication** Modular construction involves the prefabrication or semi-prefabrication of structures. They are also increasingly seen

[6] Materials, Design, Production, Distribution, Construction, Use and End of Life (Waste Management). Being Supply Chain (Take-Back systems) a final, more transversal issue that interlinks the different parts and allows the creation of complete cycles and systems. appendix A.2.3

[7] Materials stage and materials selection (also with potential for CE) will be discussed in an integrated way

[8] Ellen MacArthur foundation[18] conducted a study on Denmark's economic potential as a circular economy and the results indicate that in the case of the adoption of the circular economy in the construction sector, there is an economic potential amounting to 7.75 billion of euros per year until 2035[14].

as structures that allow adjustments over time to the changing needs of their occupants. This also influences the options open to a circular building sector, as modules with suitable functional characteristics will ultimately be reusable in conversions or new construction. This will allow a much higher fraction of the value of the original prefabricated module to be retained [9].

- **New Partnership**The formation of partnerships with other construction industry actors from the beginning of a project enables the assimilation at an early stage of innovations and improvement potential. In a context of circularity, this can drive to solutions involving wider reuse of building materials, design for deconstruction or adaptability for instance, and also can lead to the absorption of a the concept of material passport and modularity.

3.1.4.5 *Enablers*

In addition to the drivers for the transition that are already taking steps towards circular economies, and the new trends in the sector that are opening up new stages and opportunities, there are a number of other concrete potential enablers (which will be discussed further in section 3.3 that can represent a major support to the prevalence and implementation of circular models in the sector and represent a turning point in these economies and their viability.

3.2 Analysis of the main stages in the building sector for CE enhancement

3.2.1 Design

One of the main objectives of the circular economy in the building is to consider the end of the useful life of components and materials used in the design phase.

To this end, different strategies can be used to develop the circular design, several of them even in combination (if they are compatible) to have a more significant impact on the life cycle of the building in the design phase.

Seen from an economic point of view (economic sustainability), the design has to allow the product, component, or building, at the end of its useful life, to have the greatest possible economic potential and to lose as little value as possible throughout its life cycle.

The different strategies identified are discussed below.

3.2.1.1 *Strategies*

Functional approach - Adaptability and Durability

Adaptability means ”the ability of a space to be modified for uses beyond the one originally designed for” [19]. Having the capacity, once the use for which the building was constructed is over, to reuse it, thus extending its lifespan and adapting it with minimal disruptions and added economic costs.

This strategy focuses on extending the lifespan of buildings and their components and materials as much as possible. Avoiding new material costs, the whole circuit associated

[9] Is also important to be aware that the design of prefabricated buildings has its risks. Their reduced costs and manufacturing times and their adaptability can lead to early obsolescence and low durability (due to the use of cheaper and less resistant materials) or difficult separation, as many focus only in the reduction of energy consumption (NZEB - Net Zero Energy Building, buildings with net energy consumption in use close to zero). Other important factors can be overlooked by focusing on their high economic profitability, or on their environmental sustainability only at the use stage, without taking into account their entire life cycle.

costs (with the demolition and construction of new buildings) and the impacts that this entails at all levels [10].

To this end, it focuses on:

- Robust structures.
- Use of simple (pure), low-maintenance materials with long service lives.
- Layered design and separation of systems to renovate each building service without damaging others.
- Use mechanical fastenings and minimal adhesives such as cement for quick and easy replacement without affecting other parts.

Other strategies discussed below, such as designing systems that are easy to repair and replace, also provide an excellent and necessary incentive for this strategy.

This strategy focuses on future adaptability, thus avoiding building obsolescence and the environmental and economic costs associated with material consumption and waste generation. This is achieved by treating buildings as dynamic systems [20]. It can thus adapt to new conditions or needs as they arise.

Among other benefits attributed to this strategy are the cultural and economic preservation of buildings.

This strategy of adapting buildings is already being applied to existing buildings and giving them new uses, as in former factories, warehouses and other examples that are being adapted for tertiary services, housing, cultural applications (e.g. museums or theatres) and many others.

However, the aim here is to take it into account in the design phase, to make the minimum adaptation after the change of use, and for the application, especially in buildings to which it usually is and naturally not so easy to apply this strategy if it is not thought of in the initial phases, such as residential buildings.

The main disadvantages of this strategy are the higher initial costs, as more materials may be needed. Besides, the initial embodied impacts (the environmental costs of creating the materials) may also be higher. This is an important consideration, as avoiding later embodied impacts is one of the main objectives of designing for adaptability, and there are no assurances. Although designing for adaptability makes it more likely that a building will be reused, no one can predict whether this will happen [19].

Technical Approach - Deconstruction and Separation
This strategy is based on the fact that building components, systems and finished buildings are designed from scratch so they can be disassembled again. This can and must be done at different levels [21].

- **Building level:** Design in such a way that the whole building can be dismantled or moved as a whole for other uses (along the lines of the design strategy for adaptability).
- **Block level:** So that spaces and floors can be rearranged easily, or even blocks can be moved within a building (modular building).

[10] As impacts that the development of new constructions and demolitions have on local life where they are developed during the construction period (air pollution, noise, visual, disruption of streets, etc.).

- **Component Level:** In such a way that the systems and components can be easily dismantled and reused for other uses in the same or another project (Example of the use of prefabricated materials such as walls or walls and assembled by easy-to-dismantle joints).
- **Material level:** So that they can be easily isolated and recycled or reused by using pure materials (If materials such as concrete, wood and plaster can be easily insulated from other materials). Be aware that substances must not be toxic or miscible to allow for their circularity

The recycling hierarchy must be considered when designing, whereby reuse of the complete component for the same purpose as the original comes before the reuse of unmachined parts and components.

A building designed for separation has a higher potential life expectancy by being able to adapt to many different needs and to move from one function to another by dragging walls, floors and changing functions; it will be essential to design buildings in a way that does not fall into cost-cutting that may jeopardise a high level of circularity to maintain the materials and components of value but to find a balance between initial costs and qualities that allow for future circularity and long life.

The "Circle House" project[11] [21] proposes a series of action areas of interest to help design separation. Taking these areas as a starting point, a list is presented[12].

- Use recyclable and recycled materials
- Simplify systems, components and joints
- Use less variety of materials and Avoid toxic and hazardous materials
- Made parts that cannot be dismantled of a single material and without surface treatment
- Document materials and components
- Use mechanical and reusable seals
- Design Modular and standard
- Design simple to fit into a larger system and with a focus on separation of systems and layers.
- Design easy access to each layer and system
- Use durable, quality materials to increase service life and preserve market value after use.
- Draw up dismantling plan

A final approach that has not been included could be to view finishes as temporary and use less customised designs, this can be suitable when the uses are short-term and frequent

[11] "Circle House": Project of 60 social housing units on the outskirts of Aarhus that serves as a scalable demonstration and can provide the construction sector with new insights into circular construction.
It is based on the objective that 90% of the materials used for the buildings can be reused without significant loss of value. The key is to approach design principles for disassembly and circularity to maintain their economic and aesthetic values [22].

[12] Some approaches fit well with the design for adaptability strategies discussed in the previous section due to the idea of designing systems that are easy to understand and dismantle. Others are more unique to design for deconstruction.

changes are made to the installations, in order to provide flexibility in the installations and to be able to use the components for other services or projects.

This strategy challenges the way we build. Assessing how individual parts are best recycled in five, ten or fifty years is not easy.

The principle of design for separation is to make reuse and recycling possible [21], reducing waste and increasing the flexibility of construction. This ensures the longest possible service life of buildings, systems, components and individual materials. Minimise the environmental impact of construction and create added value in terms of greater flexibility, better management and maintenance, and less waste [21].

From an economic point of view, designing for deconstruction can also add financial value to a building, as many materials can be sold or donated for a tax benefit at the end of the building's life. Landfill fees associated with the disposal of materials are also avoided. These economic benefits could increase as reuse markets develop and economies of scale help make used materials available for larger projects and beyond local limits. As methods of deconstruction, storage and transport of used materials begin to match those of freshly harvested materials, the trend towards reuse could start to make even more economic sense [19].

The ultimate goal of this strategy is to change the perception of the life cycle of buildings from the linear to the circular model through the dismantling and dismantling the building, which has been foreseen from the design stage.

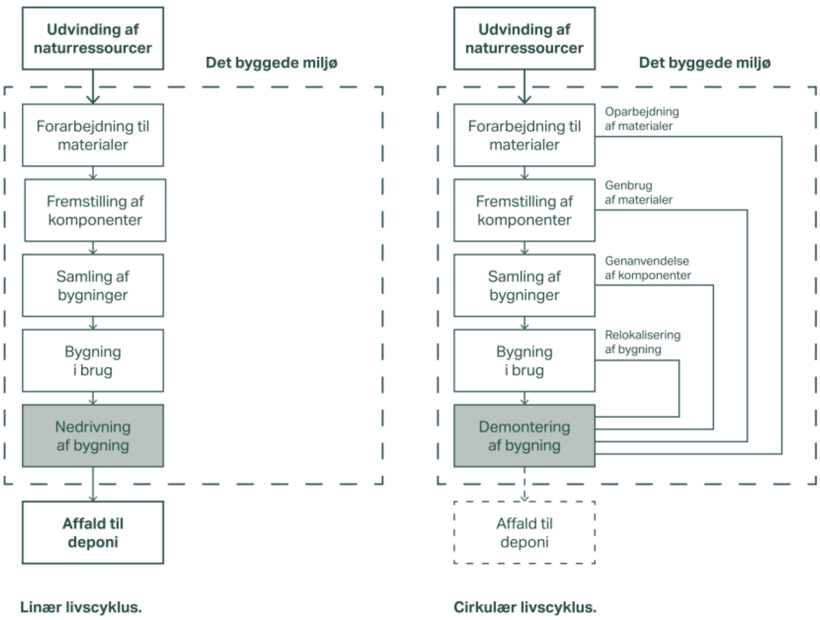


Figure 3.2: Disassembly cycle

To achieve this (for this strategy as well as the previous one), it will help to develop a common language for the industry, ensure a greater degree of standardisation (innovative building designs based on standardisation), and achieve cost savings in the dismantling of building components (usually relatively high due to under-utilisation of economies of scale, as each dismantling job will be different due to the diversity of materials and other conditions). Qualified and experienced personnel are needed to dismantle efficiently).

The aim is to improve processes and lower costs to make these processes more economically sustainable.

Layered design: It partly arises from the need to design for separation, and it can be argued that it is part of this strategy or a way to reach it.

This strategy, which is transversal to the rest of those mentioned above and to which reference has been made in several of them, is discussed separately in the annexes. For further information, please refer to (appendix A.1.1). The importance of adopting this practice for an efficient design from a circular point of view is highlighted from whatever perspective the design is finally approached.

Other Strategies
As mentioned above, the different strategies can be combined and are not mutually exclusive in most cases. Below are two other strategies or approaches to circular design that can be considered and that complete the framework of circular design together with the two main strategies mentioned above.

Cultural Approach: It is based on giving cultural value to existing or even new designed materials to encourage their reuse in new projects.

- Use of second life components[23] [24].
- Integration of scrap, waste and by-products into new components [23] [24].

Material Approach: It focuses not only on the separation and deconstruction of the product, but also on its recyclability at the end of its useful life. [13] In this strategy, the selection of materials is of great importance.

- Design for building material recycling (Recyclability in EoL) [23] [24].

3.2.1.2 *Assessment and Measurement*

This section highlights several indicators relevant to design, as well as the importance of design evaluation in both circularity and impact measurement (sustainability) and the main challenges and future developments needed to achieve correct measurement.

- **Circularity:** It is essential to highlight the relevance and importance that ”Level of Separation” is acquiring as an indicator of circularity to evaluate the design. However, tools still need to be developed to evaluate the level of separation in an efficient and standardised way.

  Other indicators, such as the ”Recycled material index”, among others, allow the evaluation of different points of circular design, in this case, the insertion of reused materials or components in the design.

  It will also be necessary to develop or find indicators or tools to evaluate adaptability, durability or the preservation of cultural heritage, these being other strong points to be assessed in circular design since if they are not considered, information would be lost in the process of evaluating the design and in decision-making.

  It would also be necessary to think about how to value each indicator and its weight on the final decision, a more difficult point to scale from project to project.

- **Sustainability:** To measure the sustainability impacts of designs, it is also necessary to develop calculation methods, documented environmental assessment and

[13] This strategy, is sometimes taken for granted in circular design but it is important to highlight it. Could also be viewed as an intrinsic part of the design separation strategy.

operational Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) systems in the design phase to be able to quickly assess the impact of choosing one strategy over another and to make sound decisions.

The tools must measure design strategies regarding economics and environmental impact in a standard design process.

High circularity will allow the design to maintain its value, extend its life and life cycles, and has to be taken into account in the design process; indicators will help to do so.

While being both economically and environmentally sustainable underlines and allows to visualise the impact on both monetary and environmental levels of the design, after the realisation of the design, taking into account its circularity, a quick assessment of sustainability will allow a good comparison of impacts between different designs and accurate decision making.

3.2.1.3 *Challenges*

In addition to the challenges noted throughout the design analysis and those especially highlighted for evaluation and measurement in the previous section (section 3.2.1.2), there are some others to be addressed at this stage.

The first, is the current lack of incentives to use recycled or discarded materials and components or to design for adaptability, durability or separation. Mechanisms must be sought and established to promote the use of these materials to give them a second life, either through bidders setting a level of reuse or policies that enable these strategies or penalise linear models.

The costs associated with certain design strategies are also a dilemma and challenge to address with the existing system and current policy; in many cases, the ”Total Economics” of models with durability strategies where higher upfront costs are usually undertaken is unclear and cannot be determined as uncertainty and risk come into play; as with reuse strategies for materials used in the design.

Another major design challenge is finding ways to reduce uncertainty and risk, both real and perceived by consumers, in designs with durability strategies or reusing used materials.

3.2.2 Supply Chain

The supply chain can be understood as ”the network of organisations involved, through backward and forward linkages, in the different processes and activities upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the final customer” [25].

This definition captures the necessary integration between the stages and companies that make up the chain to improve the delivery of value [26].

In the building sector can be defined as upstream for suppliers, subcontractors and specialised contractors and downstream for contractors and material manufacturers [26].

The supply chain is also crucial for the change towards sustainable models due to its significant impact on emissions, waste generation and consequently the consumption of raw materials, especially in an intensive sector such as the construction industry.

In the recent years have seen developments towards a more sustainable supply chain, trying to minimise the flow of materials or the associated environmental impacts. A clear example is green supply chain management which seeks to ensure that green and environmental objectives are aligned with operational supply chain objectives [27].

Besides, closed-loop supply chains have been developed where environmental performance is improved by returning products to the producer to recover their value.

These could be seen as necessary steps towards system optimisation at the environmental level. But they can be taken a step further by implementing the circular economy model in the supply chain, which advocates the reuse of materials and their reinsertion at different points in the system, further improving the process and results and collaborating with other organisations in the same or even other sectors.

In this way, the circular economy pushes the boundaries of green supply chain management and closed-loop systems by discovering new ways to keep materials flowing.

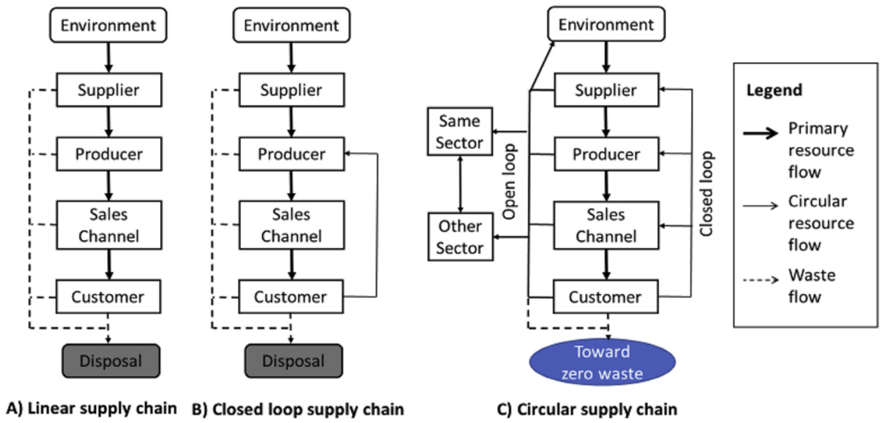


Figure 3.3: Linear and Closed loop vs Circular supply chain[28]

This can be implemented by designing ”circular” or ”reverse” chains that allow the product to re-enter the chain at the end of its useful life. This is how the ”reverse supply chain management” model arises. Measuring and benchmarking environmental performance remains a challenge due to the difficulties posed by the complexity of chains, non-standardised information and geographical differences, among other things [27].

3.2.2.1 *Take Back systems and Reverse Cycles*

The take-back system is the primary strategy for moving towards a circular supply chain. It is the idea that manufacturers, distributors or suppliers ”take back” products at the end of their useful life. This concept is closely related to Waste Management, whose strategies (such as selective demolition, discussed below) allow for implementing this strategy.

This involves facilitating the recovery of components, products and materials for introduction at another point in the process or other lines outside the model while maintaining their economic value to the maximum.

Take-Back systems are fundamental to a circular economy but they place high demands on the purity of materials and the ability of companies to document and trace products. On the other hand, there are both economic and resource benefits in sight for successful companies.

It is essential to consider the overall process framework when implementing CE as all stages influence each other. Here we can see that the less processing we do of the resources used (an aspect that has to be taken into account in the design stage), the better.

At the same time, concerning the waste hierarchy, the starting point is that the more economic value the resources used can bring to a new product, the better. Economic value is important because it will stimulate demand for the resources used, so the hierarchy must be taken into account by trying not to devalue products that can provide more economic value than would otherwise be the case.

The waste hierarchy can be used to guide the best way to recycle the materials used in construction and to establish better take-back strategies[14]:

1. **Maintenance:** Extending service life through maintenance.
2. **Reuse:** Extending the original use of the product by reusing it.
3. **Refurbishment:** Re-manufacturing of the value of the product through refurbishment of its parts or materials by the manufacturer or parts.
4. **Recycling:** The product can be re-melted or otherwise processed for use in a new context.
5. **Recovery:** If the necessary conditions are met, and as a last resort this process can be used before final disposal in a landfill. Resources are reused so that their original value is considerably reduced. Waste incineration and shredded construction waste as paving are examples.
6. **Disposition:** Taking the waste to a landfill. The final solution and the one to be avoided if possible by any other means, including recovery.

Some examples of existing systems within the waste hierarchy are given below [29]:

1. **Withdrawal of own products:**
    - **Reuse:** Reuse of roof tiles, bricks, windows or other components of dismantled buildings for use in new construction.
    - **Recycling:** Companies that collect their own products for use in new production.
2. **Supplier agreement on residual product of others:**
    - **Re-use:** Ad-hoc builder/demolisher markets for the sale of dismantled products and materials.
    - **Recycling:** Buying and selling of iron for re-melting.
    - **Recovery:** Incinerators.
3. **Recycling reuse platforms:**
    - **Reuse:** Recycling stations and material banks.

As can be seen, there is still some way to go, and strategies can be expanded at each hierarchical level by applying new business models. However, as mentioned at the beginning of the chapter, several enablers will be essential to adopt to facilitate and unify the transition towards recovery models that allow the implementation of the circular economy in buildings, such as the importance of taking into account the design stage in the future for the separation of materials, the use of pure materials and the correct documentation of

[14]Some products and materials fall outside the hierarchy, as they contain harmful substances to such a degree that they must be landfilled.

products; where the material passport will be of great importance as a potentially crucial tool for the effective and rapid change and development towards these models.

3.2.2.2 *Steps towards a circular supply chain*

Starting from the idea and theoretical model of what a circular supply chain is, the first step towards implementation in an environment would consist of a more detailed understanding of the chains for the theoretical design of circular models in each sector; in this case, the building sector.

For applying these theoretical models, it will be necessary to have standardised information to facilitate the processes for which the implementation of BIM models, which are not yet a common practice, gains great importance. Still, further development of these can facilitate the implementation of circular models, and many authors advocate for it.

The material passport idea is also of great relevance for the practical application of reversible models. It should be adopted to standardise certain documents and relevant information to achieve greater traceability of products.

Another factor that is more than relevant and necessary for a supply chain that is not only circular but also efficient is a collaboration between actors and good communication and information exchange.

3.2.2.3 *Framework, assessment and measurement*

Nowadays, SCOR framework [30] is one of the most widely used and accepted to define and represent the supply chain, and consists of six processes (plan, resource, make and deliver and return and enable). It can be used as a reference system to represent circular models.

What is essential when measuring and assessing a circular supply chain is, in this respect, the circularity itself, to be able to assess the functioning of the circular supply chain, monitor its performance, to enable improvements so that it becomes a key enabler of circular models and economies.

In the second part of the study (section 5.1) will be examined different reviews that have developed and selected relevant indicators in recent years to measure circularity and that can be useful to take into account for supply chain assessment[15].

The key challenge here will be choosing a good set of indicators to measure chain performance effectively.

3.2.2.4 *Challenges*

One big challenge is to Develop efficient and effective systems to measure supply chains' economic and environmental impact and circularity and to make them quantifiable.

It should be also noted that there is currently a lack of incentives for actors to adapt to circular models, so a significant challenge is the search for both intrinsic incentives within the supply chain that can move companies to adopt these systems, as well as possible incentives (positive or negative) that can be applied to supply chains to encourage the adoption of these models. At the same time, it is essential to discover the mutual interests between agents so that these models are beneficial and attractive to them and expose the need for collaboration.

[15] They include indicators such as $Recirculatedeconomicvalue/Totalproductvalue$ [31], which in this case allows for the quantification of product-level circularity [28], and which may be relevant.

Another challenge is to work on reducing risk, developing compatible systems, and reducing uncertainties. This could be achieved, with risk diversification systems, allocating risk to actors who are capable of absorbing it, standardising procedures as far as possible, with transparent techniques for managing and detailing the information, improving return processes by making them more efficient, secure and consistent with well-designated material flows (especially in reverse loops which are still under development).

The clash of perceptions and interests in the supply chain is one of the main barriers to implementing circular models. Therefore, to develop circular models, it is necessary to change the perception of the business (where each company fights for its interests and where there is a struggle of forces and powers) for the idea of collaborative business, looking for common interests, where each company must have the capacity of joint vision of the system.

3.2.3 Waste Management

Waste management is the term used to refer to the process that encompasses the activities necessary to take care of waste after it has fulfilled its mission of service for which it was produced.

According to Eurostat [32], 820 tonnes is the construction and demolition waste produced annually by the European construction sector. This represents 46% of the total amount of waste in EU countries. This waste mainly consists of concrete, ceramics, masonry, wood and plasterboard. Given that currently, only a minimal proportion of all construction materials are recycled, it is strategically essential to strengthen the circular economy in this resource stream [33].

Waste management is closely related to the supply chain in circular economy models and will be an essential part of reverse supply chains and systems design.

3.2.3.1 *Selective Demolition*

This is a crucial strategy for the implementation of CE concepts into the waste management, by which the selection and separation of materials are carried out on-site to be reused in other works or processed in recycling plants, from where the materials are correctly managed for their reuse, remanufacture or, in the last case, recovery and disposal.

Is an essential step in take-back systems and reverses cycles. It is also critical due to the impact it has on waste generation.

There could arguably be two types of selective demolition:

1. **Conventional Selective Demolition:** In-situ separation of materials is carried out without attention to maintaining the product's value as such, undoubtedly destructive to the product.

   It should be noted that the current ordinance (Affaldsbekendtgørelsen [34]) already stipulates that demolition companies must always separate hazardous waste, PCB-containing waste and double-glazing waste from their construction and demolition waste and that these companies must also classify the waste on-site into at least the following fractions: Unglazed brick, Concrete, Mixtures of materials, Iron and metal, Gypsum, Rock wool, Jordan and Asphalt.

2. **Soft Selective Demolition:** The aim is to maintain the product's value, trying to damage it as little as possible.

The selective soft demolition and resale of used building materials is today a resource-intensive and manual process that can be difficult to justify financially. Buyers of used products do not pay much for materials, and agreements made with buyers cannot yet be streamlined and scaled up.

Even so, as an essential strategy to create circular economy models in the construction sector [33], it is necessary to continue searching for compatible models. Seeking strategies that revalue products to persuade buyers, and developing tools that speed up and facilitate selective demolition. As well as collecting relevant information and studying actual viability of the processes to show where to focus the progress and justify the financial investments.

Soft Selective demolition involves [33]:

- **Mapping** pre-demolition buildings with the intention of knowing and identifying components with potential for reuse and recycling as well as tracking other building issues such as harmful materials or products and how to manage this.
- **Demolish** and accurately sort waste on-site.
- **Transporting** the waste to its new destination so that it can be reused, remanufactured, recycled or recovered.
- **Rethink** and implement new and more efficient work processes.

Figure 3.4: Selective demolition diagram. Based on Miljøstyrelsen, Cirkulært Kvalitetsbyggeri [33]

The ultimate goal of selective demolition is to use used building materials in new construction. This is done by recycling as much of the demolished materials as possible in the best possible way (at the highest potential economic value and with the lowest possible climate and environmental impact). The more harmful substances a material contains, the lower its recycling potential. Therefore, it is central to map and clean up materials and sort hazardous waste.

3.2.3.2 *Assessment and Measurement*

To enable effective and efficient selective demolition (the central circular strategy of waste management), it will be necessary to have tools that allow correct accounting and mapping, including indicators and methods for determining product quality, the importance of estimating the remaining useful life of products and their residual value, and to have ratios and estimates of losses in the demolition process and mapping information; This is also key not only to analyse the demolition process and to have relevant information for decision making in this process but also for its subsequent use and integration in more advanced assessment models that take into account other stages and serve for more far-reaching decision making.

To develop the best alternatives for the salvaged products and to allow the best routes for their recirculation, it is essential to have relevant and well-defined information on the demolition stage, such as the one highlighted above, as well as methods or indicators to facilitate decision-making.

Comment that the analysis carried out in the next part of the project will review these key indicators and models for both the assessment of demolition and salvage product opportunities and circular models, giving a range of possible options to be applied depending on the project and a series of recommendations based on available information and comparison of models and indicators.

It is important to stress the importance of this point for the project since many of the indicators evaluated later, will be used for the development of the case, which, as will be explained later, studies, among other things, the economic viability of applying selective demolition, for which the selection of indicators and an appropriate evaluation method becomes one of the critical parts of the it. Therefore, both indicators will be used to determine the selective demolition process, and to decide on the proposed models developed by the selected evaluation method.

3.2.3.3 *Challenges*

Developing professional markets for reuse and recycling is vital, and as become one of the main challenges for both the waste management and the supply chain (reverse cycles). One of the critical challenges is selling used materials; therefore, incentives must be provided to create digital and physical needs for reuse and recycling.

Minimising construction waste poses other key challenges for this stage, such as:

- Seek methods to reduce the expected costs of cleaning and rehabilitation of recycled materials.
- Simplify decision and accountability processes, currently marked by a fragmented value chain and a wide variety of actors on construction sites.
- Generate incentives to improve current waste practices, currently almost non-existent due to their low impact on construction project budgets.
- Seek methods and models to predict the value of end-of-life material are currently difficult to predict due to the uncertainty of future resource prices.
- Raise awareness of complete life-cycle cost analyses to avoid using non-recyclable materials with lower initial investment but higher total costs.

Besides, if Denmark is to meet the European construction and demolition waste reduction targets of 70%; The industry must design and support innovative concepts for decommissioning and recovery schemes as soon as possible.

Innovative examples: For interesting case studies illustrating innovative ways to ensure both environmental and economic success of selective demolition, see appendix A.1.2.

3.3 Analysis of Key Enablers

The principal purpose of this section is to analyse some of the main enablers and potential drivers of the circular economy for the building industry in the near future. This will provide a review of the current situation and listing in the same block the main facilitators with their barriers, recommendations and lines of progress; what will make it possible to see the difficulty of their implementation and the dependence on them to improve the efficiency of circular models and their future profitability.

3.3.1 Material Passport

The material passport will be, if not the main one, one of the main facilitators of the EC in construction. In addition it will also be a facilitator and a driver of other facilitators discussed below, such as the materials bank (section 3.3.4). For all these reasons, a more detailed analysis of this point will be made in the following block.

Documentation and the fact that it is possible to trace where materials come from and what they consist of is a crucial requisite and a significant enabler for recycling to become even more widespread in construction.

After all, things that are not registered have no direct intrinsic value and need to be given a value using tests or estimates, which can be wrong and increase costs.

Therefore, the material passport is a tool that gives buildings and materials social security numbers. So materials gain direct value instead of becoming waste ”until proven otherwise” once they have been in use. This would, among other things, enable traceability of products and materials (key to improving reuse systems and their scaling up), a value practically essential for adopting circular models. On the other hand, it would allow the sector to determine the value and quality of the individual material and of the building in general, which the passport could enable. Finally, it ensures competition on a level playing field in the circular market.

This makes it essential to develop standardised, passable building passes and materials.

If the materials in today's buildings are to be reusable in the future, it must indicate what the materials contain and their properties. Building owners should also be able to estimate what value the building constitutes after use and how materials replaced in the current operation can be used elsewhere.

Several formats are currently available for declaring and certifying building materials. But there are no standardised guidelines on what a construction passport or materials should contain. Neither in Denmark, in the EU or internationally. But we should expect that there will be more and more precise requirements for the use and consumption of resources in the coming years.

The EU and Denmark are developing targets and strategies to increase circularity and reduce resource use. And the Danish Government's Strategy for the Circular Economy discusses a recognised construction passport. Therefore, there is a high probability that the construction and material passes will be defined as standards for the industry and that the measures may end up as construction legislation in Denmark and the EU. Currently, the EPD (Environmental Product Declaration) is a document that communicates the environmental performance or impact of any product or material over its lifetime and is used as a reference, a prelude to implementing more valuable documents. Still, it does not register building products as a material passport would and certainly does not allow the full traceability demanded by the sector.

Barriers, Challenges and Recommendations

They have been identified several barriers and challenges to develop practical solutions to support traceability and documentation and proposed a model approach to material passport [33]:

1. **Documentation and data collection:**
    - The construction value chain is made up of many different parts. The transfer of data between the parties runs the risk of losing information. To ensure data quality, it is necessary to involve the entire value chain.
    - Digital building information models (BIM) can provide a framework for handling the relevant data. However, the large amounts of data make the models difficult to manage. This raises the challenge of structuring and managing this information. The most viable solution so far is to compile all the information in a database, which allows each item to be identified and tracked.
2. **Standardisation:** Data standardisation will be necessary to ensure that the new solutions do not just become another scheme among many but that they are integrated into existing structures at the Danish and international levels and that the guidelines are interpreted and enforced equally between the parties.
3. **Structuring of the data and information available in the passport:** Structured data should be available to create an overview of the number of materials and products and their location, quality and recycling potential. The information in the passport should also describe the current state of the building elements in the form of data on, among others:
    - Review of material groups; including life-cycle assessments.
    - Chemical processing of materials and fabrication processes.
    - Review of the systems and components in construction and their separation into material categories.
    - Assembly, maintenance, sorting and recycling instructions.
    - Positioning of the elements in the building.
    - Carbon footprint, operational specifications.
    - Labelling and certifications.
    - Upgrades for maintenance and renewal.
    - Material background.
    - Environmental impact assessment of its entire cycle.

The high complexity of components and construction processes makes it difficult to trace the materials used in buildings. Increased documentation to provide transparency will, all other things being equal, entail additional costs and administration.

The passport will also have to be flexible enough to allow all companies to integrate it, so that small, medium, and large companies can incorporate it.

All in all, the main challenge is to create an overview and to ensure that the information is structured and easily accessible in a database.

Approaches towards a material passport

The following initiatives are aimed at documenting building or building materials and can therefore serve to generate or directly generate a material passport.

The EU has developed 4 initiatives:

1. **Buildings as Material Banks (BAMB) [35]:**[16] It is directly working on the development of a digital construction and materials passport. Proposed and to analyse the construction and material passes from the perspective outlined in the fig. 3.5, where information from several passes is included in a construction pass, which then links the information to specific elements of the construction.

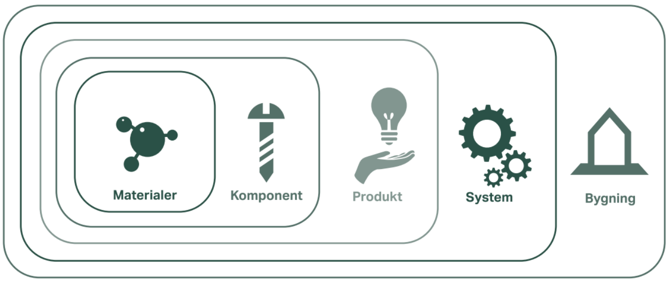


Figure 3.5: BAMB's Material Passport proposal

2. **Guidelines for the waste audits before demolition and renovation of works of buildings:** Develops guidelines for the categorisation and documentation of materials in construction.
3. **Raw Materials Information System database [36]:** Classifies resources according to whether they are scarce or not, the degree of sustainability, circularity, etc. The aim is to provide producers and decision-makers with sufficient knowledge about the resources used.
4. **LEVEL(s) [37]:** Is a voluntary reporting system, developed to create a common EU standard to support sustainable construction. Reporting is required in the areas of building life-cycle C02 footprint, resource efficiency, water management, recycling, health and climate change prevention. The standards are being tested in Denmark.

A number of initiatives are also being developed in Denmark:

- **Ressourcekortlægning af bygninger [38]:** A guide to mapping the resources of existing buildings.
- **Studie af hvordan materiale- og bygningspas er beskrevet i den danske byggesektor:** The study brings together the analyses and examples developed so far for building and material passes.

Some countries have already developed some material passport initiatives, such as in the case of the Netherlands with the "CIRCULAR IQ" [39].

[16] "Circle House Lab" [29] project also supports and endorses this model for the passport.

In addition, there are already known formats for preparing product and construction documentation in the construction sector. These can play an essential role in creating joint public guidance on how to construct materials and construction passports. Some of the formats are defined in legislation; others are voluntary. Some are methods of documentation, while others are real quality marks. The most commonly used declarations and certifications are:

- **Miljøvaredeklarationer (EPD'er) - (Environmental Product Declarations):** Previously commented, they describe the environmental characteristics of a product based on a recognised methodology. EPDs can be used to compare the environmental profile of different materials, e.g. their environmental impact from production, use and disposal. EPDs are a means to build material passports and are key to scaling up circular construction business models.
- **Sikkerhedsdatablade - (Safety data sheets):** They are prepared by suppliers of hazardous chemicals. They state the properties of the substances, the risks and the precautions to be taken when using them.
- **Construction certifications:** Quality labels for construction, construction products and construction companies based on specific criteria. Certifications such as DGNB, Swan, EU Flower, Cradle to Cradle, etc. They provide data that can be used to determine the circularity of a product [16]. They will be analysed as a distinct enabler later in this study. (section 3.3.3) and also as a possible method of evaluation (section 5.2.9).

Digital mapping tool: This tool is an attractive, observed and undeveloped proposal. Its objective is to build a digital tool to map the properties of a specific secondary material at a given time. This tool could be integrated into the material passport, complementing and completing it. The tool can serve as a basis for a new standardisation and regulation of secondary materials. Two fronts are proposed for this:

- Documenting external influences on materials over time.
- Develop sensors and non-destructive methods for the continuous assessment of material properties.

Information on external impacts would be included in the building passports. The specific information in the building passport is thus the entry point for using the digital tool to predict the properties of secondary resources in a specific case.

3.3.2 Policy enablers

Policy enablers are a key element of CE to support business model innovation by providing appropriate laws and regulations, financial support, economic incentives and other policies that enable circular business models to succeed. Some established legislative measures, such as the "EU Eco-design Directive", have already started to regulate energy efficiency and some circularity features of energy-related products.

Besides, new regulations are gradually being developed at the European and Danish levels to encourage the EC and punish models with negative environmental impacts.

Review of some of the measures in recent years:

- 2014: Approval of the resource plan for waste management by the Danish Parliament.

- 2015: Adoption of an action plan to put in place a regulatory framework for developing the circular economy by the European Commission.
- 2017: The Danish government presented an action plan, including a proposal to bring the national building code in line with the circular economy.
- 2020: The Danish government introduced the ”New Voluntary Sustainability Class” in the building regulations [40][17].
- 2025: The Danish government has agreed to introduce a corporate carbon tax from 2025, which should progressively increase, and which will provide a significant incentive for recycling.
- Next years: Broadening of the ”Extended Producer Responsibility Legislation”. It makes producers responsible for the waste phase in the life of their products. Producers have to pay for waste treatment, and the easier it is to recycle the product, the cheaper it is for the producer. This creates incentives for circular product design. In the coming years, producer responsibility will be extended to packaging. This will affect manufacturers of construction products, as the legislation places the responsibility for packaging on the packager and importer of the packaging. [29].

In the ”European circular economy action plan” [41] the new measures that the EU introduces legislative and non-legislative con be seen, to pave the way for a cleaner and more competitive Europe.

Emphasising economic incentives, apart from taxes on construction waste and until the carbon tax of 2025, there are still no strong incentives for reuse and recycling in legislation right now.

All indications are that reuse and resource optimisation requirements will become increasingly stringent in the regulation of the Danish construction sector in the coming years.

The legislation will pressure the sector to transition to a circular economy. Measures in the form of growth strategies, waste management plans and resource optimisation are designed to stimulate private and public sector companies to adapt to these models.

However, there are still several barriers to current regulation, mainly because the legislation does not actively promote the principles of the circular economy [14]:

- Life cycle costing is not a major concern in building procurement. It is permitted but not required by legislation.
- Difficulties in making statements on the performance, content and durability of the construction materials used.
- Low number of value for money requirements in legislation.

Moreover, current policies still hinder, among other things, the supply side, as the approval process for recycled construction products is complex. The demand side is also hampered, as it is difficult to demand a circular economy in, for example, public tenders if there are no clear definitions and standards for this [42].

Markets are not developing effective business models independently without policy incentives and support systems. To create circular business models, the construction industry must find even more policies that compensate for market imperfections and support the development of a circular resource economy [42].

[17] The new class will be tested and evaluated over the next two years.

3.3.3 Declarations and Certifications

Certifications and declarations connect different tools and parameters that establish an area or building score. Some fall into one sustainability group, and others cover several or all of them. They serve to certify and state that specific requirements are met. It is a very powerful verification and communication tool as it allows transmitting a certain quality to the recirculated products, increasing their perceived value in the market and by the users.

In circular business models, customers are often reluctant to buy reused products, perceiving them as inferior [43]. Labels and certifications can play a critical communicative role in changing consumer perception. However, it remains to be seen whether applying a labelling strategy to products, components, or circular projects can deliver accurate results and whether the extra costs involved in labelling are worthwhile.

It should also be noted that sensitivity to labels varies from country to country due to varying levels of trust in institutions or awareness of eco-labelling schemes [43], so it is essential to develop labels that build trust and capture what is being assessed in the labels.

There is a wide variety of labels for the building sector. In the following figure some of the most relevant ones are presented together with the parameters they cover, the level to which they are addressed or can be applied and the type (declaration or certificate):

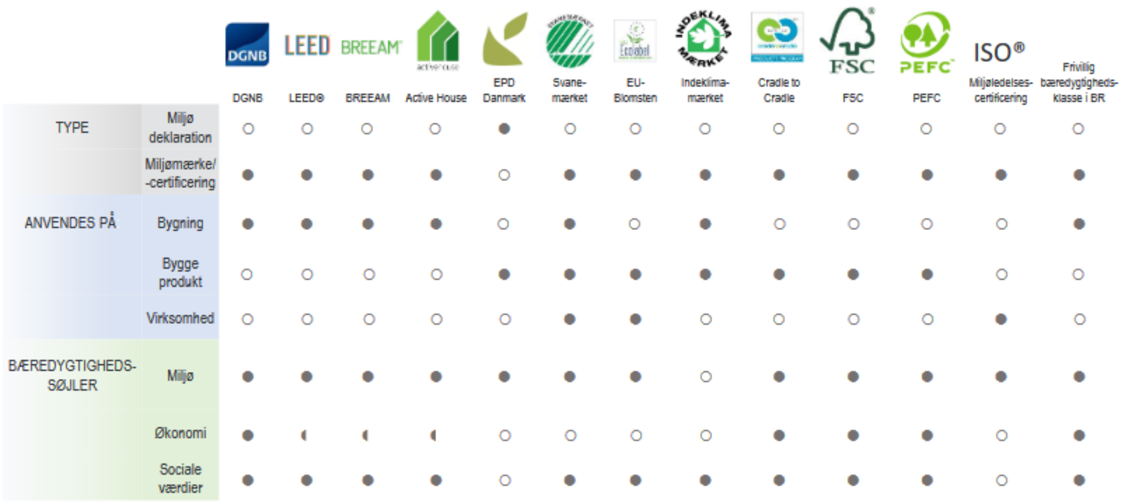


Figure 3.6: Declarations and certifications chart [44]

3.3.4 Material Bank

Exchange platforms make it possible to sell, buy and distribute used resources.

Creating a common, robust, quality and verified information pool of materials can be a significant enabler of circular models in the sector, allowing for improved systems, more straightforward implementation of models and reduced costs.

One of the challenges of this is that it is difficult to declare the materials used in a way that is to say the materials used in such a way that they can then be held accountable for the quality of the product.

Today they are best known by scrap dealers and resource stations that trade in known recycled materials and local initiatives in municipalities where local construction resources are distributed to municipal construction sites [42].

It should be noted that several projects for the development of materials banks are already underway at the European level and in Denmark.

3.3.5 "Circle Bank" project

Project in Denmark that is expected to be launched in 2030. It will seek to bring the construction sector onto a unified digital platform that integrates new knowledge in digitisation, demolition, material handling and architectural design. Circle Bank's ambition is to create a decision support tool and market platform that supports circular construction in Denmark and internationally [45].

3.3.6 Behavioural and Education Enablers

Both education and willingness are crucial enablers, as the decisions made by consumers and actors with decision-making power and market power can support or hinder the adoption and scaling up of circular business models. To achieve this, consumers and other sector actors need to be informed, able and willing to move towards circular products and services, for which good education on the need to move towards these models is essential.

3.3.7 Collaboration among Actors

The need for collaboration between actors is another critical point. This is essential to developing profitable and efficient business models. This collaboration must be based on shared interests and principles of transparency.

Companies within and across sectors should join forces to test new solutions.

3.3.8 Real Estate Investors and Construction Clients

Within the group of all stakeholders in the construction sector, it can be said that both real estate investors and construction clients (together with policy makers[18], already mentioned), are best placed to lead the transition to a circular environment, as they have the greatest capacity to influence decision-making, set direction and catalyse action along the value chain.

Therefore, investment justification is essential to drive the adoption of circular economy principles.

Investors and construction clients set value and how it is created from real estate assets through investment requirements, tenure models and design briefs. Despite this, the business argument for applying circular economy principles has not yet been explicitly articulated to investors or construction clients to incentivise a shift in this direction [46].

The successful adoption of circular economy practices will largely depend on investor acceptance, so the importance of investor perception, as well as their understanding of the financing of an asset is important. Valuation standards are essential to build investor confidence; applied by trusted professionals, they aid transparency [47].

Innovations are also being made in how business is done from the investor and customer point of view, taking ideas from circular models and trying to make them more profitable. As an example, the creation of tradable futures contracts related to the value of building materials at the time of deconstruction. In this way, during construction, customers can sell these futures contracts, which could then be traded. At the same time, the building is operational, changing in value in response to local real estate and global commodity

[18]Policy makers need an evidence base of the benefits of a circular economy developed by investors and construction clients.

markets. The transfer of ownership and cash settlement takes place at the time of deconstruction, after which the materials re-enter the market for re-use. This model can reduce the lifetime cost of ownership [47].

3.3.9 Uncertainty and Risk

In this case, risk and uncertainty act as a constraint rather than an enabler, so being able to reduce them would be a very positive point for circular models.

There are several traditional approaches to study risk and try to reduce it, among them ”Sensitivity Analysis”, which is used to analyse risk in the presence of few observed data. It can be defined as a repetition of multiple estimations adopting the same model and systematically varying the input variables. According to a general definition, sensitivity analysis measures the ”propagation of uncertainty” produced by uncertain input variables in the output value of the model. It can be used to visualise different scenarios and possible outcomes [48].

Another primary method of risk evaluation is the ”Risk Assessment”, which usually involves assessing the risk by measuring the parameters in the different stages or actions identified in the process of the model studied, the magnitude of the loss and the probability of it occurring, obtaining a level of risk to which specific actions can be applied to try to reduce it.

Risk analysis models can be tried to be implemented in the assessment methods so that risk is taken into account in the impact measurements of the business models.

To give some examples, a ”Sensitivity Analysis” can be integrated into the study of the total costs of a project by considering several scenarios (for example, the most probable, the most favourable and the most unfavourable) so that the result can be seen in the case of these or a combination of these scenarios.

Another example could be to integrate ”Risk Assessment” into an evaluation model; taking the same case in which it is wanted to calculate the total costs of a project to obtain an estimated level of risk at a monetary level that would be integrated into the final result obtained, in such a way that the possible impact of the existing risks is accounted for.

3.3.10 Available data on the built environment in Denmark and Copenhagen

Relevant data and information on the built environment can also enable more accurate circular economy models to be developed and articulated.

The SAVE record is the local regulation that records the demolished buildings.

The Danish Building Register (BBR) contains a wide variety of metadata information on all buildings, such as year of construction.

Interactive spatial mapping including data on the built environment of the city of Copenhagen is available through the SpatialMap service [49].

Other large open datasets (geographic or otherwise) that are relevant to the built environment can be accessed through the Danish Opendata website [49].

3.4 Partial Conclusions

This first block of ”Results 1”, has tried to provide a clear vision of CE and its role in building.

To this end, it has proposed strengthening TBL’s vision with the economic dimension as an enabler.
The analysis of the supply chain, waste management and design, highlights the different circularity strategies in each of these areas, gives recommendations on assessment methods and sets the existing challenges in this areas.
The review of enablers highlights their importance as a lever for conversion to circular models, which will mean a paradigm shift in the sector in terms of the sustainability of circular projects.

Furthermore, the study and analysis of this block facilitate the understanding of the practical framework in which the case study is situated (chapter 6). It also provides relevant information on key points of selective demolition, design and recovery systems to be taken into account to develop the business models of the case. It also highlights the importance of risk reduction and allows making the final decision on using the ”Sensitive Analysis” tool to strengthen the case study.

After this study, it can be concluded that progress in this area is increasing, and there are more and more forces towards change on the part of institutions and companies, which observe the real needs and new opportunities. Despite this, it is essential to continue reiterating the concepts, so that they are clear and do not become distorted. It will be also necessary to continue working on new business models and their appliance in projects in order to seek greater efficiency and sustainability and to reduce risk and uncertainty, one of the most important challenges today.

4 RESULTS 1.B - BUSINESS MODELS (BM)

This section will:

1. *Clarify the concept of BM and other key concepts around it. This is necessary due to the confusion still presented in the literature.*
2. *Present an analysis of Conceptual Frameworks with subsequent tracing. Useful for selection and application in actual cases.*
3. *Present a proposal for the classification of strategies based on the literature review so that a more complete picture of existing strategies is obtained in a classified form. Facilitates strategy selection. It will also present examples of BM associated with strategies.*
4. *It will also discuss other tools to assist in the development of BM, how actors can benefit from CBM and future challenges.*

In essence, this block provides the necessary tools to have a complete picture of the role of BM in the CE, facilitating the understanding and design of circular models (it helps to take into account circularity from the design phases).

This analysis simultaneously serves to assist the project case development (chapter 6) in selecting and designing proposals for the different business models to be evaluated.

4.1 Introducing BM

A business model is a plan for the successful operation of a business, and it can be presented and analyse in different ways (conceptual frameworks). The strategy express how such a business model is to be implemented, the strategies are translated into specific actions to implement it. For a strategy to become action, it is determined which key processes are necessary to create and deliver value and which performance targets must be met to execute the strategy [50].

The shift towards a circular economy requires disruptive business models to replace existing ones or seize new opportunities [46]. The linear economic models currently predominant in the sector are incapable of managing sustainability issues, hence the importance and impact of the study of business models for the adoption of circular models.

There are multiple definitions of a circular business model (CBM), each with different nuances. However, it can be understood as how a company creates, captures and delivers value with the logic of value creation designed to improve resource efficiency by contributing to extending the useful life of resources and closing material loops through various strategies. Understanding value creation, capture and delivery as the utilisation of the economic value retained in products after their use in the production of new offerings [31].

Business models were not generally recognised as major facilitators of the circular economy until recently [51], But key aspects within different business model strategies such as product-service systems and factors such as the internalisation of social and environmental costs are becoming increasingly established [9].

Circular Business models offer significant cost savings, reduced environmental impact, and improved business opportunities for product-related services involving direct and reverse supply chains.

The importance of business models as an enabling axis of the circular economy and the application of circular models in the sector should be highlighted, as it allows to design, visualise strategies and communicate them accurately and in an easy way, as well as its relevance at a strategic level and in the early stages of projects (design stage).

For industry practitioners, business model innovation is seen as a critical lever for implementing the circular economy at the organisational level, as it enables a systemic change in the core business logic and the alignment of incentives of different stakeholders. A circular economy system requires the design and implementation of business models that are based on using as few resources for as long as possible while extracting as much value as possible in the process. Organisations willing to adopt the circular economy model must implement new types of business models by rethinking value propositions and developing value chains that deliver feasible cost efficiency, production efficiency and business performance. As a result, research on business model innovation related to the circular economy has received increasing attention in recent years [51].

So far, there are no scalable or widespread business models for circular construction. This lack of a business model results from the complex multidisciplinary nature of the construction sector and the fact that the type of business that can link resource flows has not yet been established in the industry. It is therefore essential to understand and be aware of the different strategies that can be developed for new business models and to be mindful of the existence and facilitating power of design tools such as conceptual frameworks. So that generating new proposals and model designs is more straightforward, more intuitive, and easier to evaluate for their subsequent application or integration.

4.2 Conceptual Frameworks

One of the most critical points for developing business models is to have proper conceptual frameworks that allow them to be correctly presented, analysed, developed and evaluated. Conceptual frameworks allow circular business models to be designed and compared in the early design phases and other implementation stages if necessary. They also ensures that participants have the exact definition, minimising the potential for confusion [52]. Choosing and creating a good framework allows an easy communication of the model.

This frameworks for circular business models are related to the static view of circular business model innovation, supporting the conceptualisation of how a business model for the circular economy should be structured or represented (Employed to support the ideation and modelling of circular business models) [51]. These reference models are visual frameworks used to represent business models in terms of their elements.

Most of the reference systems used to represent circular models are based on the traditional, ”Business Model Canvas” or ”Value Logic Framework” models, which are based on the concept of the value proposition. Even today, in many cases, these frameworks are still used directly without adaptations.

Newly developed frameworks adjust, add new elements, rearrange their positions or change their interrelationships to accommodate more closely the characteristics of circular models in case they are adaptations of previous models. There are also new frameworks specifically developed for applying circular models that do not use as a reference, or at least not as directly, as the typical conceptual models.

4.2.1 Traditional frameworks

The main conceptual frameworks traditionally used so far are presented below, and their potential or weaknesses for use in circular models are presented and analysed.

4.2.1.1 *Canvas*

The Canvas is a strategic management template that can be used for developing new business models as well as for documenting existing ones.

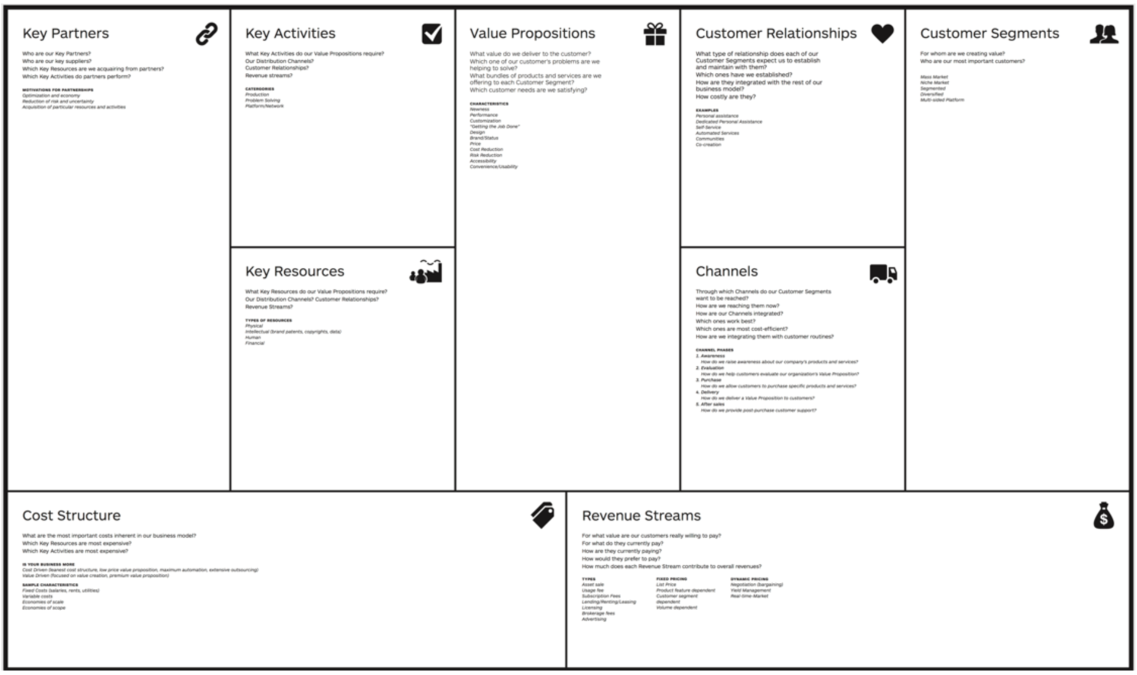


Figure 4.1: Traditional Canvas

The Canvas model provides a static view where the business model is described and represented in 9 blocks, one of the most traditionally used and very useful for linear models. In the case of circular models, it could be used, but it leaves out many of the concepts to be taken into account, so information and analysis capacity would be lost. One of the advantages is the knowledge of the tool in the sector and its standardisation, which allows quick comparisons and easy use for professionals. On the other hand, the disadvantages are the lack of analysis capacity of the circular models, as there are no blocks that consider these new models.

It should be noted that there is also a ”Value Proposition Canvas”, which is understood as an extension of the canvas model to analyse in more detail the blocks of ”Value Propositions” and ”Customer Segments”.

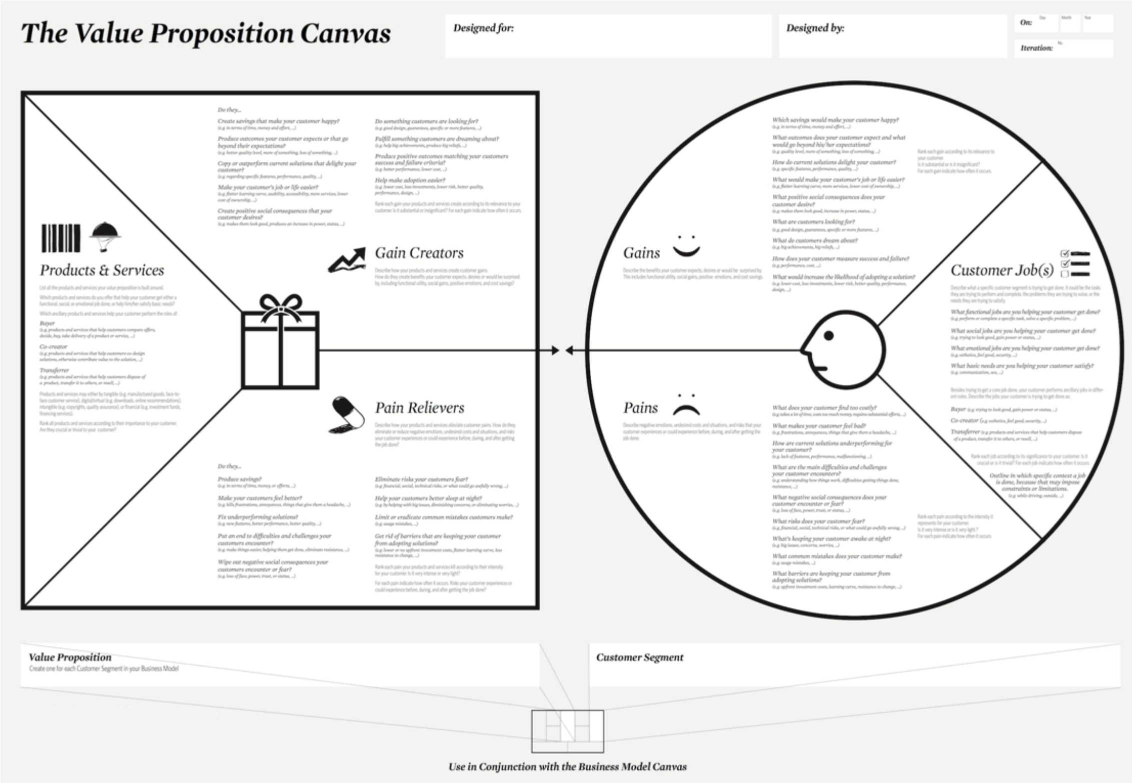


Figure 4.2: Value Proposition Canvas [53]

4.2.1.2 *Value Logic Framework*

An outline of the value logic is presented below. This model tries to highlight the axes on which a business model is to be based on maintaining economic viability and function in the market; it analyses the core of the business proposal directly without going into other points that may be more related to the functioning of the business. This logic is fully compatible with different models and has historically been used in line with the canvas model.

VALUE CREATION ⇨ VALUE TRANSFER ⇨ VALUE CAPTURE

Figure 4.3: Traditional Value Logic Framework

With a view to its adaptation and use together with the Canvas model (or with subsequent updates proposed for circular models), this study suggests incorporating the "Value Proposition" box, which can be understood as a statement of the analysis carried out that could be defined after carrying out the logic and in such a way that it can be integrated into the respective block of the Canvas framework.

This framework provides information in a very visual and synthesised form and is easier to use and analyse than the previously mentioned "Value Proposition Canvas" extension.

VALUE PROPOSITION ⇨ VALUE CREATION ⇨ VALUE TRANSFER ⇨ VALUE CAPTURE

Figure 4.4: Suggested Value Logic Framework

Due to the characteristics above, the "Value Logic" framework, even though it is a traditional framework, can be used perfectly well in circular models without the need for adaptations, as can be seen in the following example, where strategic proposals are provided for each of the three blocks of the value logic. Moreover, this framework is very interesting as it allows for more information by adding a block of context factors and another of cross-dimensional managerial practices that could be developed and that completes the report and continues to be entirely complementary to the canvas model that does not contemplate (although these blocks can be taken into account) in a direct way, which facilitates the analysis and generation of the framework.

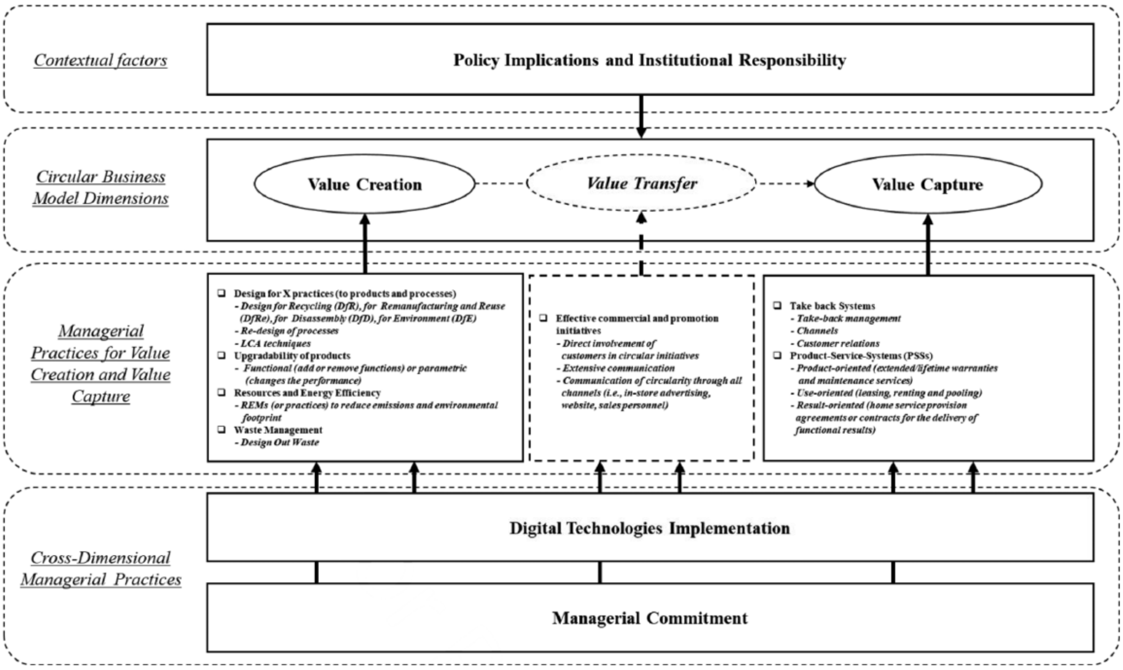


Figure 4.5: Value Logic Framework[54] applied to CE

4.2.2 Newly developed frameworks for CE

The following is a presentation of the conceptual frameworks that have been considered the most important in the literature developed explicitly for circular models, commenting on their use, characteristics, strengths and weaknesses, as well as possible improvements or lines of development.

4.2.2.1 *Three-layer Business Model Canvas (TLBMC) and Flourishing Business Canvas*

Both frameworks are developments of the original Canvas model and try to frame the business model statically through not only the original blocks but new blocks that allow visualising the model not only from an economic point of view but also from the TBL point of view in a way that allows having a broader perspective.

The TLBMC proposes to develop three separate canvases, each directly linked to each sustainability dimension. It allows for a detailed analysis and considers the study of impacts. The environmental canvas allows for concepts of circularity to be taken into account but it is not explicitly focused in this. The ”End of Life” block can be related to waste recovery and management systems and reverse chains so it can be used for circular models and can have a more impact-based approach.

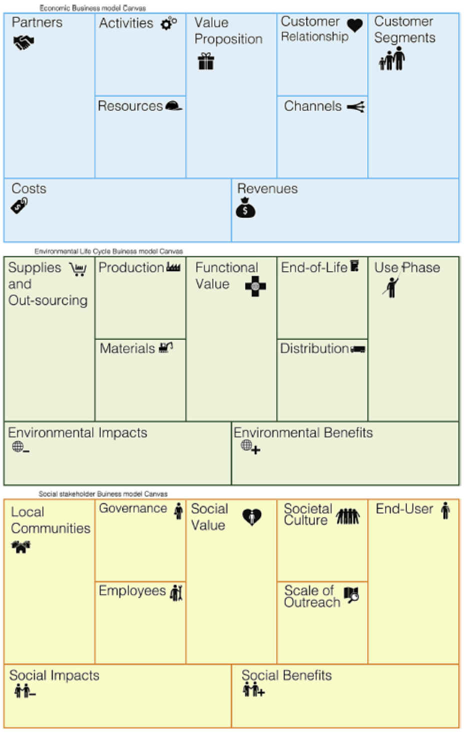


Figure 4.6: Three Layer Business Model Canvas (TLBMC)

Flourishing Canvas proposes to have all three dimensions of circularity in the same painting.

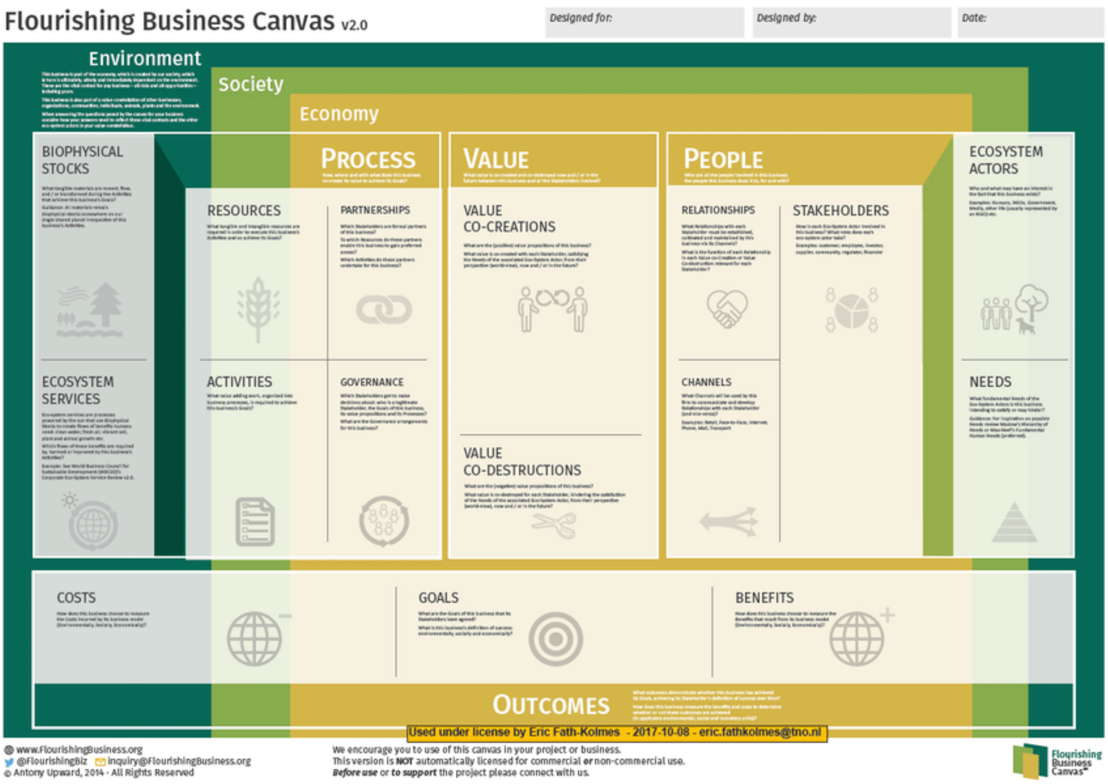


Figure 4.7: Flourishing Business Canvas

4.2.2.2 *Circular Canvas*

It is also an adaptation of the original Canvas model, in this case, trying to insert certain blocks that complete and allow for thoroughly assessing the circular models in the analysis. It is a very valid and recommendable proposal for those who want to maintain the working model and not make any changes. It follows the same format as the original Canvas, which makes it a framework that can be easily integrated into the sector as it does not involve many changes when working with the tool. Throughout the literature, several different proposals have been found on which blocks to incorporate to integrate the circularity analysis. This proposal combines the ”Take-Back System” and ”Adoption Factors” blocks.

Partners
- Cooperative networks
- Types of collaboration

Activities
- Optimising performance
- Product Design
- Lobbying
- Remanufacturing, recycling
- Technology exchange

Key Resources
- Better-performing materials
- Regeneration and restoring of natural capital
- Virtualization of materials
- Retrieved Resources (products, components, materials)

Value Proposition
- PSS
- Circular Product
- Virtual service
- Incentives for customers in Take-Back System

Customer Relations
- Produce on order
- Customer vote (design)
- Social-marketing strategies and relationships with community partners in Recycling 2.0

Channels
- Virtualization

Take-Back System
- Take-back management
- Channels
- Customer relations

Customer Segments
- Customer types

Cost Structure
- Evaluation criteria
- Value of incentives for customers
- Guidelines to account the costs of material flow

Revenue Streams
- Input-based
- Availability-based
- Usage-based
- Performance-based
- Value of retrieved resources

Adoption Factors
- Organizational capabilities
- PEST factors

Figure 4.8: Circular Canvas [55] adapted from: [56]

The ”Take-Back system” is added, as reverse logistics may require different partners, channels and customer relationships so that a new component can be distinguished to differentiate the specificity of direct and reverse logistics [55].

The ”Adoption factors” block is added so that the various reasons for rejection of circular business models can be identified for the company to anticipate and counteract them through different organisational capabilities and external factors [55]:

- *External factors, PEST(EL) Analysis*[1] *Factors*:
  - Political: Significant socio-economic benefits justify lobbying efforts to change legislation and political incentives to accelerate CE.
  - Economical: Economic forces such as foreseeable demand for future products or past difficulties of business entities in adopting CE principles.
  - Sociocultural: Sociocultural issues, such as customer habits and public opinion.

[1] Political, Economical, Sociocultural, Technological, (Environmental), (Legal)

- Technological: Use appropriate IT and data management technologies to support material tracking and other specific technologies.
- Environmental: Environmental issues include demand for improvement and reduction of impacts, public opinion, and possibilities.
- Legal: Legal framework in which the models to be implemented must be carried out and their possibilities and barriers.

• *Organisational capacities*: These capabilities require intangible resources, such as team motivation, organisational culture, knowledge, and transition procedures. These components are based on human resource development and team building, change management tools, business model design methods and tools, and evaluation models. Assessable through SWOT (Strengths, Weaknesses, Opportunities, Threats and Opportunities), where the capabilities (or organisational weaknesses) are strengths and weaknesses while threats and opportunities are external forces that can be extracted after conducting the PEST(EL) analysis.

4.2.2.3 *Circular Business Framework (CBF)*

The so-called Circular Business Framework [57], is based on the BMC (linear).

This model, presented in the figure below, comprises eight blocks. In the same framework, the sub-blocks are specified, and the key questions are formulated to identify the necessary information and data.

Figure 4.9: Circular Business Framework (CBF) [57]

The figure below shows the entire framework in the context of its supporting materials and the roadmap for its development, designed to help understand and apply the framework and present the key points.

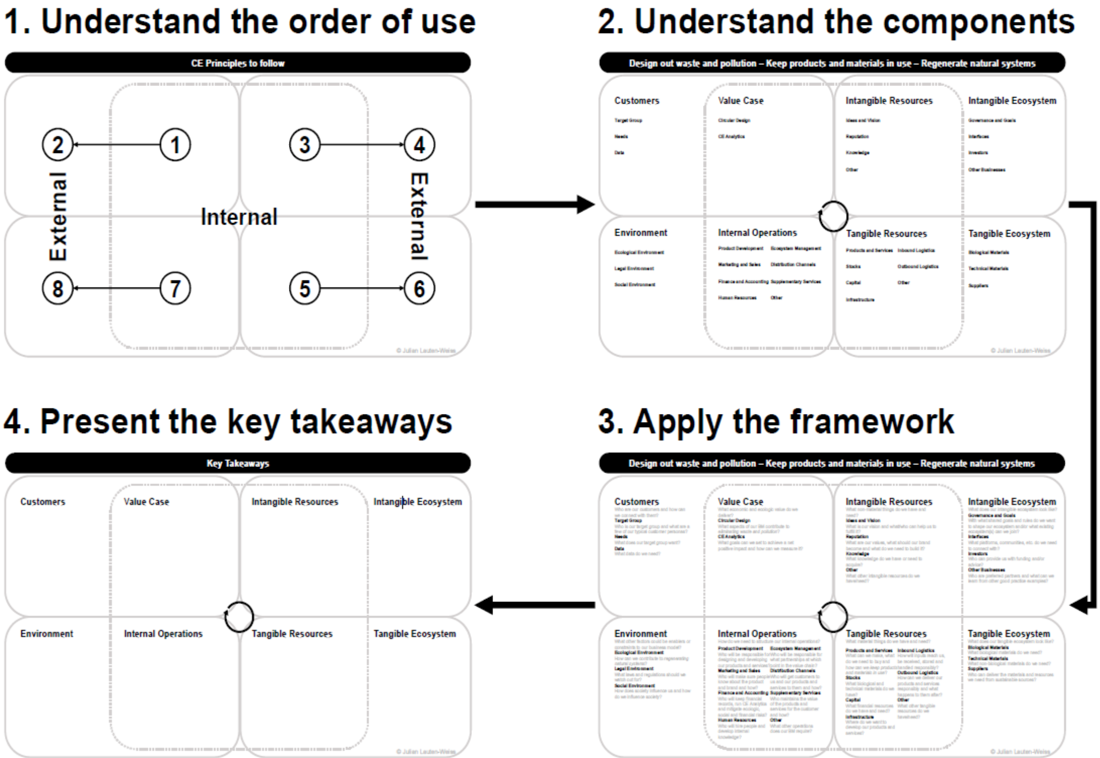


Figure 4.10: Steps to understanding the CBF [57]

A significant conceptual difference is an explicit alternation between an internal and external perspective, which follows a continuous logic from the abstract to the more functional blocks. In addition, the ecosystem perspective reveals external elements that are not under the company's direct control but have been systematically included; something similar is attempted in the Circular Canvas by adding the ”Adoption Factors” block [57].

As discussed in other models, this can add some complexity. Still, the level of detail and the guiding questions can also be an advantage - the CBF can give some initial guidance on how to improve their adherence to EC principles and reinforce their circularity.

4.2.2.4 Circular Value Proposition Framework (CVP)

This framework is based on the Canvas and Value Logic models.

Like the circular Canvas, although somewhat more complex, it facilitates the consideration of CE objectives during implementation and is adaptable to different contexts.

This framework contains four partial architectures [55]:

- (I) Bottom-up architecture (i.e. value creation processes; partnerships and collaborations).
- (II) Top-down architecture (i.e. offerings; value delivery processes; revenue mechanisms; target customers).
- (III) Value generation architecture (i.e. overall benefits; value propositions; value for partners; value for customers).
- (IV) Financial architecture (i.e. cost structure; financing options).

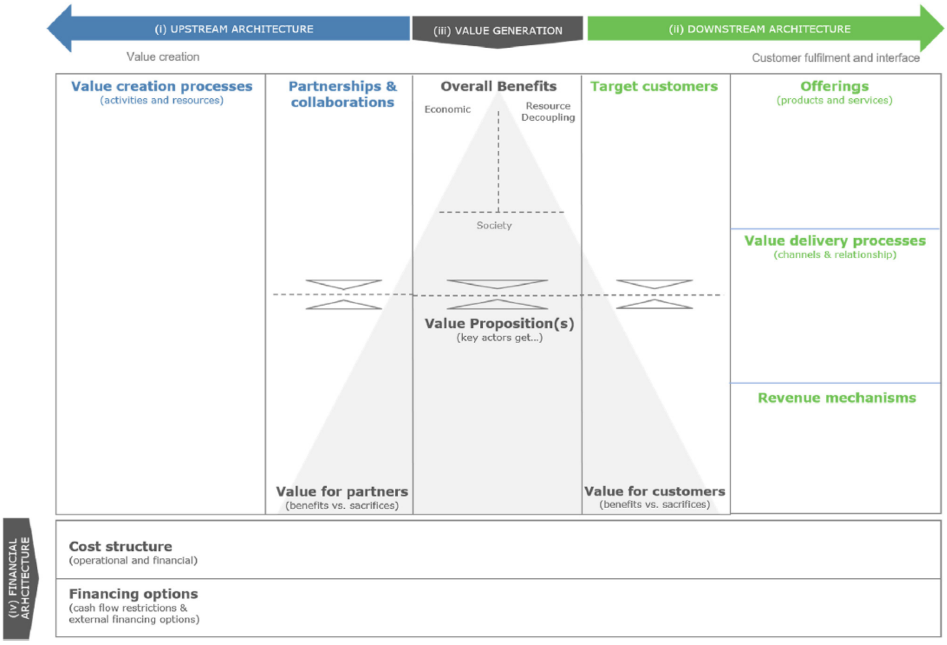


Figure 4.11: Circular Value Proposition Framework (CVP) [55] adapted from: [58]

4.2.2.5 *EEA analytical framework*

Specially designed for circular models, where five blocks are identified, representing the different stages within a circular circuit[2]. The first level represents the innovations carried out in the business model under study; the second the enablers that support the creation, and the heart of the framework represents the circular objectives to be achieved [59].

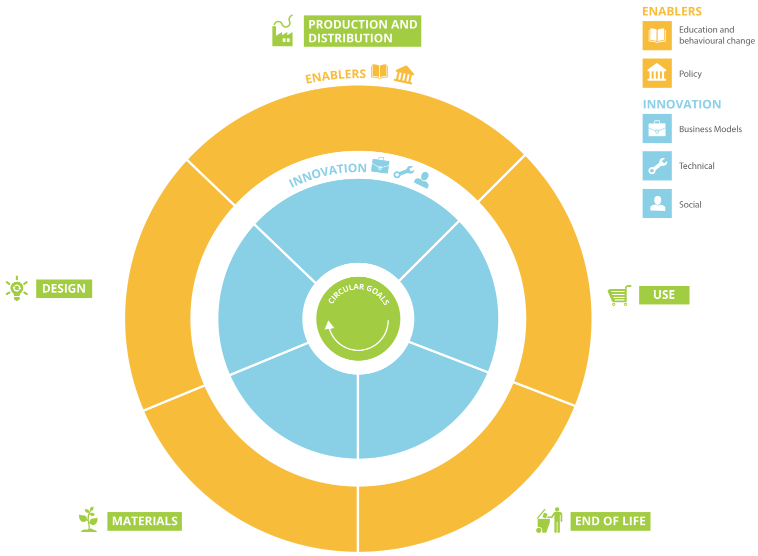


Figure 4.12: EEA Analitycal framework [59]

[2]Materials, design, Production and distribution, Use, and EoL

If the business model focuses only on one of the phases, it can be isolated and analysed as in the example attached in the appendix A.2.10.

It is a very visual model aligned with the concept of CE; it focuses on the process of the product or component and highlights the phase or stage in which the model will be developed. As a weakness, it does not directly identify other vital points such as partners, channels or revenue streams, which could be omitted or forgotten to be represented with this tool.

It can be a handy tool for complementary use with other frameworks, first completing this in such a way that it facilitates the creation of the main framework and also helps to structure the general idea of the business model to be carried out, this being its greatest strength.

4.2.2.6 *Circular Business Model Tool (CBMT)*

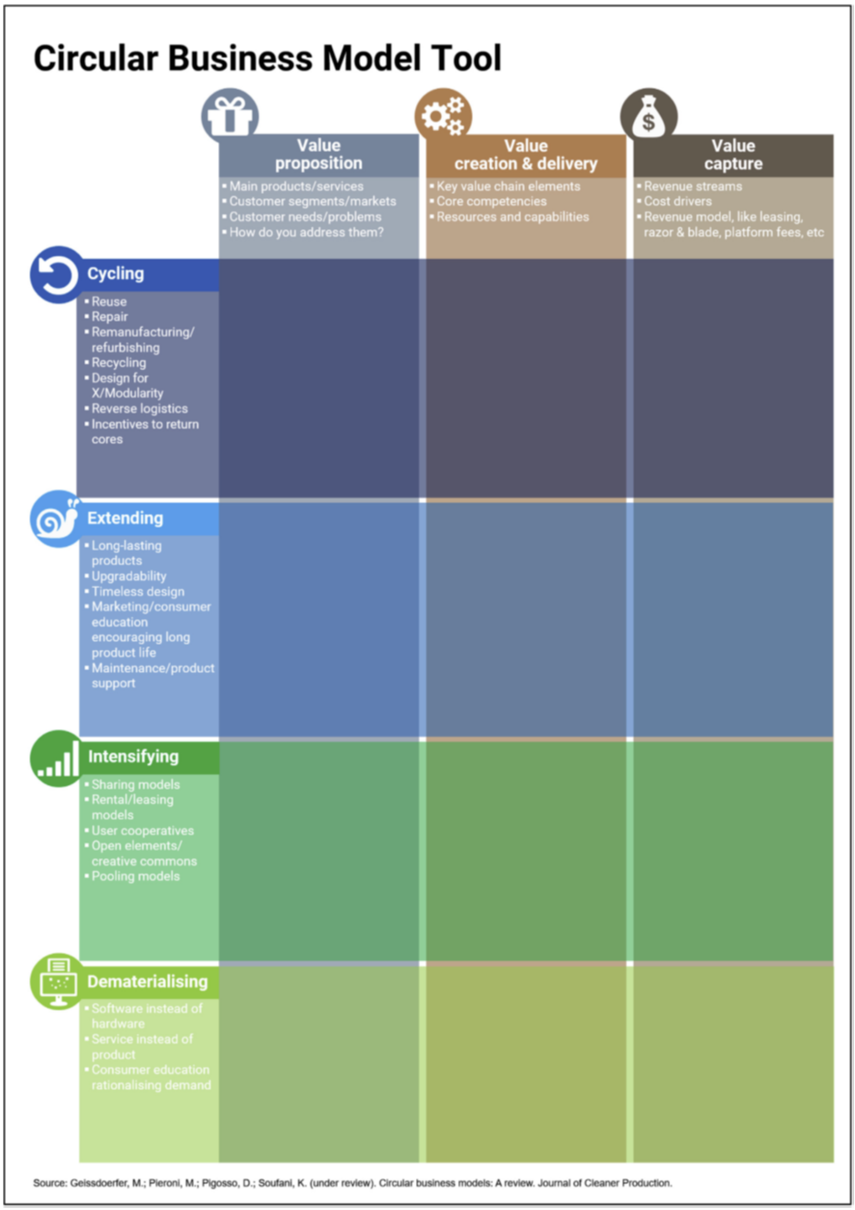


Figure 4.13: Circular Business Model Tool (CBMT) [51]

This tool combines the traditional Value Logic Framework with the core strategies of the circular economy (which are discussed in the section 4.3), in a way that represents the strategies with the conceptual framework at the same time. It allows to discuss how implementing these four strategies of the circular business model will affect the three elements of the Value Logic Framework [51].

An attractive tool that combines the strategies business model strategy (including actions) to be analysed with the static vision of the same.

4.2.3 Concluding Remark

The relevant literature on the topic of CBMF's remains fragmented by different uses of the term "business model" and conceptions of circularity, pointing to the need for further standardisation of terminology.

In that way,it should be noted that a number of tools understood as CBMF in the literature cannot be taken as conceptual frameworks as they cannot be used to contextualise and analyse business models. These must be differentiated from conceptual frameworks and their use clarified, the most important of which are:

- ReSOLVE (section 4.3): Although it is presented as a conceptual business model framework in the literature, it is not by not presenting a static view of the business model. Is a control list made from different strategies based on the CE principles.
- Environmental Value Proposition Table (EVPT) (appendix A.2.12): It is not so much a conceptual framework as a table where the environmental value proposition to be achieved is represented against the models that are proposed and compared so that after a review and evaluation of each model, a comparison can be expressed graphically and visually[3].
  Oriented to representing results after the evaluation and after establishing the conceptual framework (which reflects the business model's value proposition).
- Banckasting and Ecodesign CE (BECE) (section 4.4.1): BECE is a methodology (not a conceptual framework) that serves as a guide to help companies develop sustainable business models following the steps it proposes.

4.3 Strategies

Having discussed the importance of the conceptual frameworks that can be used to frame business models, the most relevant strategies and circular models are studied.

These strategies are presented as classifications within the literature. They are merely a categorisation of possible structures or configurations of a circular business model. They include typological, archetypal, taxonomic or morphological schemes. The strategies themselves will shape the business models and can be easily visualised; these strategies will become concrete actions when applying the model to reality.

Just as the conceptual frameworks are related to the static vision, the classifications are related to the dynamic image of circular business model innovation, supporting the determination of how business models should be configured or modified to adapt to the principles of the circular economy. They serve as a reference for the development of business models.

[3]This table is perfectly combinable with conceptual frameworks, it can also evaluate value propositions that consider economic and social dimensions.

The classifications will allow and facilitate the selection of strategies to be incorporated into the conceptual framework forming the final Business model. After that, the theoretical model is articulated in practice through actions; in parallel, the process is evaluated and measured to analyse its impact from the design stage, through the implementation stage and then the operational phase.

ReSOLVE Control List : Highlight among all the categorisations in the literature the ReSOLVE control list (Regenerate, Share, Optimise Loop, Visualise and Exchange), proposed by the Ellen MacArthur Foundation [60] is the categorisation that has been the most frequently used in the academic studies.

There are six defined strategies to identify circular economy opportunities and shape the business model.

Furthermore, the ReSOLVE framework shows how the principles of the circular economy are translated into business actions that implement CE.

Figure 4.14: ReSOLVE Control list [60]

4.3.1 Classification Proposal

Nevertheless, In this project, a classification based on the circular principles[4] will also be developed (given some business model examples in some of them). With the objective, to be more precise and concise, to make it easier to differentiate different strategies and try to order them in a way that makes them simpler to understand, select and apply.

Should be marked that in reality many of the the strategies are interrelated (as will be seen throughout the reading, sharing many points between them) or can be intermingled to obtain a business model by combining different strategies, since depending on the company or project there may be combinations that optimise the model [5].

[4]The following will be recognised as circular principles in this study: Cycling, Extending, Intensifying, Dematerialising

[5]Other strategies such as optimisation and regeneration are essential for the search for sustainability, but they are not based on circular principles but on sustainable ones. These are indeed concepts to be considered in the design of circular models since the objective of these designs is the search for sustainability and efficiency. Still, they are not the direct object of study in this project.

- **Cycling:** materials and energy are recycled within the system, specially through reuse, remanufacturing, refurbishing, and recycling [51].
  - **Design for deconstruction and separation and/or recyclability** A business model strategy that bases its potential on foreseeing events from scratch to be able to apply cycling models in the future.
  - **Circular supply chain:** A strategy based on the supply chain, where the product components are disassembled, traceable and reusable. Completing the circularity of the product when it enters a new cycle either in an internal company of the supply chain itself (closed cycle) or in another chain or company to which the product has been sold or supplied. This model ensures that value is retained as tradable commodities or cost-free materials from in-house manufacturing in materials that would otherwise be discarded as waste.
  - **Reuse and Refurbishment:** Products or components reused as replacements for similar new products in a building. The products are used in the functions for which they were originally intended. The business is linked either to the sale of the company's own products or those of other companies, or to the internal use of these components as lower-cost (refurbishment) or zero-cost (direct reuse) components. This strategy is closely linked to life extension, depending on small factors it can be related to cycling or life extension, such as whether or not it is used for the same building for example.
  - **Remanufacturing and recycling:** This takes advantage of the fact that products or resources previously wasted or of little use are being used as more vital resources. For example, waste concrete can be crushed and cleaned into slag, which can be used in new concrete instead of road fill. Or used wood can be used in new chipboard instead of going to incineration. In recycling and upcycling, the business is linked to the sale or cost-free use of the used resource as a substitute for new resources [42].
  - **Intrinsic value maintenance for future cycling:** It can be understood more as a business model for cycling strategies. It seeks to secure the life cycle of materials during the construction of the building by entering into a contract with a buyer of future demolition materials [47].
- **Extending:** Entails that the use phase of the product is extended, through long-lasting and timeless design, marketing that encourages long use phases, maintenance, and repair [51].
  - **Adaptability and Durability:** There is long-term value in buildings that can adapt over time and maintain a high intrinsic value over the time; frameworks that can adapt to changing market, social conditions and new programmes, thanks to their long-lasting and adaptive design [47].
  - **Product life extension:** a business model that tries to extend the useful life of the product and focuses on preserving the original intrinsic economic value of the product as much as possible, e.g:
    - Renovating and recovering products for sale
    - Withdrawing products with a view to resale
    - Improving already manufactured products to increase their durability

* Repairing products for further use

– **Repair and maintenance:** Repair and maintenance of construction products and buildings to extend their lifetime, e.g. known model, e.g. window manufacturers with a lifetime repair; or projects where the person in charge of the construction of a building also operates the facility and thus generates total economic benefits [42].

- **Intensifying:** Implies that the product's use phase is intensified through solutions (such as sharing economy or public transport).

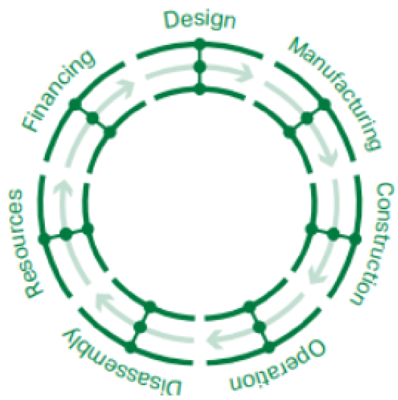


Figure 4.15: Intensifying Strategy Representation

– **Share platforms:** Sharing platforms are based on sharing products or activities by bartering, renting or exchanging goods or activities so that more than one actor can benefit from the same resource. This is a model with many potentials still to be exploited and discovered in many of the sub-systems and sub-sectors within the construction industry, exchange of used materials, sharing of transport of components and sharing of construction tools for the same project-operated by different companies, connecting owners with companies and individuals wishing to use their products, etc.

– **Flexible square metres:** New value can be created and resources saved through better use of existing square metres. With flexible solutions, it can be given different services to the same space depending on the day and time, maximising its utilisation [47].

– **Portable buildings:** Semi-permanent and portable buildings can create value in developing new areas or adapting and hosting events for different dimensions, kind of events or places. In some way and depending on some nuances, it can be seen as a life-extension strategy [47].

- **Dematerialising:** Describes the provision of product utility through substitution with service and solutions. Offering services or product-service systems (PSS) instead of physical products to fulfil the same function for the user. Can reduce, among other things, the number of produced products [51].

– **Product as a service:** Instead of buying products, a product as a service is a business where customers rent or lease the product. It encourages to increase lifespan, increases efficiency and reduces the drain of materials from producers. It allows the producer to innovate with different strategic proposals such as expanding the product's lifetime, changing the elements, or refocusing it for new consumers over time and lifetime. Leasing as a business model can also be applied to entire building complexes [47].

The product as a service covers:

* **Pay-as-you-go:** Where the consumer pays for the use made, it is not an ongoing charge.
* **Leasing:** Where the consumer agrees to the right to use the product for a certain period of time.
* **Renting:** Where the consumer is entitled to the use of the contracted product for a short period of time.
* **Performance scheme:** When the consumer purchases a specific level of product capability.

– **Complementary Services:** Base the business model on the value of complementary services that the company can sell to get the product to work in its original form at maximum value for as long as possible [14].

4.3.2 4 BM's as examples of how circular strategies can be tackled

1. *Dematerialising (Product as a service) plus Extending strategies:* The Technical University of Delft and several commercial partners have developed a leasing model for building facades. The building owner pays for the energy efficiency gained from the envelope but does not buy the façade elements. It relieves building owners from maintaining the façade and gives manufacturers a greater incentive to keep, design for separation and develop recovery plans for their façade products.

2. *3 examples of different take-back system models - cycling strategy (circular supply chain) [42]:*

   (a) Companies that base their sustainable products on residual production from other industries.

   (b) Companies that create their own waste production cycle and thus are suppliers and customers.

   Real example: STARK, the consultancy Golder and the waste management company Solum have teamed up to offer a recovery scheme that removes construction waste timber from the construction site and returns the product to the market. The contractor collects the wood, STARK delivers the timber to Solum, which carries out the cleaning process. The products are placed on STARK's shelves for resale. In addition to using a circular strategy, it also uses a traditional strategy of synergies between companies to generate the business model.

   (c) Companies that create products by recycling other people's used materials. It can be challenging to determine the exact content of the materials in these models, as they are collected from many different sources.

   Real-world example: StoneCycling® develops 100% recycled bricks with a positive carbon footprint. They comprise a minimum of 60% construction waste, mainly demolition and new build waste, which is collected, sorted and turned into granules for use in new bricks. They meet all European market standards.

At present, between this three, it is the second model that generates the most business. Still, the third model has a more significant business perspective if the content of the materials used can be documented.

4.4 BM's elaboration methodologies

There are a series of methodologies that are used for the elaboration of business models, but they are neither conceptual frameworks nor strategies.

Methodologies such as the BECE support the elaboration of circular models, marking the steps to follow systematically; and they can be combined with conceptual frameworks and even help their formulation and development.

4.4.1 Banckasting and Ecodesign CE (BECE)

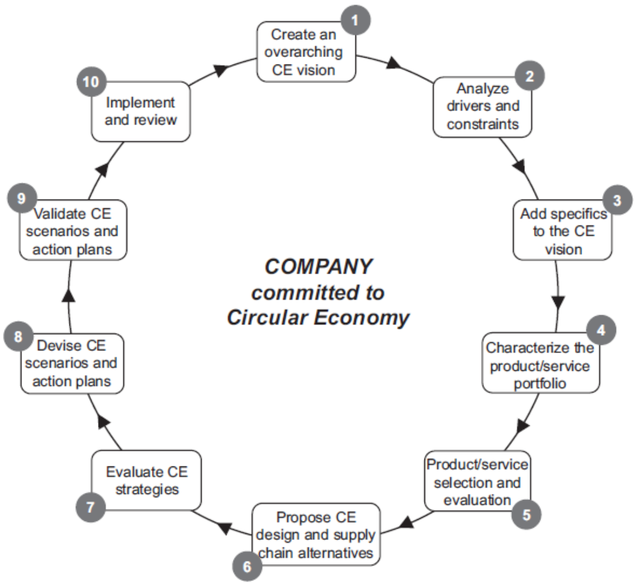


Figure 4.16: BECE Framework [61]

The "Backcasting and Eco-Design Circular Economy" (BECE) is a participatory tool that combines strategic planning and operations.

It consists of ten steps, created by combining the relevant steps of backcasting and eco-design [61] (appendix A.2.11):

1. **Steps 1 to 3:** Application of backcasting. Assist in formulating a CE vision.
2. **Steps 4 to 7:** Eco-design analysis. Aim to achieve the CE vision through strategic (re)design of products, services and supply chains.
3. **Steps 8 to 10:** Implementation of the vision by defining and validating scenarios and action plans.

In this way, backcasting stages guide the strategic development of eco-design, while eco-design refines and translates backcasting ideas into concrete solutions.

BECE is a methodology that serves as a development guide to help companies develop sustainable business models that translate CE principles into industrial practice [61], following the steps it proposes. In addition to guiding not only in the development process but also in the evaluation and implementation process.

4.4.2 Note on the methodologies for the elaboration

Knowing of their existence, one could opt for:

- Do not use methodologies and rely solely on the formulation of conceptual frameworks for the development of the models to be studied. This is not a bad option as long as the sector, company or project and the opportunities are well understood, and a complete framework is chosen to provide information and guidance for its development. For this purpose, a classification of strategies like the one presented in this project can be beneficial.
- Use existing methods such as the BECE to assist and guide the elaboration, which is likely to be more tedious and require understanding.
- Formulate their own company-wide methods for modelling, which could contain, e.g. a pre-analysis, a conceptual framework and supported by a classification of strategies. A SWOT and PEST(EL) studies could be carried out beforehand to identify relevant factors.

4.5 Examples on how sector agents can benefit from CBM

Construction actors can benefit from circular business models in different ways. Below are several examples of how they can create business through services and products that support the circular economy in construction [42].

- *Engineers and Architects:*
  - Sale of new design principles and terms as differentiating parameters.
  - Sale of resource mapping.
  - Sale of impact projections (economic, environmental and social).
  - Sale of quality testing of used materials.
  - Documented experience as a scoring criterion in tenders.
- *Contractor:*
  - Provision of new logistics management: handling, resale or storage of used materials.
  - Undertake to carry out the work with sustainable, local means.
  - Assume Assurance of qualified personnel to undertake implementation.
  - Documented experience as a scoring criterion in tenders.
- *Constructor:*
  - Save on resource budget by reusing materials from buildings ready for demolition instead of using new ones.
  - Attracting citizens called by sustainable principles.
  - Certification schemes as a market revaloriser.
- *Demolition company:*
  - Provide new logistics management: handling, resale or storage of used materials.

- Provide soft selective demolition.
- Documented experience as a scoring criterion in tenders.

• *Resource Centre:*
  - Sale of resource products.

• *materials manufacturer:*
  - Documented sustainable products
  - Demountable products
  - Adaptable products

4.6 Partial Conclusions

After this second block of ”Results 1”, it can be concluded that it is essential to clarify the concepts and differences between conceptual frameworks, BM’s, actions and strategies to know how to design the best action plans or select the best lines of model design according to the needs of each company or project.

More concretely, it is observed that conceptual frameworks are handy tools for the early stages of design for communication and idea generation. Highlight that the Canvas and Value proposition models are a bit outdated, as they leave aside essential concepts to be taken into account in circular models. The study propose a series of more interesting frameworks for this purpose throughout the block.

The conceptual framework to be used will depend on the people who have to make the decision, the project, what is to be analysed and conveyed (and to whom to share). Any of the variants or options presented can be used for this purpose.

The frameworks have to be combined with a series of strategies that complete the vision of the model, in order to then develop concrete actions. For this purpose, the use of classifications is recommended to help in the selection of strategies. In this project a proposal based on the literature review is proposed, which will also be used in the case study for the elaboration of the business models.

In essence, this block provides the tools to have a picture of the role of BM in the CE, facilitating the understanding and design of circular models (it helps to take into account circularity from the design phases).

In addition, this analysis also serves to assist the project case development (chapter 6), by applying various concepts studied. The Circular Canvas is used to make a first iteration and frame the case when looking for possible strategies. On the other hand, the classification of strategies proposed in this block will also serve to help the in the selection and design of circular business models.

5 RESULTS 1.C - ASSESSMENT AND MEASUREMENT AS DESIGN PARAMETERS

This section will identify and analyse available assessment and measurement methods and their application and usefulness in circular models for accurate selection. Particular emphasis is given to indicators and tools for measuring and evaluating the economic dimension and assessing costs [1]; analysing them from a decision making perspective.

It Provides an understanding of the assessment tools and indicators available; clarifies key concepts and differentiates between types of indicators and evaluation methods for proper selection and use.

This analysis simultaneously serves to select the most suitable evaluation method and indicators for the realisation of the project case study (chapter 6).

The first part (section 5.1) of the section looks at indicators. The second part (section 5.2) discuss the main assessment methods available and other methods identified, focusing primarily on evaluation for decision-making in the design phase. Many are composed of, or articulated through, the indicators discussed in the first part of the review to either generate or provide the results.

5.1 Indicators

The OECD defines an indicator as ”a quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievements, to reflect changes related to an intervention or to help assess the performance of a development actor” [62].

Indicators are part of the control systems and serve, among other things, both to evaluate business models and make decisions in the design phase and to control the strategy or business model during implementation and once it is up and running, among other utilities that can be assigned to them.

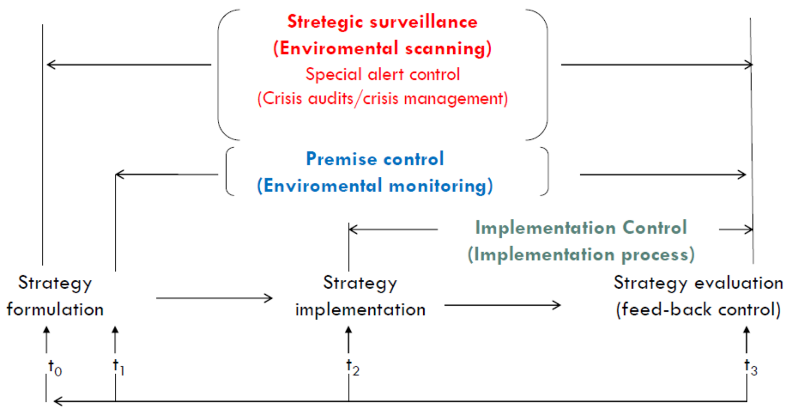


Figure 5.1: Strategic control components in the strategic management process

[1] Critical to integrating circular models into the system.

One of the main reasons why it is essential to study and use relevant and impact indicators in the sector is to provide companies with reliable information that enables them to make decisions and apply suitable measures for implementing CE solutions, as well as being especially relevant for carrying out performance assessments of circular models on environmental, economic and social sustainability, and to obtain information on the functioning of the models at different levels.

Indicators need to have the ability to summarise, focus and condense the complexity of the dynamic environment into a manageable amount of meaningful knowledge [62].

At this point, the needs of the sector and the indicators available to measure and quantify both circularity and sustainability in its three main pillars (environmental, economic and social) have been reviewed at a general level.

There is a wide range of indicators, ranging in form, complexity, the points at which they can be applied in the lifecycle and many other characteristics, hence the difficulty, among other things, of classifying and selecting them.

It is important to note that many first-level indicators are sufficiently relevant and do not need to be processed. At the same time, others (or even the same ones that are also relevant on their own) can serve and be used for further assessment in models such as LCA or LCC or more complex assessment tools. Many others (high-level indicators) are obtained through the results provided by evaluation models or after the combination or processing of previously achieved or realised indicators or evaluation models.

5.1.1 Circularity Indicators

Measuring circularity is currently one of the main issues at stake. Among many other relevant issues that need to be measured the following can be listed:

1. How to measure progress in the transition to CE.
2. How to measure the performance of the circular economy with its objectives being substantially different from those of the traditional linear economy [63].
3. How to measure circularity in companies and economies.
4. How to measure circularity at each level (city, building, component and product level).

Effective circular economy indicators will allow actors to measure the circularity of their activities and their activities' performance, identify improvement opportunities, and communicate their circular economy actions consistently and comparably [64]. In addition to allowing the application of these indicators in models to measure and obtain new data and impact indicators, to assess the sustainability of the models applied.

Circular indicators can also be used to:

1. Support the tools used by organisations to identify the additional and circular value of their products.
2. Enable manufacturers to mitigate the risks of material price volatility and material supply when combined with other actions.
3. Enable policymakers to design optimal interventions to promote the circularity of material flows in the built environment.

Circular indicators are crucial in enabling the supply chain to understand achievable performance levels and set targets/benchmarks to drive and track improvements [64].

These indicators can also help, at the municipal level, to support evidence-based policy development, planning and decision-making to support the circularity of material flow within buildings and throughout the life cycle of materials.

Numerous indicators have been found in the literature, and multiple circularity indicators have been developed in recent years, but in a somewhat confusing way regarding their scope, purposes and possible applications. There is no clear consensus on their classification. Lack of knowledge about CE indicators is a barrier to their further application [62].

They can be divided and classified in many ways. Still, from the analysis carried out and in line with the literature, it is observed that the most relevant and most used classifications are the classification by levels (where there is a certain unanimity on the different levels; materials, products and components level, building level and city level), and the classification by lifecycle stage, which are very useful when it comes to selecting an indicator. The more specific or detailed the classification (with different levels of subdivision), the easier the selection of indicators will be and the easier the task will be.

5.1.1.1 *Highlighted studies and indicators for circularity*

The **CIRCuIT project** in one of its most recently completed **WorkPackages (WP3)** [64], carries out a study and classification of the most relevant indicators for measuring circularity at each level.

The study identifies 510 indicators that are refined and prioritised, identifying 34 indicators of significant relevance (ten at macro level, thirteen at meso level and eleven at micro level) for the sector and for the environments in which the project is framed, including Denmark and more specifically the city of Copenhagen, which makes this study particularly relevant and worth considering.

It presents a mix of impact metrics (e.g. recycled content, material use), productivity metrics (e.g. by surface value) and enabling metrics (e.g. several projects with circular economy requirements). It can be said that these are KPIs that do not measure circularity as a concept, i.e. they do not bring together several indicators to measure circularity at the global level of a project, but each one measures different circularity relevant points. If a global indicator of circularity were to be obtained later on, a model would have to be applied that combines several of these KPIs to achieve this indicator.

This study is of great interest due to its recentness and the fact that the indicators are explicitly focused on the building sector.

It should be borne in mind that the recommended indicators measure circularity criteria, not environmental, social and economic impacts. For these, it will be necessary to use other indicators or models.

As already discussed, such indicators can be put to direct use; they will feed into the life cycle, urban mining and circular design indices and help, to support evidence-based policy development and planning and decision making, as well as at the project level, in terms of the availability and use of recovered and recycled materials. In addition, they can also be used to measure the environmental, economic and social impacts of circular economy decisions and validate their benefits (or not) using LCA (life cycle assessment), LCC (life cycle costing), social approaches or other approaches and performance assessment methods and tools [64].

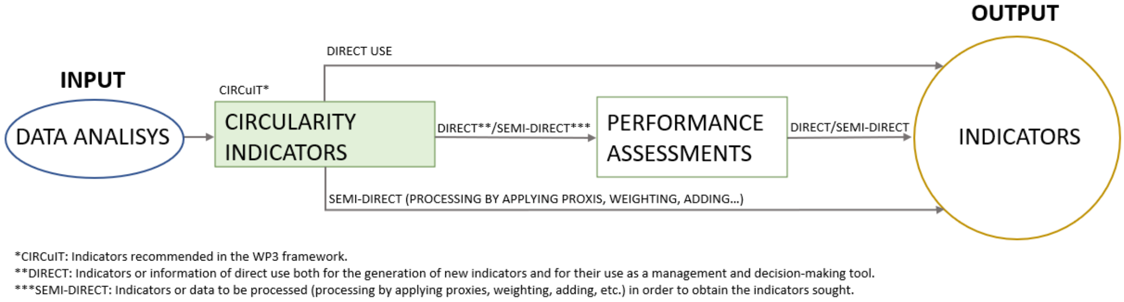


Figure 5.2: Possible applications of circularity indicators (appendix A.2.13)

As can be seen in the tables with the recommended indicators attached in the appendix A.2.26, These are sorted in the first order by level and second order by category (Materials input, Design, Lifespan and in-use performance, Circular potential, Material Outflows and recirculation, etc.[2]).

In addition, all indicators are classified into one or more of the following indices:

- Urban Mining Index: Indicators measure the secondary resource utilisation through the reuse/recycling of existing materials, products, buildings and cities.
- Life Span Index: Indicators that measure the service life, use efficiency and potential for extending the service life of existing materials, products, buildings and cities.
- Circular Design Index: Indicators that measure how cities, buildings and products have incorporated designs and principles into new constructions that facilitate life extension and the recovery of materials after their life cycle within buildings and products.

The tables also present information on the attributes of the indicators, including a description of the indicator, the measurement (where possible) and units of the indicator and the relevant stakeholder/user of the indicator.

In addition, several valuable enablers were identified to drive the circular economy process, which are also presented as appendix A.2.26.

In addition, it is also worth highlighting the recent work **"Critical review of nano and micro-level building circularity indicators and frameworks"** [65] which identifies a large number of relevant indicators, at material/product/component and building level,

2

- Material input: this category describes all indicators that will influence the cradle to gate stage of buildings and products/materials/components.
- Design: this category describes any indicator that influences the way the building and products/materials/components are constructed.
- Lifetime and in-use performance: indicators of the efficiency with which value is extracted and waste is avoided from materials in their use phase in products, buildings or buildings (cities).
- Circular potential: indicators that demonstrate the potential of products or buildings in buildings in use to retain the value of materials and minimise waste.
- Outputs and material recirculation: indicators of the actual quantities and destinations of materials left at the end of their useful life within a building.
- Circularity enablers: indicators of the presence or absence of factors that could enable the acceleration of circular decision-making.

mostly proposed and developed by the academic sector and specifically designed for the building sector, hence their relevance. They are more complex to obtain than those previously mentioned and developed by the CIRCuIT programme (which it complements to a certain extent), as they try to cover several aspects and dimensions of circularity at the same time, trying to measure it with a single indicator and using performance assessment frameworks developed specifically for obtaining these indicators.

Many of the frameworks used to obtain these indicators combine different circularity or performance assessment tools (discussed below, such as LCA, LCCA, for example) and other indicators.

The indicators identified by this review share that they all take circularity into account. Still, many of them also take into account other factors such as economic and environmental factors.

Given the difficulty of combining several dimensions of circularity in a single indicator, the study analyses the KPIs covered by each one, as seen in the appendix A.2.28, This will allow visualising which indicator can be interesting depending on the aspects to be covered and which can be combined to form a total view of circularity. It should be noted that this indicator study is only intended to measure the level of materials, products, components, and buildings.

5.1.2 Indicators for measuring impact on sustainability in CE models

Sustainability impact indicators can be used to measure circular economy decisions' environmental, economic and social impacts and validate their benefits.

They often go hand in hand with using performance assessment tools such as LCC, LCA, social approaches or other models. Many can be obtained with information and data from these models to assess total impacts on each dimension separately or even in aggregate. In contrast, others can be used for application in these models or can be obtained and used directly, without the need to apply models or proxies.

5.1.2.1 *Environmental Indicators*

The main and most widely used environmental indicators in the sector are:

- **The Embodied Energy (EE):** Can be assumed as the primary energy (MJ) contents obtained as sum of:
  1. Fuels production and delivery
  2. Energy content of delivered fuels
  3. Energy use in transport
  4. Feedstock energy
- **The Embodied Carbon (EC):** Is a measure of CO2 equivalent emissions related to energy production and supply (kg CO2 eq) over the years.

Both can be calculated through the LCA standard taking into account the life cycle. The EC and EE can be split-up into initial, recurring and end-of-life.

Counting the tonnes of material used and tonnes of waste saved can also be directly relevant indicators of environmental impact although they can be understood as circular.

5.1.2.2 *Economical Indicators*

In the case of economic indicators for impact measurement, both traditional indicators and new indicators that take circularity into account can be used. In this particular case study, the focus is on indicators for cost analysis for decision-making in the design phases, so the focus is on indicators or adaptations that allow measuring, comparing and comparing in this framework. In addition, other indicators relevant to circular projects are also presented.

Listed below are a number of purely economic indicators that are already, are becoming, or may potentially be relevant for the measurement and evaluation of circular models:

- **Residual Value (RV):** This is an important concept, especially in renovation and demolition processes, as it determines the intrinsic value of a component, product or material. At the accounting level, the definition is that the residual value is the value of a fixed asset at the end of its useful life, after deduction of depreciation and amortisation expenses. To apply this concept to the construction sector, it is necessary to estimate the value of the product at the end of its life cycle, for which tools such as destructive and non-destructive tests (depending on the component) can be used to estimate its remaining useful life and to give an economic value to the product, thus allowing to measure, among other things, the money that can be made from the reuse of a product Demolition. For components where the useful life has not yet been completed, but the component is to be removed from the building, it is proposed to estimate the RV as the Present Value of the component, subtracting from the initial value the depreciation done, taking a conservative perspective, in case no other tools for calculation or estimation are available.

- **Return of Investment (ROI):** The return on investment is a financial ratio that compares the benefit or profit obtained from the investment. In other words, at a simple level, it is the yield generated divided by the investment made.

  $$((Revenue - Investment)/Investment)x100[\%]$$

  This concept can be useful and can be applied when comparing circular projects in the design phase from an economical perspective by calculating a ROI that takes into account the total life-cycle costs to compare the benefits or detriments over costs of adopting circular policies. Taking as a dividend the difference in total costs between the circular model to be compared with the linear base case and taking as a divisor the initial investment or initial costs of the project to be evaluated, it can be argued that by applying this ratio in this way one is talking about the **Savings to Investment Ratio**[3].

  $$SIR_1 = ((LCC_1 - LCC_base)^4/InitialCosts_1)x100[\%]$$

  It can be argued that the ROI-SIR expresed like this takes into account the circularity and works as a kind of Circular ROI (CROI), as it takes into account the whole life cycle costs and as it allows to measure the return on investment on the benefits of one proposal over another over its lifetime. This concept presented only takes into account economic sustainability and not environmental or social sustainability.

[3]Representative of the ratio between the amount of savings in relation to the investment sustained to obtain it

[4]When reference is made to the LCC, it refers to the NPV calculated using this method.

- **Net Present Value (NPV):** Representing the amount of discounted cash flows considering costs and incomes of a project solution. NPV is the main indicator, representing the amount of discounted cash flows considering costs and incomes of a project solution. NPV permits to consider the single cost items referred to the different life cycle stages, including the end-of-life stage. It permits to breakdown into detail and analyze the single amount of relevant cost items. For this reason, NPV is indicated to analyze not only the investment as a whole, but also each cost component impact on the overall financial result. It allows investments to be compared and ranked according to their interest by discounting magnitudes of future years to the present time. In order to calculate the NPV it is necessary to know the discount rate, which represents the cost of funds for the company. The calculation of this rate is not easy in practice, so in most cases an estimated discount rate is used[5]. Today it is considered one of the best existing tools for economic comparison of projects and decision-making in the design phase.

- **Net Savings:** which represents the difference between the NPVs of two alternative options.

- **Pay Back:** which represents the time necessary for the repayment of the initial investment costs (discounted or not discounted). To adapt this concept to the cost study for decision making in the design phase, one could take as initial outlay the initial investment of the circular project and as generation of funds the difference in costs of the circular project with the base case year by year. If the generations are not the same each year (which is likely to happen), the system consists of accumulating the generation of funds until the initial disbursement is completed and calculating the moment this occurs. It is an indicator with weaknesses but is easy to obtain and understand at a general level. While the proposed adaptation for the analysis and comparison of costs between projects, it has a strong weakness that makes it not a good indicator. The main weaknesses are that it forgets the time value of money. At the same time, if a discounted pay-back is used, the advantage of clarity and simplicity of the method is partly lost, and there are better methods in the case of a discounted method. The second problem is forgetting what happens after the investment is recovered. If a project recovers in a particular year and from that year onwards has lower Cash Generations or (even negative) than another that recovers in the same year and that through the evaluation with this indicator appear to be the same. This criterion has gradually given way to other more sophisticated and useful ones. Although an adaptation has been proposed for the case of a cost study, it is neither valuable nor advisable to use this indicator for cost analysis due to the last-mentioned weakness.

- **Profitability index (PI):** Ratio between the discounted cash flow generation and the initial outlay, it is to put in the form of a ratio what the NPV puts in the form of a difference.

  $$PI = D/InitialInvestment$$

  When ranking and classifying projects, discrepancies can arise between PI and NPV. The NPV logic makes it the more superior criterion in most cases than the PI, except in an exception where there are limited funds, in which case the IR takes into account the initial investment,where it can be useful.

[5]depending, for example, on prevailing interest rates and risk where this is taken into account. If certainty conditions are used as an assumption, the risk-free rate is used, which is calculated on the basis of the interest on the state's financial assets,

- $(LCC - LCC_base)/In.Costs_base$[6]**:** If the ratio is negative, you will have more total costs than the base case, while if it is positive, you will have lower costs. In the comparison between models, the model that has a higher percentage will be the one that gives the best performance.
- LLC/LCC_base**:** It allows a direct comparison between projects; if the result is higher than one, the total costs will be higher than the base case, and if it is lower, it will have better returns; it also allows for comparing and ordering proposals.

As can be seen, for the pure study of the impact on economic sustainability in circular models, many of the more traditional indicators are still relevant either directly or by adapting them a little; even some that were not traditionally used in the construction sector (or in other sectors) are implemented in methods such as LCC to determine the total costs over the life cycle of a project, such as NPV, yet these (as NPV) are concepts that already existed and were widely used in other areas such as the financial sector; this does not detract from the fact that they are particularly interesting to implement in cost analysis, model comparison, and decision-making in the design phases of the building sector.

5.1.2.3 *Social Indicators*

To highlight from the literature that the social dimension is the least explored dimension so far, more and more studies are seen on the determination of relevant indicators. However, a comprehensive view of the social dimension of CE and the selection of indicators is still far from being achieved. Most studies focus mainly on the single study on the impact of employment, while there are many more areas of impact yet to be explored in more depth. When assessing the full impact of circular models on the social dimension with models such as the SLCA (Social Life Cycle Assessment), there is a gap in reaching a formal consensus on which social metrics and indicators are the most relevant, transparent, accurate and feasible, which does not allow this to be a sufficiently reliable tool for the time being.

Highlight the study **"Social circular economy indicators: Selection through fuzzy delphi method"** [66] It proposes an approach to identify critical social indicators through qualitative (Delphi) and quantitative (fuzzy logic) tools that objectively take into account the uncertainty associated with data collection and judgement making and the number of attributes (indicators) taking into account the vagueness of the data. This method also applies to the collection of indicators in the other two dimensions.

The indicators explored do not focus on the construction sector, but this method could be used to obtain relevant indicators in this sector. It also provides relevant information and indicators that can be extrapolated or considered. In the appendix A.2.27 the list of all evaluated and selected indicators can be seen. Although the proposed method can be interesting for future applications in the search for indicators, it is recognised that the study of indicators is confusing and does not provide relevant, easily accessible information on the indicators studied, nor does it detail or describe the proposed indicators or their use or mode of use, unit of measurement, etc.

Within the study of social indices, It would also be interesting to highlight the **Social City Index (SCI)** developed by the International Federation for Housing and Planning (IFHP) which deals with social sustainability[67]. It was specially developed to assess the macro-level, although they also advocate that it can be used at the building level with some adjustments to the indicators. The current index considers 35 different indicators at three levels: household, neighbourhood and city. However, all levels are represented at the

[6] Initial Costs (cost at year 0) of the base case.

case level (e.g. neighbourhood, city or national level). Many indicators are based on survey data, so collecting the necessary information can be quite extensive and time-consuming. Assess that it not only presents a single total aggregate index taking into account the 35 indicators it uses, but also presents its own index for each level studied, as well as evaluating the 35 indicators and also presenting its estimate [7]. A graph showing the final view of the index is attached in the appendix A.2.6.

It may be interesting to take into account some of the indicators used for future studies or implementation of social indicators in models that evaluate several dimensions.

5.1.3 High-level Indicators covering more than one aspect

5.1.3.1 *High-level circularity indicators covering the economic dimension*

Given the importance in this study of taking into account economic sustainability for decision-making in the design phase, it was decided to carry out a benchmarking of the different relevant high-level indicators that attempt to evaluate circularity and which, take also into account or cover the economic factor, as well as being specifically dedicated to the building sector [8]. Four are highlighted as the most relevant, the first two being particularly interesting.

1. **Modified Building Circularity Indicator (MBCI) [68]:** Assesses circularity and economic sustainability, for all levels of the building.

   Born as a development of the Building Circularity Indicator (BCI) [69]. Tool to assess the circularity of buildings at multiple levels. The basis of the BCI is the Materials Circularity Indicator (MCI) [70]. The MCI is complemented by the Disassembly Determining Factors index (DFF) [71], which together establish the Product Circularity Indicator (PCI). Products are also classified into systems based on the layers of the building system. The relative quantity of each product within the system is determined by its mass. The System Circularity Indicators (SCI) are multiplied by a lifetime factor resulting in the SCI score.

   The modified model tries to improve the tool as the theoretical BCI model only determines the level of circularity during the initial construction phase (the BCI assessment focuses only on the input of materials at the beginning of the manufacturing of a product and does not consider the materials needed during the entire lifetime of a product). The model presents the final results with a circularity indicator with values between 0 (not circular at all) and 1 (fully circular) and the NPV of the costs per scenario separately.

   Interesting in that it presents two final values for decision making and the idea of building the final indicator through the materials, products, and systems that form the layers of the building, breaking it down into different indicators for each level. It does not measure environmental and social impacts.

2. **Support for assessment of socio-economic and environmental impacts (SEEI):** Assesses circularity and sustainability both economically and environmentally. Evaluates all levels of the building. Indicator focused on decision making at the end-of-life of buildings, although it can also focus on other phases.

[7] It could also be considered an evaluation method instead of an indicator. It could even be categorised as an MCDM tool (section 5.2.5), as it deems multiple criteria to develop a final evaluation.

[8] it should be noted that some of them would also include other dimensions such as environmental or social.

Developed in the study ”Economic-Environmental Indicators to Support Investment Decisions A Focus on the Buildings’ End-of-Life Stage” [48]. It is a unique indicator that brings together environmental, economic and circularity factors for decision-making between different business models in the demolition phase of buildings. It expresses the result in easily comparable monetary terms.

It combines the results obtained by LCC for the calculation of costs throughout the life cycle of the product with indicators that evaluate the environmental impacts, EE[9] and EC[10] (obtained through LCA) and circularity indicators, RM[11], LD[12] and WP[13]. To monetise the impacts, it uses different proxies so that the results can be compared and adhered to with those of the LCC.

Clear, simple and logical, it also uses two widely used tools, obtaining a final indicator but being able to break down the results and use the indicators obtained separately. The use of other indicators for the evaluation of circularity, or even the use of social indicators, could be considered.

Easily implementable in companies already using LCA and LCC as they know how to apply these models and with which tools. It does not take into account the time value of money in assessing circularity and environmental sustainability indicators.

3. **Circular Building Assessment (Prototype) CBA(P) [35]:** Evaluates circularity and highlights the environmental and economic benefits of each proposal. Focused on decision making in the design phase. It takes into account the whole life cycle of the building to generate the indicator. Future advantage of being an online tool which will facilitate its use and standardisation.

   Designed for use in buildings (Building Level), it is a methodology that compares and assesses resource flows of products and materials over the lifetime of a built asset and beyond. This method is being developed into a prototype online tool that can quantify and compare design approaches, focusing on the difference between ’business as usual’ and circular construction scenarios. These include reuse of the previously built environment, design for future reuse through reversible building design, and the potential for transformation, highlighting the corresponding net environmental and economic benefits [35].

4. **Circularity Calculator (CC):** The only one of the four that is not focused on building use but is Designed for generic application by IDEAL & CO Explore Consulting Company [72]. It is intuitive and easy to use, as it is a semi-automatic calculation tool. Made specifically for the design process. Allows testing ideas quickly for the product and business model. Show the potential financial benefits of circular products. As a calculation tool, a licence is required.

[9] Embodied Energy, as [MJ/kg] and [MJ]
[10] Embodied Carbon, as [kgCO2eq/kg] and [kgCO2eq]
[11] Recycled materials index [%]
[12] Level of disassembly [Points]
[13] Wastes production [kg]

5.1.3.2 *High-level indicators integrating several dimensions of sustainability*

1. **Social Return of Investment (SROI):** This indicator takes as its starting point the ROI concept, which does not include the social and environmental dimensions, and tries to include them in it. In this way, it provides a broader framework and combines the three dimensions of sustainability in a single indicator.
This indicator is increasingly used, although there are models to estimate it, it is not entirely defined, so for its estimation all the assumptions and steps taken must be justified, so that when it comes to providing the information and results to third parties they are aware of precisely what is being measured. Very interesting indicator.

At a general level it can be argued that the model tries to measure the social, environmental and economic impact with different indicators and methods and after that, with the application of different proxies, it tries to monetise the environmental and social impacts so that they can be grouped together and finally calculate the SROI.

Standard calculation: "A guide to Social Return of Investment" defines the standard SROI framework and the steps to obtain the indicator. Although the steps for getting the indicator are outlined, many assumptions, calculation of the necessary KPI's and proxies used for standardisation fall on the side of the person conducting the study and are therefore subject to multiple interpretations. The model tries to standardise the process to some extent, leaving multiple decisions to the choice of the person developing the indicator [73].

Over the years, this process or model has been refined, and various proposals have been made to simplify and develop the model to deal with certain conflicts that could arise during its use.

CESME SROI "Circular Economy & Return on Investment Toolboox - Green and circular Assessment tool"[74]: It proposes a model for identifying business models using an online tool (Circular Economy Toolkit). Based on this assessment, it searches for different business models on which to apply the method developed for calculating SROI. SROI evolved from traditional cost-benefit analysis and social accounting through the mapping of stakeholder impact and the search for indicators to measure these impacts. In the end, each dimension is measured and standardised so that an indicator of the business model or project can finally be achieved. This model provides a clear framework for SROI calculation, however, by leaving the selection of indicators for the calculation of SROI to free choice, this method does not ensure that the concept of circularity is taken into account even if sustainability is measured; hence, a modified model is proposed based on this concept and model.

Terraética SROI: The Impact Measurement and Sustainability Consultancy "Terraetica". [75] It also proposes its framework for calculating the SROI, trying to simplify the steps of the original model. As main points for obtaining the indicators of the information necessary for the calculation of the SROI it proposes:

1. Establishing the scope:
   (a) Scoping through the theory of change[14].
   (b) Identifying stakeholders through "stakeholder mapping"[15].

[14] A theory of change is a methodology for presenting graphically, with a causal logic, the objectives that an intervention seeks to achieve and the concrete way in which it intends to achieve them.

[15] A stakeholder map is a visual representation of the type of relationship that stakeholders have with an

(c) Determine how each stakeholder is involved through materiality analysis. [16]

2. Mapping effects: by subtracting the effects of the applied model quantitatively or qualitatively through indicators.

3. Evidencing effects and adding value to them: Valuation and monetisation process through proxies[17]

4. Establish impact: Once the indicators have been monetised, calculate the total impact.

5. Calculating the SROI: By not using or assuming that indicators that estimate the costs in each of the three dimensions throughout the life cycle are not used, this study proposes at this point to project the monetary values obtained into the future by deducting a compound percentage year by year (due to the estimated decrease due to the effect in future years, contribution to change and effect if the activity does not take place), and to calculate an NPV on this projection, which will be used for the final calculation of the SROI. On what is proposed, an exciting and noteworthy point is to carry out a sensitivity analysis or other risk assessment if is necessary and useful.

    (a) Projecting into the future

    (b) Calculating the NPV

    (c) Calculate SROI ratio

    (d) Sensitivity Analysis

6. Reporting and using information.

These models are interesting but stand out for their ambiguity, the number of assumptions to be made during their estimation, the difficulty of assessment and implementation in companies, and the difficulty of transmitting the information, since to counter the resulting data (SROI) it will be necessary to know and understand how the indicator has been developed and all its characteristics. It also has specific weaknesses when it comes to taking into account the impacts throughout the life cycle in each of the dimensions; it is still a complex indicator, even with the modifications, although a correct application could lead to great results that manage to represent circularity and sustainability impacts at the same time.

---

organisation or project - and also allows for visual monitoring of the evolution of all these relationships over time.

[16] It is a process to identify the most relevant issues for the company and prioritise them, as well as to know which topics are of most concern to stakeholders and how they impact the business model and vice versa.

[17]

(a) Direct Proxis:
- Cost savings: Difference between the costs of the base case or model used so far and the proposed circular model.
- Marginal costs.
- Increased revenue: Extra revenue generated by the change to the new model.

(b) Indirect proxies
- Manifest preference: People's willingness to pay a certain price.
- Contingent valuation: Willingness to receive compensation.
- Disclosed Preference: Market Cost.

.

In some research, this indicator is defined as **Social-Environmental-Economical Return of Investment (S(EE)ROI)** even so, It is considered more accurate to call the indicator Sustainable Return of Investment, keeping the abbreviation (SROI), as it covers all three dimensions of sustainability.

2. **Lifecycle Savings to Extra Investment Ratio (LS(E)IR)**, for sustainability impact Assessment: The LS(E)IR was born as a proposal of this study after the analysis of the different high-level indicators reviewed, especially the SROI, with the objective of covering more than one dimension of sustainability at the same time, but also taking into account the lifecycle of the product or project in the same indicator. In addition to proposing some basic indicators from which to start calculating this index, so that it is more concise than the SROI.

It is based on widely used models, making it easier to incorporate in companies and to understand in environments where the most established impact assessment models are known.

In principle, the idea is based on taking the indicators obtained in the assessment using LCA and LCC, apply proxies to monetise the environmental indicators, bring them back to present applying discount rates and define the weights of each indicator to add them together [18].

The LS(E)IR could be calculated as the result of dividing the difference in total costs of a model versus a baseline model by the total initial costs in the assessed model.

$$LS(E)IR = [[(LCA^{19} + LCC^{20})_1 - (LCA + LCC)_Base]/InitialInvestment_1{}^{21}]x100[\%]$$

Ideally, to take into account the life cycle not only in the cost analysis but also in the environmental analysis, instead of monetising all the environmental impacts calculated with the LCA directly from both EE and EC, the results are monetise breaking them down year by year and bringing them to the present by applying a discount rate, following the same principle as NPV. Then they are added together, calculating the NPV of EE and EC (a NPV of LCA). So that it will not have the same impact, for example, to emit a certain amount of CO2 today than in 10 years.

[18] could be for instances:

- LCC: 50%
  - NPV
- LCA: 50%
  - EE: 25%
  - EC: 25%

[19] (25% x EE) + (25% x EC)

[20] (50% x NPV)

[21] sum of weighted initial economic and environmental costs (in year 0): $25\% x LCA(EE) in.Costs_1 + 25\% x LCA(EC) in.Costs_1 + 50\% x LCC in.Costs_1$

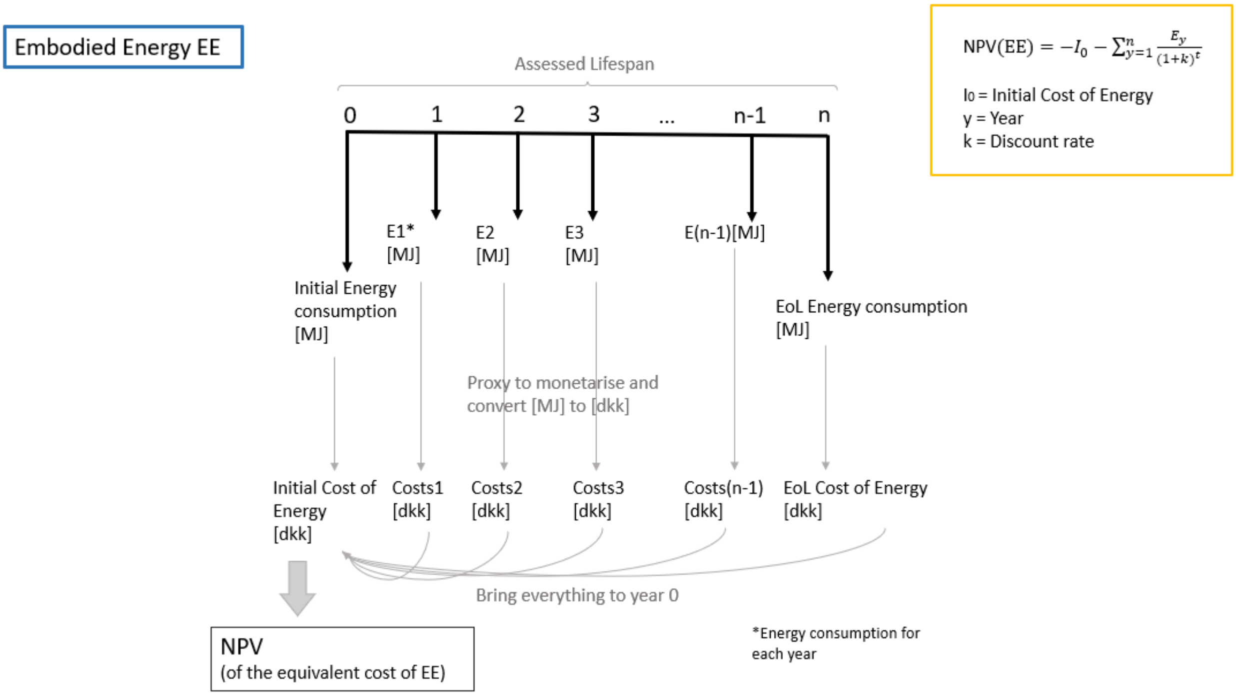


Figure 5.3: Proposal for the calculation of NPV equivalent (example for EE).Rest on appendix A.2.16

This proposal can be taken as a line of progress or development; it is perceived, among other things, that it would need to be adequately reflected upon and developed. Among other things, the weights of each indicator should be determined based on verified information. It also presents some key issues to be addressed, such as determining the discount rate[22].

Nevertheless, it is considered a proposal to think about and has the potential to combine in the same indicator at least the economic impact and the environmental impact throughout the life cycle[23].

Besides, by simply subtracting the total costs of the evaluated model minus the total costs of the base case, the "Net Savings" indicator is obtained which, when applied with this concept, adding the proposed environmental dimension and taking into account the time value of money for environmental costs, could generate a new **"Economical and Environmental Net Savings" (EENS)** indicator.

$$EENS = (LCA + LCC)_1 - (LCA + LCC)_{Base}$$

[22] For the discount rate some issues arise such as:

- What discount rate to apply to each indicator (in this case EE and EC)?
- Would it be sufficient for EE to apply a discount rate that takes into account energy inflation?
- How to estimate the discount rate for EC? Should it be negative?

[23] It would also be possible to integrate the social dimension into the final indicator in order to make it a complete indicator. To do this, it will be essential first to determine the key or most relevant indicators to assess social sustainability and to choose the weight of the final indicator.

The concept of using proxies to combine factors (in both indicators presented) is similar to that of the SEEI, the difference being that these do not add circularity indicators (as they may be more aimed at measuring impacts on the sustainability of circular models and not their circularity per se), as well as taking into account the time as a key aspect for the evaluation of environmental sustainability and not only for economic sustainability.

5.1.4 *Other Relevant Studies*

Other relevant studies have been found throughout the literature and are referenced and commented in appendix A.1.3.

5.2 Assessments Methods

Performance assessment methods can provide complex information and high-level indicators on sustainability impact and circularity for decision-making.

The main evaluation methods used today and from which many of the methodologies developed later will be taken as a starting point will be discussed below.

5.2.1 Life Cycle Assessment (LCA)

It focuses on the assessment of the environmental dimension.

LCA quantifies energy and environmental loads as well as potential effects of a product over its life cycle. In construction sector the environmental impacts, according to LCA standard, are usually calculated in terms of two indicators, Embodied Energy and Embodied Carbon.

The Embodied Energy (EE) can be assumed as the primary energy (MJ) contents obtained as sum of fuels production and delivery, the energy content of delivered fuels,energy use in transport and feedstock energy[24].

The Embodied Carbon (EC) is a measure of CO2 equivalent emissions related to energy production and delivery (kg CO2 eq) over years‘ time-horizon (usually 100 years).

LCA is a useful tool for reporting, improving and comparing EC strategies in sustainable performance. It can show how a specific functionality can be achieved, select the most environmentally friendly option from a predefined list of alternatives, or in which parts of the life cycle it is essential to improve a product to reduce its environmental impacts. It can also highlight situations where CE projects may be too focused on the ”circularity” of a specific resource and disconnected from its impact. [76]. Furthermore, this methodology is standardised (ISO 14.040-14.044: 2006).

LCA applications within the industry can serve more than one purpose (assessing site impact, total project impact, comparing possible impacts on decision making of a particular product for the site, etc.) and they can also be applied at different stages (design stage, monitoring, final impact assessment). Besides, the same LCA can even be used for other purposes within the same company or project.

[24] The total EE, can be divided or calculated directly as[48]

- Initial: The primary energy demand is required for on-site and off-site construction processes, including extraction of raw materials, manufacture of components, final assembly of products and transport.
- Recurring: The primary energy demand is required in refurbishing and maintaining the building over its life cycle.
- End-of-Life: The primary energy demand required for the building final disposal.

Embodied carbon (EC) can also be divided into initial EC, recurring EC and end-of-life EC [48].

”Life Cycle Assessment Theory and Practice”[77] is a reference book for the application of LCA, with how and forms of application and interpretation as well as an introduction to other methods such as LCC, an introduction to the S-LCA concept and information on how to apply LCA in building in particular.

LCA Analysis: One of the main strengths of the LCA is its exhaustiveness in terms of life cycle perspective and coverage of environmental issues. This allows comparison of the ecological impacts of production systems composed of hundreds of processes, accounting for thousands of resource uses and emissions in different locations and at other times. Exhaustiveness is also a limitation, as it requires simplifications and generalisations in modelling product systems and environmental impacts that prevent the LCA from calculating actual environmental impacts. Another weakness is that impacts are aggregated over time, giving the same value to emissions today as in 30 years. It is, therefore, more correct to say that LCA calculates potential impacts, taking into account uncertainties in the mapping of resource uses and emissions, modelling their impacts, and the fact that the calculated impacts are aggregated over time [77].

Another strength in benchmarking is that the LCA follows the ”best estimate” principle. This means that the same level of precaution is applied throughout the impact assessment modelling, so the comparisons are not biased. However, a limitation related to following the ”best estimate” principle is that LCA models are based on average process performance, and a regular application of the model does not consider risks of rare but problematic events that may occur. A final limitation is that, although LCA can tell what is best for the environment, it cannot tell you whether better is ”good enough”. Therefore, it is wrong to conclude that a product is environmentally sustainable, in absolute terms, by reference to an LCA that shows that the product has a lower environmental impact than another [77].

5.2.2 Life Cycle Costing (LCC)

It focuses on the assessment of the economical dimension.

The LCC quantifies the total cost of what is being evaluated, throughout its entire life cycle, calculating the total economy of the same, for which the result is expressed at a monetary level and updated to the present time, taking into account the time value of money. The main indicator is therefore the Net Present Value (NPV)[25].

Like LCA, conducting an LCC can serve different purposes. It can be used, for example, as a tool for planning, optimisation, identification of hotspots, as part of a life cycle sustainability assessment of a specific product, or to evaluate investment decisions.

Three main variants of the LCC can be distinguished [77]:

- **Conventional/Financial LCC**: Is the original method, only internal costs are considered and in many ways synonymous with Total Cost of Ownership (TCO)[26]. In conventional LCC, external costs are usually not included. Conventional LCC is mainly applied as a decision-making tool.
- **Environmental LCC:** Is aligned with LCA in terms of system boundaries, functional unit, and methodological steps. If the external costs are already expressed in some monetary unit, they can be included in the environmental LCC.

[25] NPV: Represents the amount of discounted cash flows.

[26] TCO is the cost to buy something plus the cost to operate it over its useful life.

- **Societal LCC:** Includes monetarisation of other externalities, including both environmental impacts and social impacts. Externalities can be monetarised and included in the assessment.

LCC Analysis: The industry is increasingly considering LCC as a decision-making tool for the sustainable design of new buildings. There is significant potential for LCC-related collaboration in both the publication processes of a new project and in the early design of the building project. However, LCC analysis requires data that is not often available, especially in the early stages of design [78].

On the other hand, it must also be taken into account that today, as a rule, the short-term approach to the construction budget is still a barrier. The construction sector is characterised by a short-term focus on the construction budget rather than a long-term total economic approach, including the operation, recycling and conservation of construction resources.

There is a high probability that over time, due to the current need (scarcity of primary resources) and the interest shown in the sector, there will be a greater focus on total economy and resource conservation.

However, several actions would need to be taken in all processes and from both sides to enable the exchange of information and data and to facilitate the implementation of models such as LCC. By improving collaboration with building clients, architects will have access to building performance information that can be used effectively in architectural design, improving the sustainability of buildings [78].

5.2.3 Social Life Cycle Assessment (S-LCA)

It focuses on the assessment of the social dimension.

The ambition of the S-LCA is to be a methodology that, if followed, will lead to an assessment of the social impacts of a product throughout its life cycle [77].

The main driver for the development of S-LCA so far has been to create a social assessment method that mimics as closely as possible the principles of LCA with a view to a possible integration of the two. Also recognising the importance of a life cycle perspective for social impacts, as it is for environmental impacts.

A fundamental problem with following this path is that the significant differences between environmental and social issues may be overlooked in establishing S-LCA as a clone of LCA and with the risk of ingonising on some social science developments.

Thus, the development of S-LCA could take two forms (or a combination of the two) [66]:

- The current trend of imitating LCA may continue, which will require further research in areas such as indicator development, modelling of characterisation in LCA, establishment and validation of impact pathways, aggregation procedures, standardisation references and valuation methods.

- It may recognise existing social science research more broadly, raising fundamental questions about the methodology foundation. It would lead, to revisiting recent concepts of human different social aspects to inspire a redefinition of an integrated set of social impact categories.

Regardless of the pathway, S-LCA must be a life-cycle oriented methodology aimed at social assessment in order to maintain its purpose.

S-LCA Analysis: It is still a method under development and is currently not well defined, neither in terms of indicators nor process.

As in the case of LCA, the model will entail significant data requirements and processing time.

It should be noted that social tools, such as social life cycle assessment, have a high potential to contribute to the evaluation of circular economy strategies by visualising their impact on the social dimension of sustainability, given that they include a life cycle perspective and have a multi-stakeholder assessment. Still, more efforts are needed to determine whether the social benefits of CE can be quantified using social life cycle assessment. Social tools can also help to compare linear and circular economy strategies. [66].

5.2.4 Life Cycle Sustainability Assessment (LCSA)

It tries to assess at the same time the three dimensions of sustainability.

To this end, it is proposed to standardise the results of LCA, LCC and SLCA so that they can be aggregated to form a single result that encompasses social, economic and environmental aspects at the same time. Based on the TBL interpretation of sustainability.

$$LCSA = LCA + LCC + SLCA$$

Usually, normalisation is performed in which economic values for both LCA and SLCA are calculated using proxies to quantify and add together easily.

LCSA Analysis: As for strengths, it allows comparing different circular strategies with a single indicator that combines the three dimensions of circularity simultaneously, without the need to evaluate the results of each dimension separately.

For weaknesses, it presents that one of the three models (SLCA) is not very standardised and defined and leaves many points to interpretation, such as its application, indicators to be used and appropriate proxies for these indicators.

On the other hand, many questions about what the weights of each dimension in the final result should be, whether the standardised results should be added directly or whether the number of indicators assessed should be taken into account, and also whether giving the final result in monetary value might not be realistic, especially when inserting social valuation.

Many also argue that double counting may occur when adding the standardised LCA values to the LCC values, as environmental costs may be valued indirectly through cost analysis.

On the other hand, following the models, in principle, LCA and SLCA do not take time into account. However, one could try to normalise the results of both methods year by year and then update them to the present time taking into account the time value of money. This would complicate the process a little more.

It is still a method with much potential to be discovered and room for improvement.

5.2.5 Multi-criteria approaches (MCDM)

Multi-criteria decision-making is a research discipline that evaluates multiple conflicting criteria in terms of their performance on a set of decision-making criteria. In the building environment with the objective of evaluation, it would, in principle, serve to compare proposals, projects or products; depending on the method followed or developed, it could also give an independently assessable valid indicator, but in principle, it is a model specifically designed for decision making.

When evaluating with MCDM, it is necessary to establish a set of criteria, determine how they are considered and weighed, and then rank them according to their performance on each bar.

There are many different multi-criteria methods and depending on the interests and their application new methods can be developed, all of them follow in principle the following basic structure:

1. Selection of the reference scale for indicators
2. Selection of evaluation criteria (indicators)
3. Collection of information
4. Give value to indicators (Evaluation)
5. Weightings of indicators
6. Obtain and interpretation of the results

Considering the intrinsic complexity of circular systems, several authors adopt multi-criteria and fuzzy logic approaches to evaluate them [76].

The general development of an MCDM has been explained. However, as mentioned, many models can be called MCDM and follow this methodology or approach, even if they are known by themselves and not as MCDM methods, among them some standardised and well-known tools and different certifications (e.g. DGNB).

5.2.6 Stratified Multi Criteria Decision Making Method (SMCDM)

To highlight this method as a development or extension of the traditional MCMD methods where uncertainty in the decision-making process is included, an exciting concept and even adaptable to other models. The procedure is briefly explained below.

The method takes different states starting from the base state that will form the first layer. Each new state will be based on a setpoint or event with a certain likelihood of occurrence; this event will change the weights of the indicators or even their internal values. Each new state will be given a percentage of the affair. In this way, the second stratum is created. Other strata can be developed with the combinations of states represented as a combination of events.

In case these strata formed by combinations are dependent on each other, the same process will be followed as in stratum 1 and 2, where a likelihood is given to each state. At the same time, if they are independent or very little dependent (they do not have a significant impact on each other when they occur together), the transition probability between states will be a multiplication of the events that create that state.

Finally, the relative probabilities of state one are computed, thus obtaining a polynomial equation that can be solved to get each state's possibilities. Finally, the weights obtained for each criterion can be calculated using matrices, and the options on which the decision is to be made can be evaluated so that the final evaluation has considered future probabilities and uncertainties in calculating the weights.

It is a process with the added difficulty of estimating the possibility of each event occurring and of re-evaluating the weight of the indicators in each scenario. At the same time, it is advantageous to highlight the insertion of uncertainty and risk in the evaluation model, which is not generally taken into account or to present several scenarios (pessimistic, optimistic and standard).

5.2.7 Other Assessments Methods

Other relevant assessment methods that could be used, adapted or developed for evaluating circular models, both at the level of the design phase for decision-making as well as for the implementation and control phases, are presented below.

It has been decided not to develop or carry out a very exhaustive analysis of these methods as they are the least important for this study and in the literature for the analysis and evaluation of circular models. However, it is interesting to mention them to be aware of them, and in case we want to take them into account in future studies or developments:

- **SAVE**: The Study of Architectural Values of the Environment (SAVE) system is a tool for mapping the architectural, cultural-historical, environmental, originality and condition of buildings and urban environments. The SAVE value is applied in district plans and development plan schemes. The municipality is responsible for the survey. No certification is required.

- **Input-Output models (I-O)**: Input-Output analysis is a traditional method that is easily applicable and can be taken over by circular models to measure and evaluate the variables involved in a system, whereby certain values and indicators are of interest. It can be combined with other evaluation methods to achieve impact results.

  It exists an environmental input-output approach that is called ”environmentally extended input/output analysis” (EEIOA). This is a top-down approach that also allows the construction of an inventory that can be used in an LCA alternatively to the original one[77], (build the LCI from the LCA). Used well, it can be a faster and more efficient way to calculate the inventory.

- **DEA**: Data Envelopment Analysis (DEA) is an analytical tool that can help identify best practices. In a way that highlights potential efficiency improvements that can help agencies achieve more significant potential. It can be developed from an I-O or MCDM model approach.

- **Material Flow Analysis (MFA)**:It is a method with similar principles to I-O and DEA. Like them, it also considers all the variables involved in a system throughout the life cycle from an environmental and economic point of view.
  Experts do not as commonly adopt MFA to assess the performance of CE.

- **Balance Score Card (BSC)**: The BSC or Balanced Scorecard (BSC) is a management model that allows the company’s strategy to be translated into a series of interrelated objectives, which are measured through different indicators and which are linked to specific action plans that will enable the behaviour of the members of an organisation to be fully aligned towards the achievement of its fundamental objectives [79].

  This model does not directly apply to decision-making in the design phase but is more directed to strategy control.

5.2.8 Danish Standard

The Danish and European standards (DS/EN) also provide a framework for assessing the sustainability of buildings. The standards do not offer benchmarks or performance levels like normal building codes. Their purpose is to facilitate the comparison of sustainability assessments by defining indicators, dictionaries and systems.

5.2.9 Certifications and quality labels as analysis methods

Certifications and declarations connect different tools and parameters that establish an area or building score. Some fall into one sustainability group; others cover several or all of them. They are carried out by external auditors.

The various labels, certifications and declarations could also be used to evaluate and monitor strategy and decision-making. Their use could be assessed for decision-making at the design stage, with pre-certification and intermediate certification possible for specific ones. In principle, these tools could be rigid and slow. They cannot be used internally for design processes where fast and flexible analyses are needed to provide decision-making information. In principle, these tools are not recommended for evaluation and decision-making in the design phase.

5.3 BM's evaluation methodologies

It should be noted that there are a series of methodologies and guides that are used for the evaluation of business models. It should be stressed that these are not assessment methods but a series of recommendations on the presentation of models, indicators and performance assessments to be used to evaluate business models with them.

The ”Template business cases for built environment” [80], developed by the CIRCuIT project is highlighted.

5.3.1 D7.2 Template business cases for built environment- CIRCuIT Project

Guide for the presentation of results where recommendations are given for the measurement of impacts, proposing to present them as a comparison on a base case to provide the advantages of the proposed system.

Decision-makers can use it to assess and demonstrate the broader impacts (both environmental and economic) of projects in a way that provides evidence that the project is a good investment for both the funding partner and the community through consideration of life-cycle cost and environmental performance.

The template covers the mission statement, objectives, technical analysis, and performance measures. This is interesting as it guides the development, standardises the necessary information and facilitates the understanding of the results by creating a format and presenting information that contextualises the results.

Environmental analysis: It recommends a series of circularity indicators [27] to finally calculate the environmental savings between two projects as tonnes of waste material and kgCO2eq saved.

Economic analysis: For the economic analysis, it proposes the use of the LCC (without determining which type of LCC to carry out). All results should be provided in the present value for comparison, which is not defined in the template and should be determined. The

[27] Leaves it up to the decision-maker which ones to take and complete and which ones to give more relevance to depending on the project and how to elaborate or measure them.

proposed effects presentation may not be well adapted to all projects. chapter 6. However, the final indicators proposed to be achieved (Initial Cost and NPV) are considered to be the most relevant for feasibility analysis.

It is assessed as interesting to present results in a standardised way. It could be completed by proposing a final indicator encompassing environmental and economic impacts.

5.4 Partial conclusions

In conclusion, the analysis done in the third block of ”Results 1”, allows to get an idea of the great variety of indicators that exist, and serves to go over the main ones observed in the literature related to CE and the Building sector.

Secondly, this analysis provides an insight into the main current assessment models, with particular emphasis on the most relevant ones for measurement and decision-making at the design stage.

The study has also led to two proposals for high-level indicators (the EENS and the LS(E)IR), taking concepts from other indicators studied as a reference for elaboration.

Besides, the analysis has provided insights into the real options when selecting the method and indicators for the case study. As the objective of the case study is economic evaluation, the analysis chose the conventional LCC model with NPV as the main indicator because of the qualities presented for decision-making and their feasible integration with other indicators and models.[28].

To conclude, it is still necessary to make further progress in research and, above all, in the implementation and real applicability of the models in order to see their real adaptation and their capacity for evaluation in circular projects. In addition, it will be essential to have professionals who know how to decide between indicators and methods and put them into practice.

5.5 Actual usefulness of literature analysis (”Results 1”) in addressing the case study (”Results 2”)

Through the three blocks presented in the first part of the results, ”Results 1” [29], the literature has been analysed, reviewed and organised to offer a series of recommendations and proposals throughout the study.

This allows to better address the realisation of the second part of the project, in which a case study for the evaluation of circular business models in the design phase is carried out. It has also allowed some decisions to be taken for its development:

- Use of the Circular Canvas for the first iteration of the case for model design.
- Use of the proposed strategy classification for the elaboration of case-specific circular business models.
- Application of the conventional LCC model for the economic evaluation of the case using the LCCbyg tool.

[28] In addition, the study has provided insight into other indicators to be used in the case, such as ”Initial Cost”, ”Residual Value”, ”Net Savings”, and other low-level indicators.

[29] Transition to CE in the Construction Sector, Business Models and Evaluation and Measurement as Design Parameters.

6 RESULTS 2 - CASE STUDY

The aim of the case study is to:

1. *Study for Arkitema the economic feasibility of applying different circular models to Gadehavegård's roof tiles.*
2. *Study the potential economic interest in applying circular strategies in the Danish building sector in refurbishment phases at present.*
3. *Apply in practice some of the theoretical models and tools studied, their usefulness and consistency.*
    - *Study the advantages and usefulness in a real case of applying the LCC model for decision-making in the design phase.*
    - *Study the usability of the LCCbyg tool.*
4. *Address in economic analysis the problem of poor availability of data in the design phase.*

6.1 Context

6.1.1 Gadehavegård

Gadehavegård is a social housing project built between 1977 and 1981 and renovated in 1999/2000, located in Høje-Taastrup, a peri-urban area 20km west of Copenhagen city centre in Zealand, Denmark. With an area of 72,000m2, 19 blocks of buildings and 2,133 residents. This project was created in the modernist ideal of separate functions, uniform and space-efficient buildings, with large open areas between the buildings and compact blocks. The construction is based on concrete modules and sandwich facades.

Gadehavegård was included in the ”Ghetto List” in 2018, which set out specific demands for transforming 15 listed areas. This included demands for the demolition or remarking of 60% of the dwellings in the affected areas[1].

Currently 95% of the stock in this area is social housing. In the areas on the list, the housing needs to be transformed so that maximum 40% is social housing. The aim is to create greater diversity among those living in the areas by requiring different sizes of flats, a mix of rented apartments and private residents alongside family, student and senior housing, and the task of solving this from a human and resource-saving perspective.

6.1.2 Arkitema Architects and Strategic Plan

Between 2020 and 2030, the buildings will be renovated, and the area will undergo a radical transformation according to a strategic development plan. Not only is Gadehavegård listed as one of the 15 most run-down social housing estates in Denmark, but there is also a marked need for renovation and adaptation of the ageing buildings. Several parts of the buildings are in a high level of functional degradation, and the area needs a social effort.

[1] In the publication ”Ressource Blokken” [81] the 15 social housing areas on the ”Ghetto List” were examined. The map underlines the need to develop strategies and methods for directly recycling the affected buildings in the areas where the site's development has been imposed to create a socio-economic change. In total, 1,360,300 m2 are demolished, and more than 724,300 m2 are built. The map also shows that redevelopment of the areas has resulted in different approaches, from no demolition to proposed new construction.

The main consultants for the project are ”Arkitema Architects”, direct collaborators in this case study. Arkitema is in charge of developing an urban plan and the complete rehabilitation and refurbishment of the buildings and green spaces in the area.

The overall renovation of the existing buildings aims to secure the future of the heritage and extend the life cycles through a thorough interior and exterior renovation. The renovation is intended to improve the damage to the building and contribute to eliminating the identity as a ”Ghetto” transforming the area into an attractive, open and welcoming residential area.

the strategy for the area is to take the existing housing area and refurbish, renovate, demolish, re-brand, merge and build new housing so the densification and housing type composition is changed, with the aim of saving human and material resources and emissions. (appendix A.2.17).

The district will have an urban main street running through the centre of Gadehavegård, which will function as the backbone of the area. The buildings will be located along this main street.

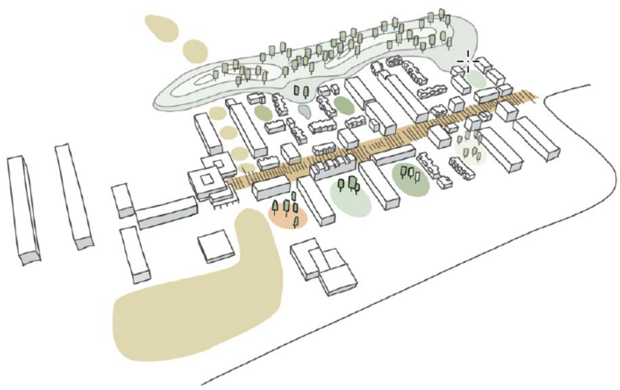


Figure 6.1: Sketch of the neighbourhood and the main street proposed

With the existing objective of minimising the use of new resources, it can be seen that in Gadehavegård, in addition to applying a strategy of minimising demolition and prioritising renovation, there is also the possibility of reusing materials from demolished buildings. In this case, the cycle prioritises on-site use, while eliminating waste and transport.

Gadehavegård currently has nineteen blocks, two of which will not be part of the project as they will be sold (block one and block twelve), and the materials from them cannot be reused. Others will be completely demolished to make way for new construction. After the completion of the project, the same number of final blocks (nineteen) will be reached, but with different characteristics and dimensions. The Gadehavegård project is intended to be carried out in three construction phases. In each phase, different blocks will be demolished or renovated.

6.1.3 Technical specifications and needs of the buildings

The blocks are constructed in concrete elements with load-bearing cross partitions. The roofs and entrance facades are made of sandwich elements. In contrast, the garden facades are made of lightweight components and a ”balcony system” consisting of load-bearing balcony walls and concrete balcony bases spanning the entire block length. It is a building system with a high degree of homogeneity of façades and very limited variation.

In the 1999/2000 refurbishment, new roofs were added on top of the original flat roofs and the façades have added latticework, which descends over the entrance façades. Still, both the facades and the roofs of the buildings that will not be demolished, have to be renovated again due to their level of degradation. At the same time, Arkitema considers that the appearance of the 1999/2000 renovation spoils the original, rationally assembled architecture.

The renovation of the undemolished blocks will solve the problem of concrete damage, snow ingress on the roofs, insulation and waterproofing layers. This will improve the energy consumption and architecturally boost the building.

6.2 Introduction and Requirements

Within the project context, the aim is to study the economic interest of applying circular models in a way that tries to achieve the sustainable objectives without compromising its economic sustainability.

When dealing with a social housing project, some extra considerations come into play, such as user participation, project economics, re-housing of residents while renovating, tendering strategy, process plan, etc. All factors can influence the possibilities and ways of working with the circular renovation strategy.

Particularly in this case, the economics of the project acts as a limiting factor, and is of particular importance. User participation will also shape, among other things, the perspective finally applied to the case [2].

Therefore, this study focuses on finding an economically attractive circular business model for the roofs of Gadehavegård. It focus on the roof skin, consisting of cement tiles, which through structure mapping has been shown to have the potential for recovery. This is to be achieved by:

1. Developing different circular BMs to provide solutions for roofs.
2. Studying and analysing the total costs of different circular models, whether the current tiles can be used in an economically sustainable way while maintaining the project's objectives of reducing resource consumption and waste generation.

Figure 6.2: Aerial view of the roofs of Gadehavegård

[2] The rest, although not taken into account in the direct elaboration and scope of the case, will have an impact on the project.

6.3 Preliminary Analysis

6.3.1 Technical specifications of the existing roof

All the buildings have the same type of pitched roof with a domed or vaulted area and skylights. In the domed, the roof has problems with snow entrance, in addition to the fact that some of the layers of the roofs are of low quality and are in a high state of degradation and deterioration making necessary to renew them again.

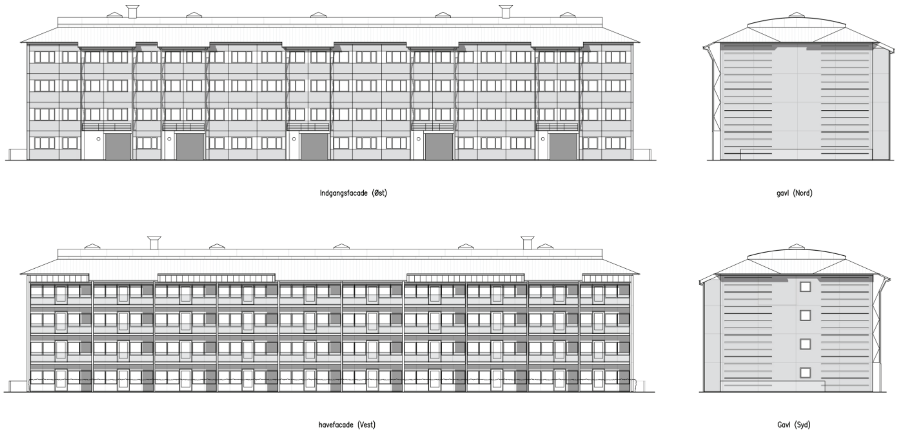


Figure 6.3: Representative unit plan. Front and side views

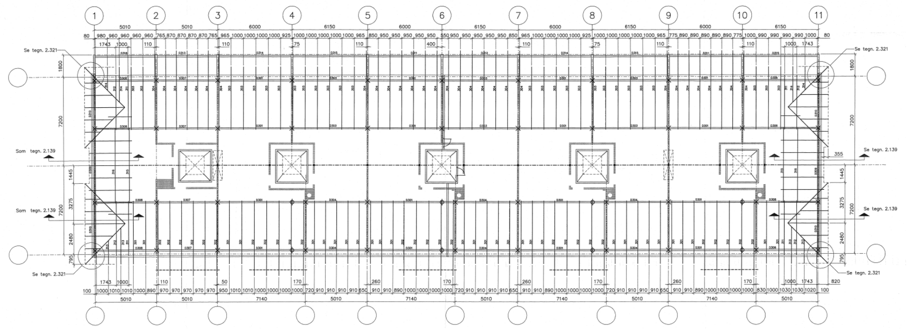


Figure 6.4: Representative unit plan. Top view

The skin of the roof skirts (the sloping part of the roofs) with slopes of 25%, is made of double concrete tiles in the form of an "S" as shown in the figure (fig. 6.5). These tiles are resting on wooden slats with nailed fastenings (fig. 6.6).

Figure 6.5: Double S-shaped Tile

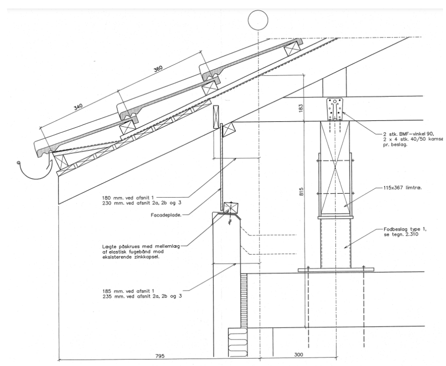


Figure 6.6: Roof. Detail view

Underline that the original roof (1977-1981) was a flat roof with rainwater drainage and accumulation problems. It was therefore encapsulated in the current roof solution in 1999-2000.

6.3.2 Roof renovation plan

To solve the current problem, it was decided to remove the dome from the roofs. The aim is to use part of the structure to rebuild pitched roofs with a traditional ridge, maintaining the roof's slope and using a single material as the roof skin product. All current overhangs will be removed. In addition, the insulation layer currently located on top of the 60-the 70s encapsulated roof and the rest of the layers, such as the waterproofing sheet, will be renewed.

As can be seen in the following drawings, starting from the present roof (fig. 6.7), part of the roof and its structure is dismantled, as well as demolishing other parts of the building such as the balconies, part of the façade and the cantilevered roofs (fig. 6.8). Maintaining, however, a large part of the original structure of the building on which the renovation will be carried out with the technical solution shown in the fig. 6.9. As already mentioned and as can be seen here on the plan, in this solution, the main renovations are carried out on roofs, façades and balconies.

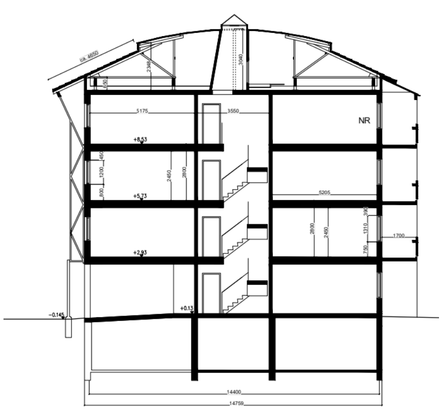


Figure 6.7: 1. Present situation of the buildings

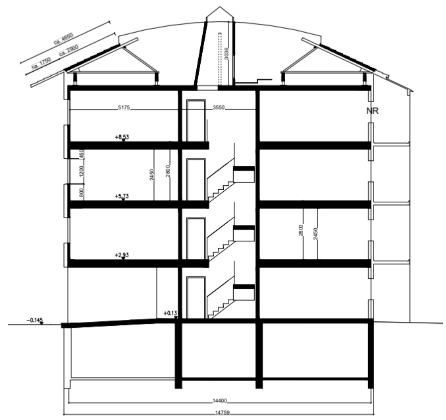


Figure 6.8: 2. Building Under renovation. Removal of parts of the roof, overhangs, façade, lattice and balconies.

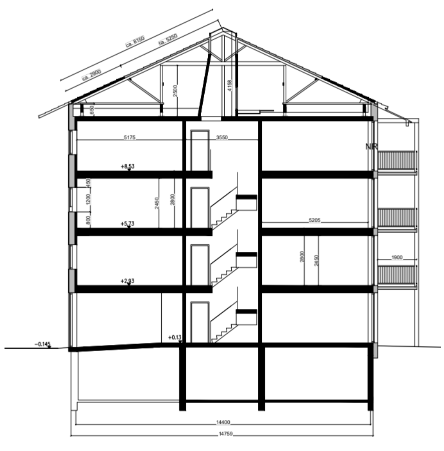


Figure 6.9: 3. Building after renovation

Of the total number of buildings to be renovated, the blocks in which the pitched roofs will be preserved amount to twelve, all part of undemolished buildings.

6.3.3 Ex-ante calculations and discussions

First, measurements are made on a plan of the current district, and a series of calculations are carried out according to the following equations (fig. 6.10) to map the tiles available and see if an on-site reuse strategy could be studied later and implemented in the project.

In this way, it is estimated that there are currently around 12,82.74m2 of roof tiles available for the project[3], as seen in the table below (fig. 6.11).

$$Average\ Slope\ [m] = 2 * \sqrt{(\frac{A.Width}{2})^2 + Height^2}$$

$$Internal\ Slope\ [m] = 2 * \sqrt{(\frac{I.Width}{2})^2 + I.Height^2}$$

$$A_{Total}\ [m^2] = A.Slope * Length$$

$$A_{Tiles}\ [m^2] = I.Slope * I.Lenght$$

$$A_{Tiles}\ [m^2] = A_{Total} - A_{Internal}$$

Figure 6.10

Height [m]	4,158
Average Width [m]	17,75
Average Slope [m]	**19,60**

16,75 18,75

Internal Height [m]	2,2
Internal Widht [m]	9,75
Internal slope [m]	**10,70**

Block	Length [m]	Total Area [m2]	Internal Length [m]	Internal Area [m2]	Area with tiles [m2]
A1	122,35	2398,24	115,35	1233,88	1164,36
A2	122,36	2398,44	115,35	1233,88	1164,56
B1	146,45	2870,64	139,45	1491,68	1378,96
1	51,05	1000,66	44,05	471,20	529,46
2	48,92	958,90	41,92	448,41	510,49
3	51,05	1000,66	44,05	471,20	529,46
4	36,95	724,28	29,95	320,37	403,90
5	61,07	1197,06	54,07	578,38	618,68
6	51,05	1000,66	44,05	471,20	529,46
7	36,95	724,28	29,95	320,37	403,90
8	61,07	1197,06	54,07	578,38	618,68
9	75,35	1378,91	68,35	731,13	647,78
10	61,07	1197,06	54,07	597,99	599,07
11	87,45	1714,15	80,45	860,56	853,59
12	87,45	1714,15	80,45	860,56	853,59
13	36,95	724,28	29,95	320,37	403,90
14	61,25	1200,59	54,25	580,30	620,29
15	36,95	724,28	29,95	320,37	403,90
16	61,07	1197,06	54,07	578,38	618,68
Total		**25321,34**		**12468,60**	**12852,74**

Figure 6.11: M2 of tiles available on the current roofs

[3]Net value (without taking into account the actual losses due to the damaged tiles)

While, if all the roofs with pitched roofs were to be renovated, a total of 10,404.92 m2 of tiles would be required. To estimate the total area needed, measurements were taken on the project plan, and estimates were made using the following formulas.

$$Slope\ [m] = 2 * \sqrt{(\frac{Width}{2})^2 + Height^2}$$

$$A[m^2] = Slope * Length$$

Figure 6.12

Height [m]	3,508
Width [m]	14,75
Slope [m]	8,15

Block	Length [m]	Area [m2]
A1n	24,4	397,72
A1s	60	978
A2s	60	978
B1n	66,5	1083,95
B1s	24,2	394,46
2	47	766,1
5	59	961,7
8	59	961,7
11	85,5	1393,65
14	59	961,7
15	34,8	567,24
16	59	961,7
Total		**10405,92**

Figure 6.13: M2 of tiles required for the proposed roofs

At first glance it can be seen that the total number of tiles available (12,852.74m2) is greater than the area of tiles needed to undertake a complete renovation of the roofs with tiles reused from the same area (10,405.92m2). In addition, it must also be taken into account that due to the plan applied in the project, different finishes are to be applied with the intention of giving the blocks and the neighbourhood their own identity, so that of the 12 buildings in which the pitched roof will be maintained, only a few (we assume a maximum of a third of them, 3.468m2) will be interested in applying this strategy. However, certain factors must be taken into account that will determine the decisions to be taken in the project:

1. Of the total number of tiles available, it must be taken into account that a percentage will be in poor condition and therefore cannot be reused. In the process of dismantling and storing the tiles before they are reused, another percentage of losses will also be incurred. After conversations with professionals in the sector, it is estimated that the total losses will be 30%, with a total of 8,997m2 tiles available.

2. It is necessary to study and take into account the phases of the project, and at what points of the project the demolition, construction or renovation of each building will take place, to see if the number of tiles available at that moment will be sufficient or not.

These preliminary analyses shows that it is possible to apply this reuse strategy to the area, but that it will be necessary to have a proper organisation plan to evaluate and take into account these factors in the strategic plan (along with other factors in case other materials want to be reused in the renovations).

6.3.4 Scope

Taking these comments into account, it was decided with Arkitema to carry out the main case study on ”Block 8” of the district, for the main study of the roofs. Since it is a representative building in the area for the following reasons:

- **Second phase block:** The refurbishment of ”Block 8” will be carried out in the second construction phase, so without the need to study the number of tiles already removed from the roofs, the availability of these tiles for the project is assured.
- **Representative block for its roof dimensions:** There are quite a few blocks with these dimensions at the moment (five), and quite a few blocks are planned with the exact final dimensions as block eight (six), which is an average size within the existing stock of buildings.
- **Reformed block:** This is one of the blocks that will not be demolished or reduced in size, as well as remaining with a sloping roof.

It should be noted that the buildings will be renovated in such a way that it takes two years from dismantling the tiles to installing the renovated roof. In this case, in ”Block 8”, the roof will be dismantled in 2023, and the roof will be renovated in 2025, which will have to be taken into account in the business models as it can have a significant impact.

6.4 Business Models

In this section, business models for the tiles of ”Block 8” have to be sought to later determine their viability from the total cost study.

Three business models are identified and presented. From these, different and more concrete proposals will be selected to analyse and compare them with each other and with a conventional roof renovation model after economic evaluation.

6.4.1 Process for developing the BM’s

As discussed in the conclusions of part 1 of the results, the practitioner has to be the one to select the method and way to analyse and develop the business models, taking into account the concrete case and its particularities.

A first iteration is carried out with a Circular Canvas of easy application and development for a first approach and analysis that allows seeing the interests and possibilities, this iteration is presented in appendix A.2.18.

As this is a very focused case, it is decided that after this first iteration that allows framing and highlighting the potential possibilities and with the relevant analysis of the same, the first selection of strategies (with the help of the list of strategies developed in this project) and development of business models will be carried out directly. After this and discussions with Arkitema and the second debugging of these strategies and specific models, it is unnecessary to carry out a second iteration of the framework for each model. The business models can be developed directly and presented graphically for communication[4].

[4] In more minor well-defined cases, broader or approached from a different perspective, it may be interesting to select other frameworks or to carry out several iterations and elaborate a final framework for each

6.4.2 Base Case - Linear BM

The base case represent the main steps that would be followed for the refurbishment that follows the known process, without considering the concepts of circularity.

Figure 6.14: Base Case

This base case will be used to check the actual economic interest that can be generated by the application of circular processes at the product level. It will be used to compare with the other proposed Business models. Later this model will be converted into costs, and the remaining costs during the period evaluated for the realisation of the project will be added for the performance assessment.

6.4.3 Circular BM 1

The BC1 proposes to extend the life of the tiles in the building by reusing them in the new roof, by taking them down softly (Selective Demolition), cleaning, and re-installing them again.

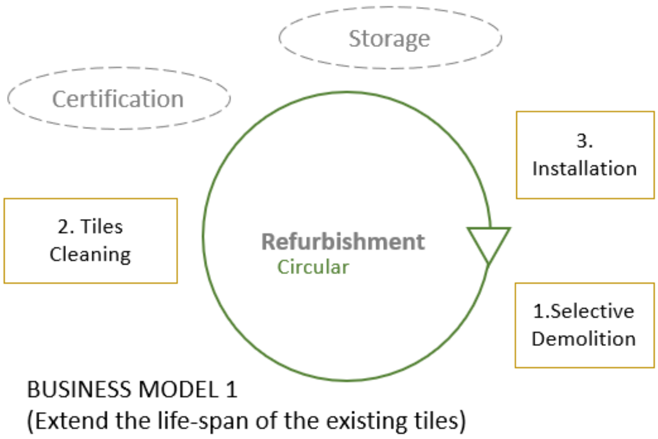


Figure 6.15: CBM1

Although, they are not finally considered in the cost study, as will be seen later on, it is interesting to take into account and evaluate the interest of certifying in some way the tiles that are going to be used, ensuring certain qualities (this can be tried to be done when testing the condition assessment tiles); with a view to the strategy or in the event of finally tackling this model.

Attention will have to be paid to the additional costs of tile removal and cleaning, taking into account the product's contained value and the project's lifespan. Other important factors

model developed to visualise better, communicate and analyse the models presented as well as to be able to rely on other analysis tools such as SWOT or PEST(EL).

will be the loss of material in the process and other factors such as the final disposal of the tiles when they complete this second cycle. The monetary benefits of this project include savings in tile purchase costs and disposal costs of old tiles, assuming a positive impact on sustainability.

6.4.4 Circular BM 2

In this model, a cycling strategy is proposed by selling the tiles so they can be reintegrated into other projects in the sector.

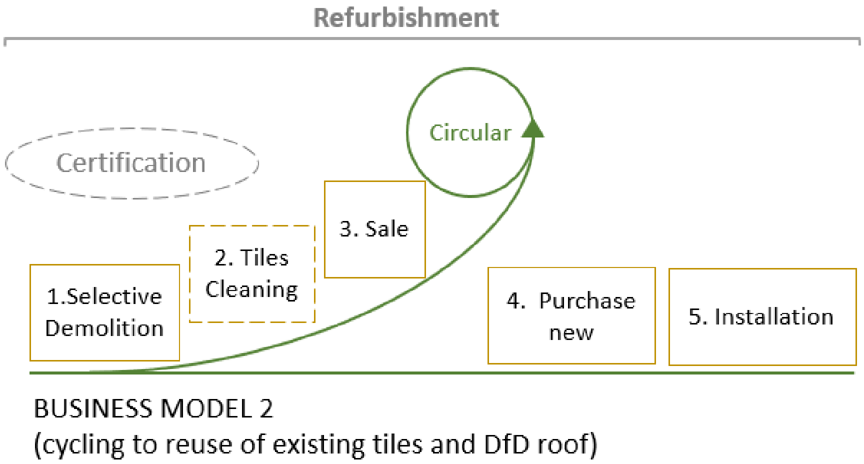


Figure 6.16: CBM2

To this end, two possibilities have been considered.

- Sale as pre-cleaned tiles (Outsourcing of risks).
- Post-cleaning (post-certification) sale.

It would be necessary to assess whether or not it would be interesting to carry out the cleaning with a view to the sale [5]. As in the previous model, comment on the possible interest in certifying the qualities of tiles for sale.

For the economical assessment, cleaning of the roof tiles in the cost calculation would be included, taking the side of safety in the cost study.

Different models can be used for the sales method:

- Sale on platforms
- Direct sale on the market
  - Option to sell to a company (generating alliances for possible future projects).
  - Option to sell to other market players.

After the sale, the purchase of new tiles is proposed, where there are also several options:

- Buy more sustainable tiles (as clay tiles).
- Use easy disassembly tiles (as cladding tiles).

[5] If cleaning costs < increase in income due to an increase in the perception of value, It would be interesting, but it should be also taken into account the extra internal risks.

- Search for a supplier of repaired tiles.

To limit the proposals studied and to study the most representative and interesting for Arkitema, for the cost assessment, this business model will be analysed considering just the purchase and installation of clay tiles. This alternative model will be compared not only with the base case, but also with an alternative of this model where tiles with same characteristics as the one used are purchased to be able to assess the impact on total costs of making a more significant initial investment in the material of the new tiles.

6.4.5 Circular BM 3

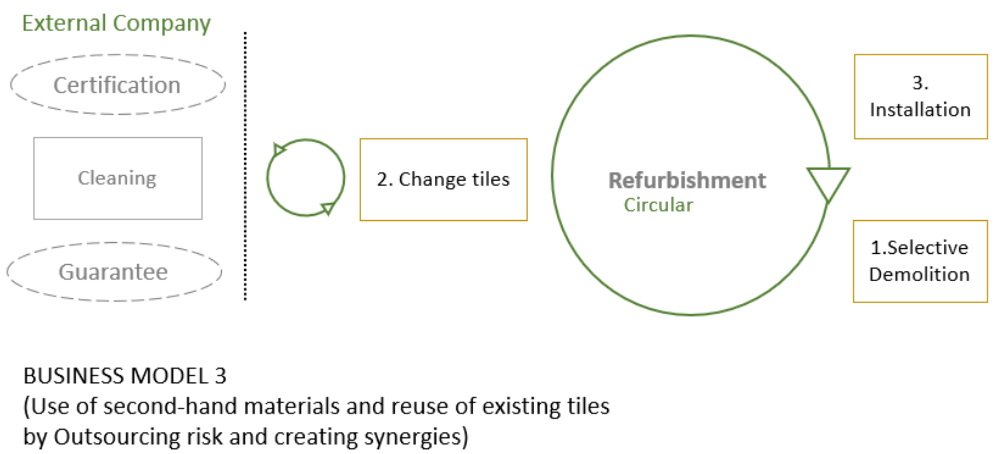


Figure 6.17: CBM3

For this last model, it is proposed to create a synergy with a company in the sector so that, after the selective demolition, this company would take charge of the removed tiles and provide other second-hand tiles that have already been cleaned. The external company, already specialised in buying and selling and restoration work, would be in charge of providing quality guarantees for the ”new” tiles purchased and restoring the removed tiles. This company would charge for this about the tiles to be supplied, applying discounts for the collected tiles. In this case, it would collect the tiles in year zero and provide them in year two so that a futures contract could even be negotiated for the tiles in two years.

This model reduces risks and uncertainties, outsourcing processes and finding new synergies.

This proposal has been presented and analysed for its interest and novelty, but no economic study has been carried out [6].

However, a possible way of estimating it is presented: It was not possible to establish a collaboration with a company in the sector that would allow a more precise cost study of this proposal [7], but assumptions could have been made using a sale price (m2) of the salvaged tiles (such as the RV) and a purchase price (m2) of the second-hand tiles in order to simulate this agreement (which could be the cost of cleaning + Extra (e.g. 10%)).

[6] In order to limit the scope of the study, it was considered more positive to carry out the study on other proposals.

[7] For this particular project, Tegllageret, a company based in the Copenhagen urban area, was approached with the precise characteristics, which did not materialise, but it is understood that it is a company of high interest for this proposal.

6.5 Economic Assessment

The objective is to economically evaluate the different models proposed by comparing them with each other and with the base case, through impact indicators and the elaboration of LCC's with LCCbyg tool.

In this way, some questions may be addressed.

- Q1: Is it economically feasible to apply circular business models to roof tiles from a micro-level perspective?
- Q2: Is it more feasible to reuse the tiles or to sell them in proper conditions to be reused and buy new ones for the project?

During the study, they may also be named other issues like Environmental reasons, the storing problem, economic interest of applying static vs non-destructive test for tiles, etc.

6.5.1 Selected Method and Tool

The conclusions reached in the analysis of the assessment models (chapter 5) led to the decision to use the LCC model for the cost analysis. This is considered the best option, as the cost analysis will be applied over the entire life cycle, allowing the costs incurred during the roof's lifetime to be considered, assessed, and brought into the present day. This will also enable a more accurate assessment of circular strategies.

As discussed in section 5.2.2, there are three primary variants of LCC [8].

It should be noted that in this case, the LCC has been used as a tool for comparing different business models (relative analysis); evaluating investment decisions and used as a planning tool as well as a tool for evaluating a theoretical-practical case study to assess the actual economic interest of applying the models explained. For this reason, and to isolate the cost analysis and avoid double counting in the case of also carrying out an LCA as Arkitema plans to do, it was decided to carry out a conventional LCC. In addition, this will allow subsequent measurements to be taken after the assessments to combine the economic and environmental impacts in a single indicator without double counting while enabling them to be analysed separately.

This as being an ex-ante LCC is going to be a prospective approach based on estimations, conducted at the early stage of decision making [77].

The LCC will be carried out with the LCCByg programme, which is widely used in the sector and with the advantages already mentioned.

6.5.2 Assumptions and Estimations for the Assessment

6.5.2.1 *Discount Rate and Price Development*

- **Discount rate:** Cost of capital applied to determine the present value of a future payment. It indicates how much money of a later date is worth now. It is the rate at which future costs are discounted to bring them into the present in the LCC model so that the NPV can be estimated.

8

1. Conventional/Financial: Applied as a decision making tool. Only internal costs taken into account. Single actor perspective.
2. Environmental: Includes the monetisation of other environmental externalities.
3. Societal: Includes the monetisation of other externalities (environmental and social impacts).

The discount rate is calculated through the interest rate, which is the price of money (the price to be paid for using a given amount of money for a given time). [9]

- **General price development:** Development over time of prices for energy, products, building systems, services, labour, maintenance and other costs.

The current situation, the variation in prices, the existing high inflation and the difficulty in estimating price developments and therefore discount rates, make it difficult to defend reliable assumptions.

In view of this situation, it is decided to maintain the discount rates used so far in Social Housing companies, where a fixed real interest rate is used[10].

The discount rate will therefore be 3.0%, being this the rate proposed by LCCbyg used by Social Housing companies in the sector and the one corroborated by Maria Saridaki (a professional in the industry and a specialist in LCC calculation and LCCbyg).

6.5.2.2 *Assessed Period*

It is generally recommended to use an average calculation period for the calculation of the total economy of 50 years, as it considers long-term considerations and future uncertainties while making visible which investments are profitable both in the short and long term [11] [82].

The fact that two years will elapse between the selective demolition of the roof and the start of the renovation of the roof has led to the decision that the case study period will be 52 years (instead of 50) since the year zero will be taken as the start of the demolition of the roof of "Block 8". In contrast, the renovation will be carried out in year 2, which is why these two years are added to the 50 years selected as a base.

6.5.2.3 *Perspective*

Both for the calculation of the LCC and the decision on the costs to be taken into account (cost strategy), it will be essential to correctly determine the perspective from which the LCC is done.

It is crucial to highlight Arkitema's role in this project to select the perspective. This company acts as a consultant for the social housing. With the recommendations provided by Arkitema, they have right to make decisions on the proposals.

Arkitema charges for its services on a project basis, so in this case, it is decided not to add the costs related to the consultancy provided by Arkitema, as these are indirect costs applied to the overall project and which the client is already aware of. Furthermore, as the objective is to see the costs during the life cycle of the renovation of an example roof, such as block 8, what the client is interested in is to know, above all, the comparison between

[9] $d = i/(1+i)$, where:
- "d": Discount rate
- "i": Interest rate

[10]
- Nominal interest measures the gross return on investment.
- Real interest includes the impact of inflation.

[11] 100 years (close to the lifetime of a building) is often perceived as too long because buildings can undergo many changes over time, creating more uncertainty about the outcome. Short calculation periods, e.g. 5 to 10 years, ignore many necessary replacements and do not allow the real impact of circular strategies to be visible.

proposals of the costs directly attributable to the renovation and specifically the impact on the strategies implemented for the roof tiles.

In this basis, it has been decided to take the perspective of the client, who will use Arkitema's consultancy services to evaluate these issues and make the best recommendations on which the client will have the last word.

From this perspective, the costs associated with demolition, purchase of reformed products, etc., are variable costs directly attributable to the customer, who has no structural costs and does not apply industrial profits.

For more on the cost theory underlying the analysis, please see appendix A.1.4.

6.5.2.4 *Estimation of the service life of existing tiles and service life of tiles of different materials*

Focusing on the roof tiles (described in section 6.3.1), according to the EPD's of the company "Gambale" [83] and "IBF" [84], both for (double cement roof tiles), the concrete tiles are estimated to have a durability of between 80 and 100 years. However, the guarantee of these tiles is usually around 30 years. Nevertheless, in the majority of cases and according to the references found [85] [86] [87], this type of roof tile is estimated to have a useful life of around 50 years without renovation. After conversations with Arkitema, 50 is the number of years that will be considered for the main assessment carried out, taking a conservative perspective.

As far as clay tiles are concerned, in the EPD found [88], as in other references [89] the estimated useful life for these tiles is 150 years. As in the case of cement tiles, this still seems to be a very high value considering with Arkitema to use 100 years for these tiles for the development of the main assessment, taking again a conservative perspective.

Bearing in mind that the useful life of the concrete tiles is estimated at 50 years and that the tiles in the actual roof were installed on the current roofs in 2000, they still have a useful life of at least 28 years.

6.5.2.5 *Costing Strategy*

For the estimation of costs, the following process has been followed:

- Direct contact with companies in the sector to estimate demolition and selective demolition costs (critical point of the project).
- use of Molio Prisdata to obtain material and construction prices.
- LCCbyg's recommendations for maintenance costs and certain renovation costs, apart from assumptions on price development and interest rates as commented before.
- For corroboration perspectives as well as for other some assumptions needed for the assessment, references are obtained from the main collaborator "Arkitema" and professionals in the sector.

It is also necessary to clarify, how is the price generation done in Molio Prisdata:

- Gross(Brutto): This is the net cost of the material (direct costs) +10 % of industrial profit and added structural costs. (To see more about the price formation, refer to the Molio Prisdata manuals [90]).
- Net (Netto): Without marginal costs (industrial profits) and structural costs (indirect costs).

It is also confirmed in discussions that the prices obtained by the demolition companies already contain the structural costs and industrial profits of the company [12].

6.5.3 Development and Results of the Main Assessment

It should be noted that this main assessment will be carried out from the side of security, following the principle of prudence when making estimations, leading to a conservative scenario in the results.

Key features framework of the LCC:

- **Implementation Stage:** Design Phase
- **System Level:** Product/Material (Micro Level)
- **Scale:** Block (Block 8)
- **Perspective:** Clients
- **Stakeholders:** Arkitema, clients and academia
- **Indicators:** Economic (NPV and Initial Costs (Ci) as main indicators) [13]
- **Assessed Period:** 52 years
- **Remaining life of the current roof tiles:** 28 years [14]

6.5.3.1 *General measurements*

From ex-ante calculations we know that the area of the roof to be dismantled (Block 8) contains a total of **619m2** of tiles (fig. 6.11), while the area to be renovated is **962m2** (fig. 6.13) [15].

With data taken from the ”IBF” data sheets [91], Danish supplier of concrete tiles with the same characteristics as those of the Gadehavegård district, it is possible to estimate the number of tiles per m2 on the current roof. As at the time of this study, the distance between Battens is not yet known and in the supplier's data sheet, the number of tiles used for different distances between battens is estimated, it was decided to average the maximum and a minimum number of tiles that can be laid per m2. The result of this estimation is **9.75 tiles/m2**.

From discussions with industry professionals it has been decided to opt for a **loss factor of 30%** for non-reusable tiles. With this it is possible to obtain:

- The number of m2 of tiles in good condition that can be salvaged from ”Block 8”.
- In view of BM1
  - Area needing to be covered with tiles salvaged from other roofs
  - Area to be demolished from other roofs to get this number of tiles in a reusable state.

[12] In the case of a LCC from the point of view of both Arkitema and the client, these costs are taken as direct variable costs and the structural costs and industrial benefits of the subcontracted company do not have to be removed or deducted. The estimated costs with Molio from this perspective will also be on a net basis.

[13] (The assessment results could be added in a multidimensional value indicator)

[14] This data is used both for BM1, where the aim is to keep these tiles on the roof, and for BM2, where it is necessary to estimate a selling price for them.

[15] As we have seen, the geometry and the area of the renovated roof will be different from the current one due to the renovation work carried out.

30% of waste

Needed area (m2)	Current tiled area in Blok8 (m2)	Area of tiles in reused state in Blok8 (m2)	Area to be covered by other roof tiles(m2)	Area needed to demolish to get the missing tiles (m2)
962	619	433	529	755

Figure 6.18

Several LCC's are made for each business model in addition to the base case LCC, all with the same assumptions. Each model will be divided by its main processes, in which costs are generated and taken into account to obtain results that will allow the subsequent comparison of the same.

6.5.3.2 *Base Case*

For the base case, the life-cycle costs of applying linear principles to the project is estimated. The tiles are dismantled in a destructive and non-reusable way (at least for the same purpose they were conceived) losing much of their value. New tiles of the same characteristics are then purchased and installed on the new roof.

The image shows the adaptation of the base case model to the LCC application with its characteristics and cost blocks designed for the analysis.

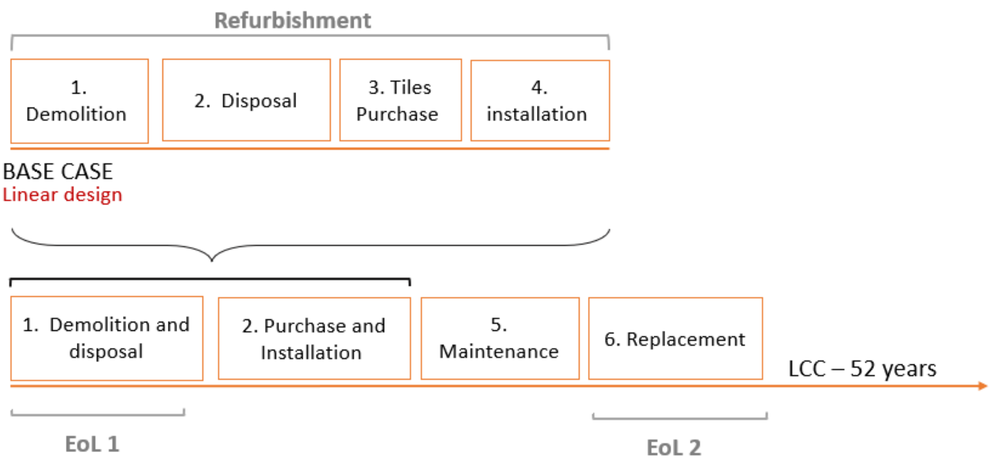


Figure 6.19: BC adaptation for the assessment

This case serves as a starting point and comparison to study the real interest of the rest of the proposed business models.

1. Demolition and Disposal - Ci

To estimate the cost of dismantling, the area of the tiled roof of "Block 8", 619m2, is used[16].

Two demolition companies, Enemærke & Petersen and J.Jensen, have been contacted for price estimates. The prices obtained have also been corroborated with other references such as Molio Prisdata and other references[92] for the purpose of cross-checking

[16] In this case, only the area with tiles is considered for the dismantling costs as this product is evaluated and not the whole roof, so the vaulted part of the roof, composed of other materials, is omitted. The same is happens for the rest of the LCC's performed under the micro level of product/material.

and corroboration. After cross-checking data, prices for normal demolition (selective destructive demolition in all cases) are between **60dkk/m2 and 100dkk/m2 per complete roof**, only the price reference per product is available from Enemærke & Petersen, who have provided the costs broken down and quoted from another project, being **45dkk/m2 charged for tiles** (This is a gross cost, and takes into account the disposal of dismantled materials).

	Code			Quantity	Unit	Unit price (DKI	Sum (DKK)	Description	
>			**Demolitions and disposals**	**619**	m2	**45**	27,855	1197m2 is the total roof area, while 619 is the tiled area	

Figure 6.20: Demolition Costs

2. New tiles and Installation - Ci

The price of the tiles and the installation have been estimated jointly with the Molio Prisdata references, taking Gross Cost with Profit, as this will be the total cost that the final customer will have to assimilate[17].

In order to estimate the costs in Molio, the construction of a double cement tile roof has been selected, to take into account only the costs due to the tiles, the rest of the elements have been removed from the calculation of the budget.

On the other hand, a factor of 1.083 tiles per m2 is applied, in order to be more precise in the costs, as this example takes into account that 9 tiles/m2 are laid, whereas in this case 9.75 tiles/m2 are laid.

The costs are calculated for the calculated roof area of 962m2.

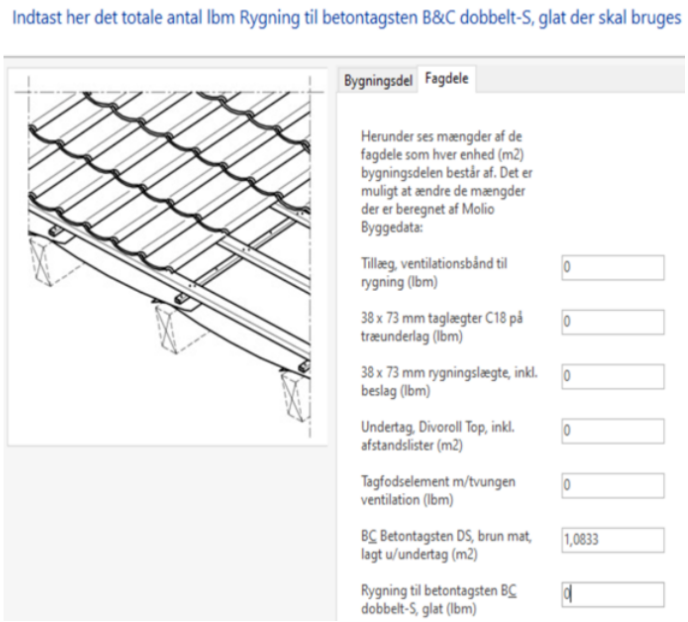


Figure 6.21: Molio Estimation

[17] Attempts have been made to take market prices directly through IBF who have this type of double cement roof tiles, but they reference retailers directly as they negotiate just with wholesalers, the price to retailers is higher than it is actually going to be so the Molio reference is chosen.

Below are the costs due to roof tiles and roof assembly per m2 and estimated totals for ”Block 8”:

List

Total Cost: 199.756,51 - Tid: 149,17 Løn: 66.323,43 Materialer: 133.433,04 Leje: 0,00

Pos.	No.	Text	*	Unit	Quantity	Unit Cost	Cost	Total Cost	Price reg.
								199.756,51	
1.1	(47)11.10,01	Betontagsten på diffusionsåbent undertag	TIC	m2	962	207,65	199.756,51	199.756,51	1

Figure 6.22: Purchase and Installation Cost Estimation

The installation of the new roof takes place 2 years after demolition and according to EPD the concrete roof tiles have a lifetime of about 50 years.

For the maintenance costs, the references obtained from professionals in the sector are followed, being 1% of the initial investment for tiled roofs.

Attached below is an image of how all these data have been taken into account in the LCCbyg tool:

Code		Quantity	Unit	Unit price (DKK)	Sum (DKK)	Description
4.47	Roofs, surfaces *Primarily concrete, terrazzo and cement mortar*	962	m2	207.65	199,759	Unit price takes into account the price of the material + price of construction

Indexdevelopment: General price development

Present value: -236,725

Residual value: 0

	%	DKK/occurrence	Interva	Lifetim	Start year	End year	Description
Acquire				50	2	52	
Maintenance	2	1,997	1		3	52	
Replacement	125	227,614	50		52	52	

Figure 6.23: Purchase and Installation Costs, LCCbyg

At the end of the useful life of the installed roof tiles (year 52), the costs of a new roof renovation will be accounted for, estimated as the sum of the demolition costs plus the costs of installation and purchase of material, as can also be seen in the picture above (fig. 6.23).

3. Results BC

The results for the base case (The initial costs at present value, maintenance costs and total project costs) are presented below:

BC	
Initial costs	-216147
0	-27885
2	-188292
Maintenance	-48433
NPV	**-264580**

Figure 6.24: BC Results

6.5.3.3 *BM1 - life span*

The aim here is to estimate the total costs of the first business model proposed, where the existing roof tiles are reused for the new roof.

The tiles are dismantled using soft selective demolition principles. As already mentioned, it is estimated that 30 % of losses occur in this process. Once the useful life of the reused tiles has been fulfilled in this case, reform will be carried out with new tiles of the same geometric characteristics (the cost impact of using different materials will be tested [18]).

The image shows the adaptation of the business model to the LCC application with its characteristics and cost blocks designed for the analysis:

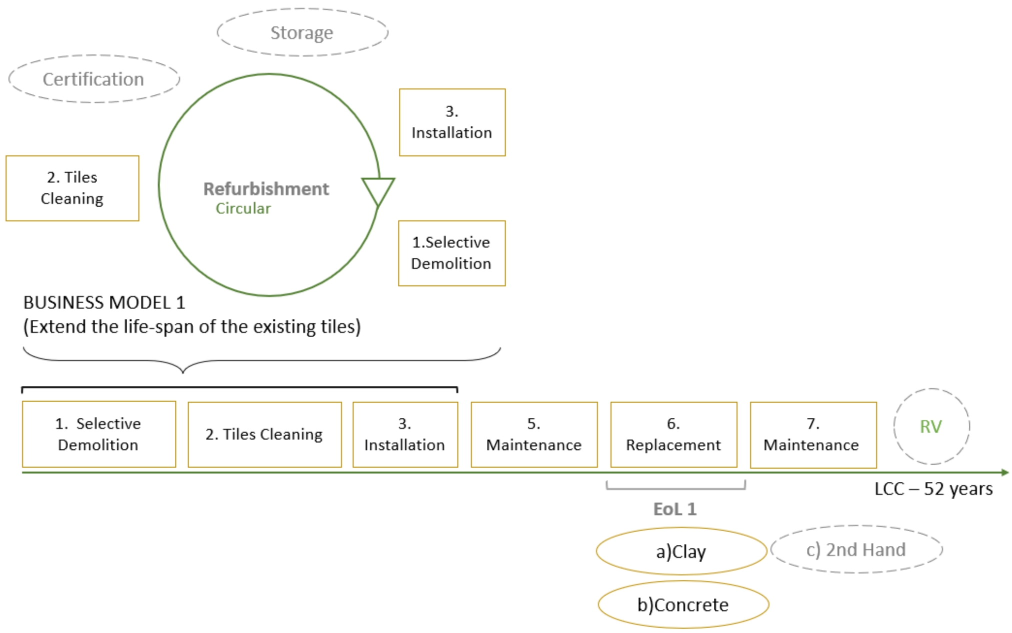


Figure 6.25: BM1 Adaptation for the Assessment

The main objective is to analyse the total economic interest in extending the lifetime of the existing roof tiles and compare it with the BC and the rest of the proposals. Secondly, the cost impact of using clay or cement tiles in the second refurbishment is studied.

Selective Demolition and Tiles Cleaning - Ci

Soft selective demolition increases the cost of demolition. This is one of the most important and variable values to estimate, for which, as specified above, various demolition companies have been contacted, information from the CIRCuIT project has been consulted and other external references have been sought in order to make the estimates.

Based on the total area of the roof and taking into account all the available references, it can be concluded that selective demolition can be between **50% and 120% more expensive** than a standard demolition (in which selective demolition is already part of the demolition but without maintaining the quality of the materials removed). Among other things this will depend on:

- The companies; their structures and capacity to carry out the work.
- The kind of project; If a complete demolition is carried out, the cost difference will be more significant than if an only roof demolition is carried out (maintaining the rest of the building structure).

[18] The use of clay tiles (more sustainable) and cement tiles will be studied as shown in the figure. The use of second-hand tiles could also be considered, although this is not part of the case study.

In complete demolition, the destructive demolition system is more straightforward and lower costs. In roof demolition, the cost difference will be more in the time required than in the system and the cost difference will not be that high than in the other example.

As commented above, it was finally decided to take the costs of the company Enemærke & Petersen as it is a reference company in the market, close by, providing real data and itemised costs to just take the costs directly applied for the tiles.

In their breakdown they apply a **extra 75% cost for the tiles** over traditional demolition, this will be used for the case, equivalent to **3.46dkk/extra in each** tile.
The cost of soft selective demolition per m2 is then 78.75dkk/m2. These costs include the packaging of the tiles for storage and a soft cleaning.

Using the total tiled area of block8 (619m2) and the dismantling price per m2 , the total dismantling price for the tiles of ”Block 8” is 48,746dkk.

As mentioned above, of these 619m2 with the 30% waste, only 433m2 of tiles will be available for roof renovation, so a soft selective demolition will have to be applied to other (1 to 2 more) buildings in the neighbourhood.

It is recommended that, if possible, these should be buildings be dismantled in phase 1 to ensure that the tiles are available at the time of the renovation.

A further **756m2** needs to be dismantled to obtain the tiles required for the new roof refurbishment [19] (529m2 of tiles after applying losses).

These costs, that must be also estimated, are associated with the renovation of ”Block 8” as this is the ”price” being paid for these tiles which are not available on the current roof, and which have to be ”purchased” from other roofs.

They would amount to the difference in the price of applying selective demolition to the selected block versus applying normal demolition, as it is assumed that the normal demolition is going to take place anyway. In other words, the normal demolition costs will take place and are attributed to the building from which the tiles are being recovered, attributing only the extra costs for selective demolition to the cost calculation of ”Block 8”.

This ”price” paid for the tiles on the other roofs is **33.75dkk/m2**. The total costs of demolition of other roofs directly attributable to this case are thus estimated at 25,515dkk.

Finally, even though the company ensures a cleaning of the tiles, it is decided after discussions to take the side of safety, and to estimate extra **cleaning costs of 2dkk/tile**, in order to reduce the risk of the case. The cleaning is applied to the total of recovered tiles (962m2).

The input Data and results from the whole demolition process are presented below:

Code		Quantity	Unit	Unit price (DKK)	Sum (DKK)	Description
	Demolitions	619	m2	78.75	48,746	
	Demolitions	756	m2	33.75	25,515	
	Extra Cleaning Costs	962	m2	19.5	18,759	2dkk/tile (9,75tiles/ m2)

Figure 6.26: Demolition Costs, LCCbyg

[19]Due to the lack of knowledge about the buildings to be dismantled in each phase, it was decided to calculate the dismantling costs on this calculated area. However, it would be more accurate to figure them by selecting a building associated with the selective soft demolition for the refurbishment of ”Block 8” so that the area would be more realistic and accurate, this being also an important planning exercise.

Total dismantling costs: 93,020dkk

There will be no storage costs during the two years that the tiles have to be stored, as this will be done on site in the neighbourhood as there is sufficient space for this.

Installation - Ci

As the tiles for the renovation are available, only the costs for the installation by the builder need to be estimated, which are estimated with Molio Prisdata by deducting the costs associated with the purchase of tiles in the budget calculation for roof renovation with double cement tiles at 9.75 tiles/m2.

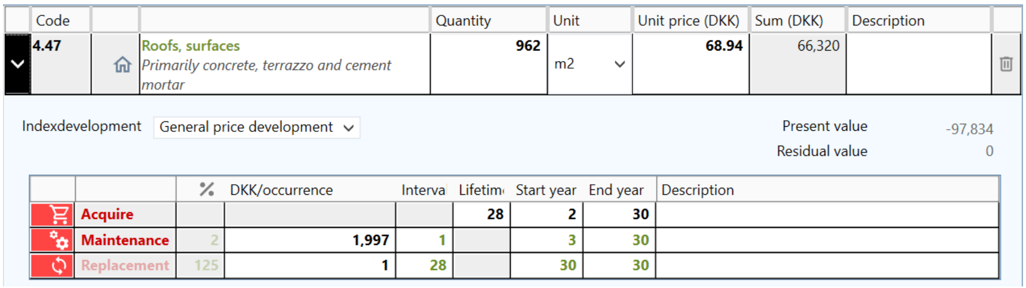
List

Total Cost: 199.756,51 - Tid: 149,17 Løn: 66.323,43 Materialer: 133.433,04 Leje: 0,00

Pos.	No.	Text	*	Unit	Quantity	Unit Cost	Cost	Total Cost	Price reg.
								199.756,51	
1.1	(47)11.10,01	Betontagsten på diffusionsåbent undertag	TIC	m2	962	207,65	199.756,51	199.756,51	1

Figure 6.27: Estimation of the Installation Costs, Molio

The cost for the installation is thus estimated at 66,323.5dkk (68.94dkk/m2). Costs occurring in year 2, as shown in LCCbyg and as can be seen in the following figure:



Code	Text	Quantity	Unit	Unit price (DKK)	Sum (DKK)	Description
4.47	Roofs, surfaces *Primarily concrete, terrazzo and cement mortar*	962	m2	68.94	66,320	

Indexdevelopment: General price development

Present value: -97,834

Residual value: 0

	%	DKK/occurrence	Interva	Lifetim	Start year	End year	Description
Acquire				28	2	30	
Maintenance	2	1,997	1		3	30	
Replacement	125	1	28		30	30	

Figure 6.28: Installation Costs, LCCbyg

The costs at present value are: 97,834dkk.

It is also possible to observe the life span estimated for these tiles that are being reused for the new roof (28 years).
This means that in year 30 a new renovation will have to be undertaken.

For maintenance costs, it is decided to use the same amount as in the base case (1,997dkk/year).

The second reform is estimated separately and not as a replacement in this section as it will have totally different conditions (hence only 1dkk, the minimum allowed by the programme, has been attributed in this box).

2nd refurbishment - Replacement (Year 30)

Once the useful life of the tiles has been extended, the process followed and the estimates made for this second refurbishment in year 30 will follow the same line as those made in the base case, this being a normal refurbishment.

First of all, the price of the second demolition has to be estimated, in this case a selective destructive demolition is chosen, because the state of the tiles in 30 years is unknown and the most probable assumption is made. As in the base case the cost will be 45dkk/m2 and the total cost will amount to 43.290dkk in year 30, being at present value of 17,835dkk.

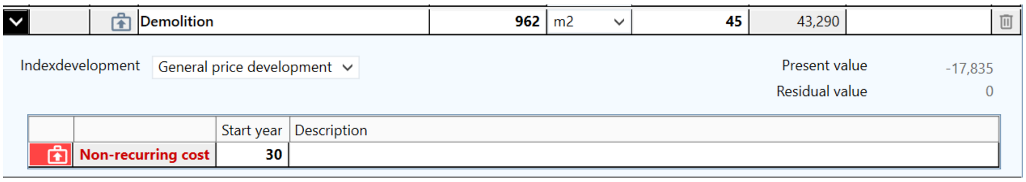


Figure 6.29: 2nd Refurbishment Demolition Costs, LCCbyg

For the second renovation, two solutions will be assessed according to the material used for the tiles (cement and clay), so their impact on costs can be studied. The geometric characteristics of the tiles are maintained as it is understood that the design of the rest of the building (façade) and of the neighbourhood will not be sacrificed as it is something that has been taken into account in the comprehensive redesign of the area, as it would lose part of its cultural and aesthetic value. In addition, it would be necessary to select tiles that adapt to the same or a similar type of anchoring and the distance between battens so as not to touch the rest of the roof structure too much if it is unnecessary.

- **Concrete (double concrete tiles):** 207.65dkk/m2 (to see the process of how the estimation is carried out section 6.5.3.2)

  These tiles have an estimated lifetime of 50 years, maintenance of 1%/year and replacement equals 125% of the refurbishment costs (taking into account soft selective demolition + refurbishment + tiles) [20]. At the end of the LCC study these tiles will still have a residual value (RV) estimated for a useful life of 28 years.

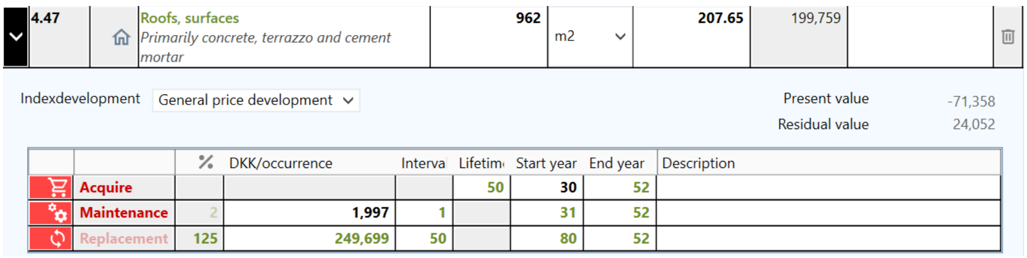


Figure 6.30: Costs Of and After 2nd Refurbishment with Concrete Tiles, LCCbyg

- **Clay (double clay tiles):** 216,45dkk/m2. In this case, the same procedure has been used as in the case of cement tiles, but several factors have changed.

  - Firstly, Molio estimates 10.5 tiles/m2 for the selected tiles, which means that the number of tiles will have to be adapted by applying a factor as in the case of cement tiles, but in this case of 0.9285 instead of 1.0833.

  - On the other hand, Molio, by making several changes to its proposal, generates a variation to be taken into account in the assembly costs (The estimated costs are lower than those calculated for the assembly of cement tiles, when they should be the same), so the total costs budgeted by Molio are adapted by taking the estimated material costs for the clay tiles added to the estimated labour costs for the cement tiles to be more faithful in the comparison.

[20] Even if the value of the renovation is inserted, it will not come into play in the cost calculation as it is outside the range of years studied.

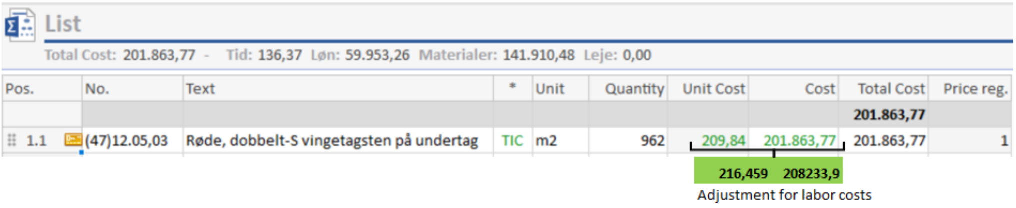


Figure 6.31: Estimation of Purchase and Installation Costs, Molio

In this case both the maintenance and replacement costs are still 1% and 125% of the initial cost, what varies in this case is the life span of the tiles which is estimated at 100 years for clay tiles. This means that although the costs are higher, it is interesting to see the impact of the proposal on the LCC of a much longer useful life and if it has a positive effect taking into account the whole process. These tiles will have a higher residual value at year 52 than concrete tiles.

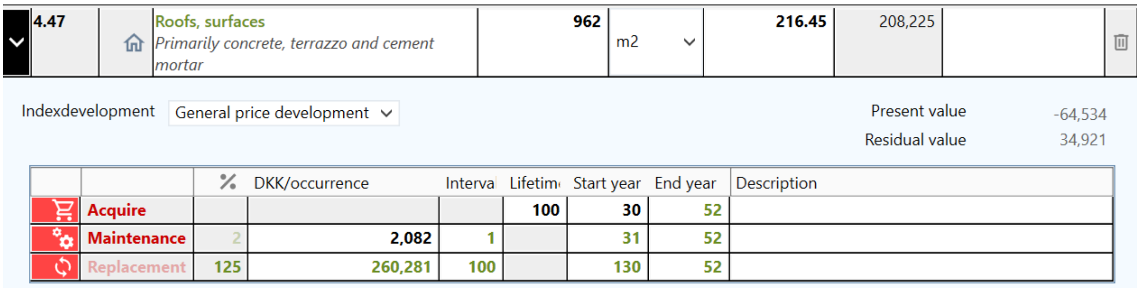


Figure 6.32: Costs of and after 2nd refurbishment with clay tiles, LCCbyg

Results BM1

The results for the BM1 (The initial costs at present value, maintenance costs, Residual Value and total project costs) are presented below, for the Replacement in year 30 with concrete and clay tiles.

BM1	2nd R-Concrete	2rd R-Clay
Initial costs	-155533	-155533
0	-93020	-93020
2	-62513	-62513
Maintenance	-48433	-48991
RV	24052	34932
NPV	**-264580**	**-264580**

Figure 6.33: Results BM1

6.5.3.4 *BM2 - Sale*

In this case, the cost assessment for the second proposed business model is applied, which involves dismantling the roof tiles in a soft selective demolition process, but instead of keeping the tiles for reuse, they will be sold after being dismantled (year 0). This will be followed by the renovation (year 2).

The image shows the adaptation of the business model to the LCC application with its characteristics and cost blocks designed for the analysis

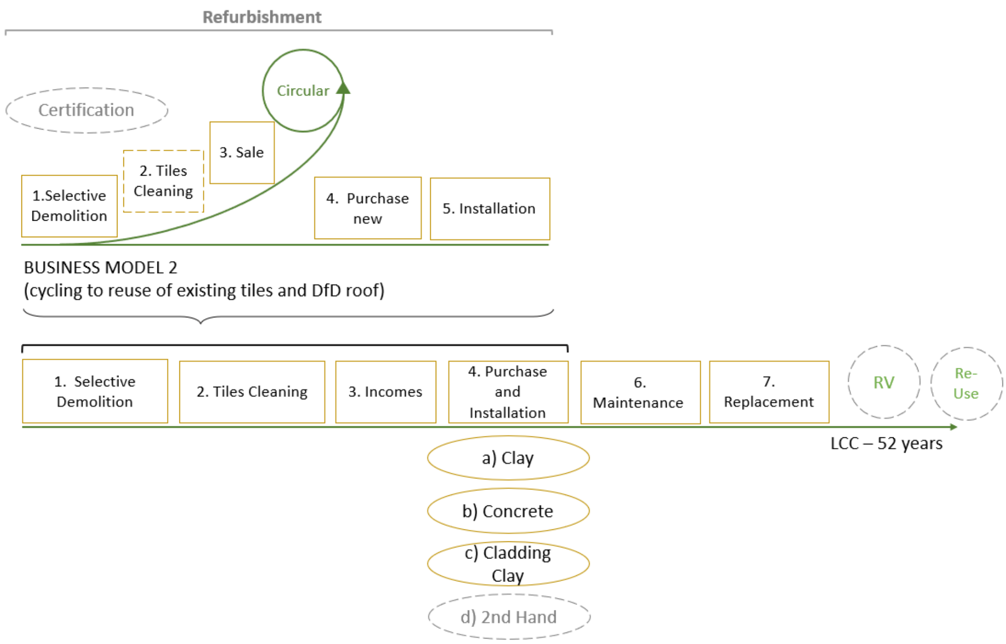


Figure 6.34: BM2 Adaptation for the Assessment

The objective is to:

1. To see if it is economically viable to apply soft selective demolition by trying to sell the salvaged material versus applying destructive selective demolition and to see if it is more interesting to apply this model or the BM1.
2. Study the impact on the LCC of the use of different types of tiles, both in terms of material and dimensions, as costs will vary taking into account these variables.

Selective Demolition and Tiles Cleaning - Ci

The 619m2 of tiled roof area will be demolished at the price already estimated and set out in the business model above for selective demolition (section 6.5.3.3), price amounting to 78.75dkk/m2. Demolition costs are 48,746dkk.

The clean-up costs will also be 2dkk/tile. In this case, the tiles recovered will only be those from ”Block 8” which, taking into account losses, amount to 433m2 of tiles, with a clean-up cost of 8,444dkk.

Incomes for the sale of tiles - Ci

To estimate the income from sales, it should be reiterated that since the tiles have not yet been tested to determine their remaining useful life, which would provide precious information for estimating a selling price, it is decided to evaluate the residual value of the tiles with the estimated remaining useful life (28 years), and use this as the selling price. It is decided to estimate the residual value of these tiles with the estimated remaining useful life (28 years) and use this as the selling price.

First, the price per square metre of double cement roof tiles is estimated using Molio Prisdata, 126dkk/m2. It is decided to use the net value in this case because we want to know the initial value of the tiles, firstly, as a building product to estimate their real depreciation, and secondly, because we want to obtain an indicative value at which the tiles can be sold without applying structure costs or profits on the sale, following a direct-costing strategy from the customer's perspective (thinking that the customer does not use margins or structure costs that he does not have), which in this case is the one who sells the tiles.

Multiplying the price per square metre by the total area of tiles to be salvaged (433m2) gives the total price, as shown in the fig. 6.35, 54,558dkk.
this initial is divided by the 50 years of useful life to obtain the annual depreciation of the tiles, 1,091dkk.

The total depreciation will be the annual depreciation multiplied by the years of use of the tiles (22 years) on the current roof, 24,005.5dkk.

Subtracting the depreciation of the tiles from the initial value gives the residual value of the tiles, 30,552.5dkk.

Dividing the total residual value by the area of tiles salvaged (433m2) gives the residual value per square metre which will be the value used as the selling price for the salvaged tiles, **70.56dkk/m2 (7.23dkk/m2)**. In this way, the intrinsic value that the tiles still have is being recovered in the sale. [21].

New [dkk]	Annual Depreciation [dkk]	Depreciated [dkk]	Residual value [dkk]	
54558	1091,16	24005,52	30552,48	
			70,56	VR/M2

Figure 6.35: Residual Value of current tiles

In the following picture you can see the movements in year 0, total costs of demolition of the tiled surface, cleaning costs and total income from the sale of the salvaged tiles.

Code		Quantity	Unit	Unit price (DKK)	Sum (DKK)	Description
	Demolitions	619	m2	78.75	48,746	
	Non-recurring costs	433	m2	19.5	8,444	
	Income from tiles	433	m2	70.56	30,552	

Figure 6.36: Demolition and Extra Cleaning cost and Incomes from sold tiles, LCCbyg

New Tiles and Installation - Ci

For this business model, three solutions have been proposed to evaluate and compare with each other. Depending on the type of material selected, the renovation with cement tiles or clay tiles is studied, so that its impact on the final result and on the initial costs can be studied.[22]. On the other hand, the impact of selecting tiles with different geometric characteristics to those used up to now is also studied, taking into account a possible design solution provided by Arkitema. In this way it was decided to study three different solutions:

[21]Mini-Discussion: This model does not recover the cost of cleaning, which will be a sunk cost. In case of wanting to take it into account in income estimation, it would be necessary to sell the tiles at a price of 90dkk/m2 (9.23dkk/tile); which is complicated in case of selling to an intermediary, who wants to apply his margins and structure costs increasing the price to more than 10dkk/tile; making it impossible to sell taking into account that the new cement and clay tiles are located between 10dkk/tile and 20dkk/tile right now (depending on quantities purchased and type of tiles). In case of direct sale is still an unrealistic price. At the end of it all, cleaning costs are going to be an expense because if are done by the seller, it is a lost cost, and if they are leave them in the hands of the buyer, the seller will have to sell the tiles for a price lower than their residual value.

[22]It is known that clay tiles are preferable from a sustainability point of view.

- Double-S concrete tiles
- Double-S clay tiles
- Simple flat cladding clay tiles[23]
- **Double-S concrete tiles:** Same costing process as in the base case and the BM1 with concrete tiles. Same maintenance and refurbishment costs as in the BM1 where dismantling costs with soft demolition are taken into account. 50 years service life.

Code			Quantity	Unit	Unit price (DKK)	Sum (DKK)	Description
4.47		Roofs, surfaces *Primarily bricks and tiles*	962	m2	207.65	199,759	

Indexdevelopment: General price development — Present value -236,725; Residual value 0

	%	DKK/occurrence	Interva	Lifetim	Start year	End year	Description
Acquire				50	2	52	
Maintenance	1	1,997	1		3	52	
Replacement	125	249,699	50		52	52	

Figure 6.37: Purchase and Installation costs for concrete tiles, LCCbyg

- **Double-S clay tiles:** Same process to obtain costs as BM1 with clay tiles. Same maintenance and replacement costs as BM1. 100 year life span.

Code			Quantity	Unit	Unit price (DKK)	Sum (DKK)	Description
4.47		Roofs, surfaces *Primarily bricks and tiles*	962	m2	216.46	208,235	

Indexdevelopment: General price development — Present value -224,389; Residual value 22,387

	%	DKK/occurrence	Interva	Lifetim	Start year	End year	Description
Acquire				100	2	52	
Maintenance	1	2,082	1		3	52	
Replacement	125	260,293	100		102	52	

Figure 6.38: Purchase and Installation costs for clay tiles, LCCbyg

- **Simple flat cladding clay tiles:** This roof tile proposal is manufactured by the company "Strøjer Tegl", they are flat roof tiles designed for disassembly and can be used for both facade and roofing. They are model U3-276, with which 12 tiles/m2 are used according to the manufacturer. Taking this and the price of each tile into account, Molio estimates the total purchase and installation price per square metre at 272.29dkk/m2.

List

Total Cost: 261.939,23 - Tid: 171,49 Løn: 75.394,25 Materialer: 186.544,98 Leje: 0,00

Pos.	No.	Text	*	Unit	Quantity	Unit Cost	Cost	Total Cost	Price reg.
								261.939,23	
1.1	04.17.65,05	Røde vingetagsten, 14,6 stk/m²	TC	m2	962	272,29	261.939,23	261.939,23	1

Figure 6.39: Estimation for Purchase and Installation Costs, Molio

[23]This Cladding type fastening systems by anchors or supported on battens make it easier and quicker to Assembly and disassemble, facilitating the process.

As in the case of double clay tiles, a service life of 100 years is used with an annual maintenance of 1% and replacement costs of 125%, which is equivalent to the cost of selective demolition and renovation with purchase of material.

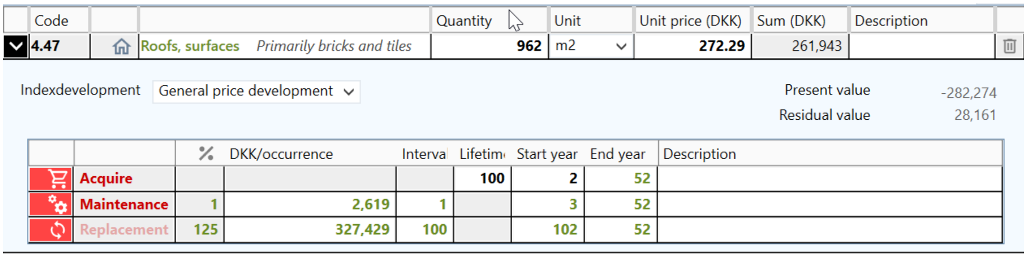


Figure 6.40: for cladding clay tiles, LCCbyg

Results BM2

The results for the BM2 (The initial costs at present value, maintenance costs and total project costs) are presented below, for the renovation with concrete and clay and the special cladding clay tiles.

BM2	Double-S Concrete	Double-S Clay	Simple flat cladding clay
Initial costs	-214931	-222919	-273544
0	-26638	-26638	-26638
2	-188292	-196281	-246906
Maintenance	-48433	-50494	-63528
RV	0	22387	28161
NPV	**-263362**	**-251026**	**-308912**

Figure 6.41: Results BM2

6.5.4 Results Analysis

LCC Analysis

		BC	BM1-1	BM1-2	BM2-1	BM2-2	BM2-3
Initial cost	0-2	-227614	-140581	-140581	-214930	-222919	-273544
	0	-27855	-74261	-74261	-26638	-26638	-26638
	2	-199759	-66320	-66320	-188292	-196281	-246906
	NPV	**-264580**	**-280047**	**-273224**	**-263362**	**-251026**	**-308912**

Figure 6.42: Results Analysis

- BC: Base Case
- BM1-1: BM1 with Double-S concrete tiles for the 2nd refurbishment.
- BM1-2: BM1 with Double-S clay tiles for the 2nd refurbishment.
- BM2-1: BM2 with Double-S concrete tiles for the refurbishment.
- BM2-2: BM2 with Double-S clay tiles for the refurbishment.
- BM2-3: BM2 with Double-S cladding clay tiles for the refurbishment.

The figure above shows the results obtained from the evaluation carried out. As already mentioned, for the analysis of the results it should be noted that this is a fairly conservative scenario, as will be seen later in the study of other alternatives.

Taking this into consideration, it is observed that all the proposed models except BM2-3, are close to being viable or are already viable according to the evaluation, such as case BM2-2.

This allows for a positive consideration of any of the proposals (apart from BM2-3), as in the "worst" case the total costs of these proposed models are close to that of the base case.

As for BM2-3, which is far from having competitive total costs, it would have to be assessed whether the cost overrun is worth it given other contributions such as easier dismantling at the end of its service life or the final appearance.

Based on the results, the BM1 has the advantage that the reuse of the tiles will allow a lower initial investment, as well as being spread between year 0 and year 2 in a reasonably balanced way, and not accumulated in the year of purchase and installation. This can be considered positive for the customer, as it can encourages them to opt for this more sustainable model.

Finally, it is confirmed that the options where double clay tiles are used instead of cement tiles for renovations (BM1-2 and BM2-2) are not only more sustainable (as already known) but also more cost-effective in relation to the total costs. Although they involve a higher investment at the time of purchase, they are amortised over the years as they have a longer life span.

The client will have to decide with Arkitema whether he prefers to have lower total costs or undertake a lower initial investment. At the same time, environmental impacts outside this project's scope will have to be considered.

6.5.5 Minimum required service life for reused tiles

To complete the analysis, the break-even point (BEP) as years of a remaining lifetime is studied. This is the point at which the reuse of the current tiles (BM1) leads to lower total costs than the application of the base case.

Deadlocked viability for remaining years of life				
	28 (Years)	32 (Years)	33 (Years)	34 (Years)
BC (dkk)	-264580	-264580	-264580	-264580
BM1-1 (dkk)	-280047	-265445	-261990	-258620
Net Savings (dkk)	-15467	-865	2590	5960

Deadlocked viability for remaining years of life				
	28 (Years)	30 (Years)	31 (Years)	32 (Years)
BC (dkk)	-264580	-264580	-264580	-264580
BM1-2 (dkk)	-273224	-267797	-262998	-259748
Net Savings (dkk)	-8644	-3217	1582	4832

Figure 6.43: Break-Even Point (BEP)

The break-even point for BM1-1 is reached in year 33 and for BM1-2 in year 31 [24].

6.5.6 Sensitivity Analysis - Assessment of Other Scenarios

In order to reduce uncertainty about the results obtained, to evaluate the consistency of the results and to know other viable options from which the case could have been approached (within the multiple existing alternatives); evaluations of different scenarios are carried out with the main scenario already presented as a starting point.

6.5.6.1 *10 extra years of useful life for reused tiles*

This scenario estimates that after cleaning and sorting the tiles and discarding those in poor condition, it can be concluded (based on professional data) that a longer remaining life of the tiles can be estimated, with 10 extra years (38 in total) being a reasonable value.

Name	BC	BM1 - -Beton-	BM1 - -Tejl-	BM2 - -Beton-	BM2 - -clay Double-S-	BM2 - -Special clay-
Non-recurring income				34,553	34,553	34,553
Net present Value without residual Value	-264,580	-278,475	-281,329	-259,361	-269,412	-333,071
Residual value	0	32,643	39,398	0	22,387	28,161
Net present value	-264,580	-245,832	-241,931	-259,361	-247,025	-304,911

Figure 6.44: Scenario 2 Results

The results with this change of assumption show that both BM1 and BM2 with double tiles are feasible, with the exception of BM2-3.

This is considered a realistic scenario.

6.5.6.2 *Without extra cleaning costs*

This scenario is built on the information provided by the company "Enemærke & Petersen a/s", which includes a surface cleaning of the parts; based on this, this scenario assumes that no further deep cleaning is necessary, adding no extra costs for cleaning.

Name	BC	BM1 -Concrete-	BM1 -Clay-	BM2 -Concrete Double-S-	BM2 -Clay Double-S-	BM2 -Cladding Clay-
Non-recurring income				30,552	30,552	30,552
Net present Value without residual Value	-264,580	-285,340	-289,386	-254,919	-264,969	-328,629
Residual value	0	24,052	34,921	0	22,387	28,161
Net present value	-264,580	-261,288	-254,465	-254,919	-242,583	-300,468

Figure 6.45: Scenario 3 Results

This is an optimistic scenario. It makes the circular models even more interesting, presenting higher Net Savings compared to the Base Case.

6.5.6.3 *Higher lifespans 1*

This scenario is based on information gathered from the various EDPs that estimate a lifetime for concrete tiles of 80-100 years and 150 years for clay tiles.

With this information, it is determined that the lifetime of the new tiles is 100 for cement and 150 for clay, while the lifetime of the old tiles is 80 years (58 years remaining) [25].

[24] It should be remembered that these data should be taken with caution and as a reference, as the results will show some variability due to the estimates made, it is still very useful information for decision making.

[25] 80 years and not 100 is taken as these are older tiles. Even so, this estimate of reused tiles is optimistic, as it is based on either the remaining lifetime being extended by cleaning the tiles or the lifetime being longer from the beginning (or a combination of both).

Name	BC	BM1	BM2 - -Concrete-	BM2 - -Clay Double-S-	BM2 - -Cladding clay-
Non-recurring income			39,555	39,555	39,555
Net present Value without residual Value	-264,580	-203,966	-254,360	-264,410	-328,070
Residual value	21,475	1,967	21,475	29,849	37,547
Net present value	-243,105	-201,999	-232,885	-234,562	-290,523

Figure 6.46: Scenario 4 Results

In addition to a clear reduction of the total costs in all models, the BM1 has great Net Savings over the Base Case.

It could be described as a realistic-optimistic scenario.

6.5.6.4 *Higher lifespans 2*

With the same assumptions as above for new roof tiles (100 years lifetime for concrete roof tiles and 150 for clay roof tiles). While the remaining lifetime of reused tiles is 38 years. Ten years more than in the conservative case, either because it is extended by cleaning as in the first scenario or because the initial lifetime was already longer.

Name	BC	BM1 - -Beton-	BM1 - -Tejl-	BM2 - -Beton-	BM2 - -clay Double-S-	BM2 - -Special clay-
Non-recurring income				34,553	34,553	34,553
Net present Value without residual Value	-264,580	-278,475	-281,329	-259,361	-269,412	-333,071
Residual value	21,475	37,797	41,189	21,475	29,849	37,547
Net present value	-243,105	-240,678	-240,140	-237,886	-239,563	-295,524

Figure 6.47: Scenario 5 Results

In this scenario all circular BM's except BM2-3 have lower total costs than the base case, but very close to it.

This can also be considered a realistic scenario, as it takes data from the EDP's and estimates an extra ten years of life for the reused tiles after cleaning.

6.5.6.5 *Without extra cleaning costs + Higher lifespan*

This scenario combines the "higher lifespan" scenario with the "Without extra cleaning costs" scenario. Based on the PDE's to estimate the lifespan and not taking into account the extra costs for clean-up.

Name	BC	BM1	BM2 -Concrete Double-S-	BM2 -Clay Double-S-	BM2 -Cladding Clay-
Non-recurring income			39,555	39,555	39,555
Net present Value without residual Value	-264,580	-185,207	-245,917	-255,967	-319,627
Residual value	21,475	1,967	21,475	29,849	37,547
Net present value	-243,105	-183,240	-224,441	-226,118	-282,079

Figure 6.48: Scenario 6 Results

This can be considered the most optimistic scenario. Still the "Net Savings" for BM2-3 remain negative.

6.5.6.6 *Comparison and Analysis of Scenarios*

1-CASE STUDY

Name	BC	BM1 - -Concrete-	BM1 - -Clay-	BM2 - -Concrete Double-S-	BM2 - -Clay Double-S-	BM2 - -Cladding Clay-
Net present value	-264,580	-280,047	-273,224	-263,362	-251,026	-308,912

CONSERVATIVE

2-10 EXTRA YEARS OF USEFUL LIFE FOR REUSED TILES

Name	BC	BM1 - -Concrete-	BM1 - -Clay-	BM2 - -Concrete Double-S-	BM2 - -Clay Double-S-	BM2 - -Cladding Clay-
Net present value	-264,580	-245,832	-241,931	-259,361	-247,025	-304,911

REALISTIC

3-WITHOUT EXTRA CLEANING COSTS

Name	BC	BM1 -Concrete-	BM1 -Clay-	BM2 -Concrete Double-S-	BM2 -Clay Double-S-	BM2 -Cladding Clay-
Net present value	-264,580	-261,288	-254,465	-254,919	-242,583	-300,468

OPTIMISTIC

4-HIGHER LIFESPAN 1

Name	BC	BM1	BM2 - -Concrete-	BM2 - -Clay Double-S-	BM2 - -Cladding clay-
Net present value	-243,105	-201,999	-232,885	-234,562	-290,523

OPTIMISTIC

5-HIGHER LIFESPAN 2

Name	BC	BM1 - -Concrete-	BM1 - -Clay-	BM2 - -Concrete Double-S-	BM2 - -Clay Double-S-	BM2 - -Cladding Clay-
Net present value	-243,105	-240,678	-240,140	-237,886	-239,563	-295,524

REALISTIC

6-NO EXTRA CLEANING COSTS+HIGHER LIFESPAN

Name	BC	BM1	BM2 -Concrete Double-S-	BM2 -Clay Double-S-	BM2 -Cladding Clay-
Net present value	-243,105	-183,240	-224,441	-226,118	-282,079

VERY OPTIMISTIC

Figure 6.49: Results of all the scenarios (appendix A.2.21)

In the light of the results, it is interesting to look at circular models.

In all but the most conservative scenario and only for BM1, the models provide Net Savings either, higher or lower (excluding BM2-3 with cladding tiles which does not provide Net Savings in any scenario).

Even in the most conservative scenario where BM1 does not provide Net Savings, the total costs are very similar to those of the Base case. And even though they are somewhat higher this BM1 provides certain advantages already discussed in the section 6.5.4.

It can therefore be determined that in this specific case study, the models (with the exception of BM2-3) with the proposed solutions, in the circumstances discussed and with the assumptions made, are economically sustainable, reaffirming the perspective and conclusions made in the analysis of the results of the main scenario. section 6.5.4.

6.5.7 Other

It should be noted that during the course of the project, although not within the scope of the it, other evaluations were carried out using LCC in order to test assumptions and explore possibilities.

An assessment at component level (taking into account the whole roof, and the impact of the other components on the costs) was carried out, yielding similar results appendix A.1.6.

In addition, the area level evaluation was started, but could not be finalised due to lack of information at the time of case development and the need for too many assumptions that would make the results much more imprecise.

Finally, an analysis was attempted from a so-called ”theoretical” perspective, in which the industrial margin and structural costs were applied to all costs, in order to try to extract the effect of the structures of the companies with which we are working. Being based in too many assumptions the results are assumed to have a too high variability.

LCC-Tiles Theorical persp.

		BC	BM1-1	BM1-2	BM2-1	BM2-2	BM2-3
Initial co:	0	23522	62269	62269		10413	10413
	2	153352	32035	32035		157970	206012
	NPV	**205251**	**216549**	**213502**		**180644**	**232415**

Figure 6.50: ”Theoretical Perspective” Results

Each analysis may have different connotations, however, after these tests, it was found that the assessment made with the available data and the information to be achieved was the most interesting for this particular case.

6.6 Partial Conclusion

After the elaboration of the case the following conclusions can be drawn:

- Based on the results analysis (section 6.5.4) and the assessment of other scenarios (section 6.5.6.6), it can be concluded that the proposed circular models can be attractive from an economic point of view, taking into account all the vicissitudes of the case discussed during the results analysis.

  This confirms the actual feasibility of applying circular models in the sector today, which is expected to improve in the coming years with the entry of new enablers and developments.

- It can also be concluded that the LCC model is an assessment method that adapts quite well to circular models, and presents results of interest for decision making, taking into account the entire life cycle.
  It has indeed been observed in this case study that it can leave out specific considerations of product circular design. An aspect that should be taken into account and evaluated in some way.

- Analysing the LCCbyg tool, it can be concluded that it facilitates the elaboration of evaluations and allows quick and easy changes once the model has been elaborated. Moreover, it is a visual tool and easy to learn. Perhaps it could be further improved to facilitate its adaptation to circular models or to automate some more indicators directly, such as ”Net Savings”, and ”Initial Costs”.

Finally, it should be noted that further work is needed to address better the availability of data in the design phase for modelling, as this continues to be one of the problems in making the most reliable evaluations possible. Another interesting point for further study is the consideration, within the design stage, of the exact moment to develop the different iterations for the assessments to have reliable information and assumptions and to have a greater impact on decision making.

7 DISCUSSION

In the course of the discussion, various directions from which the study could be continued, future steps identified as interesting and certain relevant points to be taken into account about the project, will be discussed.

Throughout the literature review, a wide variety of conceptual frameworks, indicators and evaluation methods have been presented, applying some circular business models at the product level and an economic assessment in the case study. That is why it has been noticed, that it could be interesting to continue working in this sense and test more frameworks and evaluation methods at all levels to see their possible applicability to decision-making and circular projects.

In this sense, it would be also interesting for future work to try to implement the two proposed indicators (LS(E)IR and EENS) in a case to be able to analyse their functioning or their possible usefulness.

For the case study, a sensitivity analysis on demolition costs, either on the main scenario or on another of the scenarios presented, would provide relevant information. For other studies, the possibility of studying the risk with an integrated risk assessment instead of a sensitivity analysis could be considered, which could be interesting to try to develop in the future.

From the results, it should be noted that the proposed model of clay tiles with cladding fastening systems does not show economic interests in the assessments. However, it should be evaluated for the decision making whether the positive impacts of these tiles (in terms of ease of disassembly or aesthetics) compensate for the extra costs. It could be interesting for future studies to integrate these terms for evaluation to facilitate decision-making (either qualitatively or quantitatively).

Also note, that an economic analysis in the design phase is always based on some assumptions that give variability to the results. However, the fewer assumptions and the more certainties there are, the more accurate the results will be, and the more confidence can be placed in them. On this premise, although the results of the cases are valued positively for decision making, there is still little information on soft selective demolition costs in the sector to back up the estimates made. Continuing carrying out real projects that provide more details on actual up-to-date costs will be essential to encourage the developing and implementation of selective demolition models. Furthermore, the timing of the case is also important; the information available on the condition of the tiles would have been more accurate if it had been carried out a few months later with a test to determine their actual condition (appendix A.1.5).

On the other hand, it would be interesting to integrate the obtained results in the case study (economic assessment) with the environmental or even social assessments, either with other evaluation models or high-level indicators such as those presented in section 5.1.

Besides, in order to deal with new practical cases, the adoption of a meso-level approach could allow the analysis of other interests than those seen from the micro-level study. Indeed, other factors emerge and different roles, synergies and considerations may emerge, taking advantage of more diversified strategies and business models

Finally, It should be stressed the importance of monitoring and surveillance in these projects, even if it is a task that does not provide information in the short term, will help to verify the models produced in the design phases and their accuracy.

8 CONCLUSION

Throughout this project, the aim has been to address different issues of the circular economy in buildings.

From the study of the literature it has been tried to:

1. Provide a clear vision of CE and its role in building, analyse the capacity to enhancement the supply chain, waste management and design stages towards circular models and provide a review of enablers and highlight their importance as a lever for conversion to circular models.
2. Clarify the concepts and differences between BM's, conceptual frameworks, strategies, actions and methodologies, review different conceptual frameworks and propose a classification of strategies for design assistance.
3. Provide an insight into some interesting indicators for CE in the Building sector observed in the literature, provide an insight into the main current assessment models (with particular emphasis on the most relevant ones for measurement and decision-making at the design stage), and propose two high-level indicators (EENS and LS(E)IR).

From the case study the aim is to investigate the economic viability of applying different circular business models on the roof tiles of Gadehavegård.

This, in turn, has made it possible to analyse at a practical level (with a view to academic interest) other issues such as the advantages and usefulness in a real case of applying the LCC model for decision making in the design phase, the usability of the LCCbyg tool and to address the problem of poor availability of data in the design phase.

Based on the results of the literature and the case study, it can be concluded that:

- Conceptual frameworks and strategies classification are valuable tools for the early stages of design for idea generation and communication. But specific frameworks are needed for circular models as traditional ones leave out essential concepts.
- The BM design process depends on the characteristics of the case and the developers, but having tools and knowledge facilitates the process.
- Circular models can be attractive from an economic point of view and confirms the actual feasibility of applying circular models in the sector today, which is expected to improve in the coming years with the entry of new enablers and developments (as CO2 tax).
- Applying assessment and measurement methods in the design stages helps to provide a better basis for decision making, even if there is limited data available, and the variability is not as tight due to the assumptions made. It will be essential to update the assessments as projects progress in order to control and monitor the decision.
- The LCC model is an assessment method that adapts well to circular models, and presents results of interest for decision making, taking into account the entire life cycle. (Even it can leave out some specific considerations as product circular design).

- The LCCbyg is a useful tool that facilitates the elaboration of assessments and adapt well to circular models, even it could be further improved in this way or by including some other indicators.

After this study, it has been seen that the progress in this area is increasing, and there are more forces towards change on the part of institutions and companies, which observe the real needs and new opportunities.

Nevertheless, it is essential to continue to reiterate the concepts, so that they are clear and not distorted; to continue to work on the development of assessment methods and new business models, and their application in projects to increase efficiency and sustainability; continue to address the problem of data availability and uncertainty, which remains one of the problems for reliable assessments.

Bibliography

[1] Robert C. Brears. “Building Circular Economy Cities”. In: *The Palgrave Handbook of Climate Resilient Societies* (2021), pp. 755–777. DOI: 10.1007/978-3-030-42462-6{_}3.

[2] OECD. *The Economic Consequences of Climate Change*. OECD, Nov. 2015. ISBN: 9789264235403. DOI: 10.1787/9789264235410-en. URL: https://www.oecd-ilibrary.org/environment/the-economic-consequences-of-climate-change_9789264235410-en.

[3] *Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II*. Tech. rep. Washington, DC: U.S. Global Change Research Program, 2018. DOI: 10.7930/NCA4.2018. URL: https://nca2018.globalchange.gov/.

[4] *World Population Prospects The 2017 Revision*. Tech. rep.

[5] *Environmental Impacts of Renewable Energy Technologies | Union of Concerned Scientists*. URL: https://www.ucsusa.org/resources/environmental-impacts-renewable-energy-technologies.

[6] *Links - LCCbyg*. URL: https://lccbyg.dk/lccipraksis/links/.

[7] Brian R. Keeble. “The Brundtland Report: 'Our Common Future'”. In: *Medicine and War* 4.1 (1988), pp. 17–25. ISSN: 07488009. DOI: 10.1080/07488008808408783.

[8] *Sustainable Development*. URL: https://en.unesco.org/themes/education-sustainable-development/what-is-esd/sd.

[9] Anne P.M. Velenturf and Phil Purnell. “Principles for a sustainable circular economy”. In: *Sustainable Production and Consumption* 27 (2021), pp. 1437–1457. ISSN: 23525509. DOI: 10.1016/j.spc.2021.02.018. URL: https://doi.org/10.1016/j.spc.2021.02.018.

[10] Omar Alhawari et al. “Insights from circular economy literature: A review of extant definitions and unravelling paths to future research”. In: *Sustainability (Switzerland)* 13.2 (2021), pp. 1–22. ISSN: 20711050. DOI: 10.3390/su13020859.

[11] Richard J. Hobbs, Eric Higgs, and James A. Harris. “Novel ecosystems: implications for conservation and restoration”. In: *Trends in Ecology & Evolution* 24.11 (Nov. 2009), pp. 599–605. ISSN: 0169-5347. DOI: 10.1016/J.TREE.2009.05.012.

[12] Neal Millar, Eoin McLaughlin, and Tobias Börger. “The Circular Economy: Swings and Roundabouts”. In: *Ecological Economics* 158 (Apr. 2019), pp. 11–19. ISSN: 0921-8009. DOI: 10.1016/J.ECOLECON.2018.12.012.

[13] Álvarez Pelegry and Eloy Mosácula Atienza. “Energía y Edificación Implicaciones de la normativa energética y potencial de ahorro en rehabilitación”. In: (). ISSN: 2340-7638.

[14] *Circle House-Denmark's first circular housing project*. Tech. rep.

[15] Rafaela Tirado et al. “Challenges and Opportunities for Circular Economy Promotion in the Building Sector”. In: *Sustainability (Switzerland)* 14.3 (2022), pp. 0–17. ISSN: 20711050. DOI: 10.3390/su14031569.

[16] Lejerbo, MT Højgaard, and 3XN. “Circle House”. In: august (2018), p. 124.

[17] *Cirkulær økonomi og ressourceeffektivitet*. URL: https://mst.dk/affald-jord/affald/cirkulaer-oekonomi-og-ressourceeffektivitet/.

[18] *Towards a circular economy: Business rationale for an accelerated transition*. URL: https://ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition.

[19] Ralph Bicknese et al. “Buildings That Last:Design for Adaptability, Deconstruction, and Reuse”. In: (2021).
[20] Peter Graham and Centre for Sustainable Build Environment (UNSW). “Environment design guide design for adaptability - An introduction to the principles and basic strategies”. In: April 2001 (2005).
[21] Green Paper. “adskillelse”. In: september (2020).
[22] *3XN*. URL: https://gxn.3xn.com/project/circle-house.
[23] Roberto Minunno et al. “Strategies for applying the circular economy to prefabricated buildings”. In: *Buildings* 8.9 (2018). ISSN: 20755309. DOI: 10.3390/buildings8090125.
[24] Flora Poppelaars. “Designing for a Circular Economy”. In: *Postnote* 536.536 (2014), p. 77. URL: http://researchbriefings.parliament.uk/ResearchBriefing/Summary/POST-PN-0536#fullreport.
[25] Martin Christopher. “Logistics and Supply Chain Management: Strategies for Reducing Cost and Improving Service (Second Edition)”. In: 2.1 (Apr. 2007), pp. 103–104. ISSN: 1367-5567. DOI: 10.1080/13675569908901575.
[26] Olugbenga O. Akinade and Lukumon O. Oyedele. “Integrating construction supply chains within a circular economy: An ANFIS-based waste analytics system (A-WAS)”. In: *Journal of Cleaner Production* 229 (2019), pp. 863–873. ISSN: 09596526. DOI: 10.1016/j.jclepro.2019.04.232. URL: https://doi.org/10.1016/j.jclepro.2019.04.232.
[27] Mohammed Haneef Abdul Nasir et al. “Comparing linear and circular supply chains: A case study from the construction industry”. In: *International Journal of Production Economics* 183 (2017), pp. 443–457. ISSN: 09255273. DOI: 10.1016/j.ijpe.2016.06.008. URL: http://dx.doi.org/10.1016/j.ijpe.2016.06.008.
[28] Muhammad Farooque et al. “Circular supply chain management: A definition and structured literature review”. In: *Journal of Cleaner Production* 228 (2019), pp. 882–900. ISSN: 09596526. DOI: 10.1016/j.jclepro.2019.04.303. URL: https://doi.org/10.1016/j.jclepro.2019.04.303.
[29] Lejerbo, MT Højgaard, and 3XN. “Circle House”. In: April (2018), p. 124.
[30] *SCOR Model*. URL: https://scor.ascm.org/processes/introduction.
[31] Marcus Linder, Steven Sarasini, and Patricia van Loon. “A Metric for Quantifying Product-Level Circularity”. In: *Journal of Industrial Ecology* 21.3 (June 2017), pp. 545–558. ISSN: 1530-9290. DOI: 10.1111/JIEC.12552. URL: https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12552%20https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.12552%20https://onlinelibrary.wiley.com/doi/10.1111/jiec.12552.
[32] *Database - Eurostat*. URL: https://ec.europa.eu/eurostat/data/database.
[33] Lejerbo, MT Højgaard, and 3XN. “Circle House”. In: september (2018), p. 124.
[34] *Affaldsbekendtgørelsen*. URL: https://mst.dk/affald-jord/affald/indsamleruddannelsen/affaldsregulering/affaldsbekendtgoerelsen/.
[35] *Circular Building Assessment Prototype - BAMB*. URL: https://www.bamb2020.eu/post/cba-prototype/.
[36] *Raw Materials Information System*. URL: https://rmis.jrc.ec.europa.eu/.
[37] *Level(s)*. URL: https://environment.ec.europa.eu/topics/circular-economy/levels_en.
[38] *Ressourcekortlægning af bygninger*. URL: https://mst.dk/service/publikationer/publikationsarkiv/2018/apr/ressourcekortlaegning-af-bygninger/.
[39] *Circular IQ*. URL: https://circular-iq.com/.
[40] *Den frivillige bæredygtighedsklasse*. URL: https://baeredygtighedsklasse.dk/.
[41] *Circular economy action plan*. URL: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en.

[42] Circle House Lab Bloxhub. “Forretningsmodeller”. In: *Bloxhub, Green Paper* Green Pape (2021), pp. 1–75.
[43] Robert H.W. Boyer et al. “Product Labels for the Circular Economy: Are Customers Willing to Pay for Circular?” In: *Sustainable Production and Consumption* 27 (2021), pp. 61–71. ISSN: 23525509. DOI: 10.1016/j.spc.2020.10.010. URL: https://doi.org/10.1016/j.spc.2020.10.010.
[44] *MILJØVURDERINGER I BYGGEBRANCHEN*. Tech. rep. URL: https://www.teknologisk.dk/ydelser/baeredygtigt-byggeri/miljoevurderinger-i-byggebranchen/30894,8..
[45] *Circle Bank – Construction made circular*. URL: https://circlebank.dk/.
[46] Ellen Macarthur Foundation. *First steps towards a circular built environment*. Tech. rep.
[47] Circle House. “Fra Principper Til Praksis Realisering af ejendomsinvesteringer”. In: ().
[48] Elena Fregonara et al. “Economic-environmental indicators to support investment decisions: A focus on the buildings’ end-of-life stage”. In: *Buildings* 7.3 (July 2017). ISSN: 20755309. DOI: 10.3390/buildings7030065.
[49] Graeme English, Andrea Charlson, and Martin Anker-tilsted. “D3.5 Business case for database and marketing strategy - Circular Construction In Regenerative Cities”. In: 821201 (2021).
[50] Dennis Vegter, Jos van Hillegersberg, and Matthias Olthaar. “Supply chains in circular business models: processes and performance objectives”. In: *Resources, Conservation and Recycling* 162.May (2020), p. 105046. ISSN: 18790658. DOI: 10.1016/j.resconrec.2020.105046. URL: https://doi.org/10.1016/j.resconrec.2020.105046.
[51] Martin Geissdoerfer et al. “Circular business models: A review”. In: *Journal of Cleaner Production* 277 (2020), p. 123741. ISSN: 09596526. DOI: 10.1016/j.jclepro.2020.123741. URL: https://doi.org/10.1016/j.jclepro.2020.123741.
[52] Graeme Heyes et al. “Developing and implementing circular economy business models in service-oriented technology companies”. In: *Journal of Cleaner Production* 177 (2018), pp. 621–632. ISSN: 09596526. DOI: 10.1016/j.jclepro.2017.12.168. URL: https://doi.org/10.1016/j.jclepro.2017.12.168.
[53] *Business Model Generation*. URL: businessmodelgeneration.com.
[54] Piera Centobelli et al. “Designing business models in circular economy: A systematic literature review and research agenda”. In: *Business Strategy and the Environment* 29.4 (2020), pp. 1734–1749. ISSN: 10990836. DOI: 10.1002/bse.2466.
[55] Mateusz Lewandowski. “Designing the business models for circular economy-towards the conceptual framework”. In: *Sustainability (Switzerland)* 8.1 (2016), pp. 1–28. ISSN: 20711050. DOI: 10.3390/su8010043.
[56] Y. Osterwalder A.; Pigneur. *Business Model Generation: A Handbook for Visionaries, Game Changers, And Challengers*. 2010.
[57] Julian Lauten-Weiss and Stephan Ramesohl. “The circular business framework for building, developing and steering businesses in the circular economy”. In: *Sustainability (Switzerland)* 13.2 (2021), pp. 1–14. ISSN: 20711050. DOI: 10.3390/su13020963.
[58] Marina P.P. Pieroni, Tim C. McAloone, and Daniela C.A. Pigosso. “Circular economy business model innovation: Sectorial patterns within manufacturing companies”. In: *Journal of Cleaner Production* 286 (2021), p. 124921. ISSN: 09596526. DOI: 10.1016/j.jclepro.2020.124921. URL: https://doi.org/10.1016/j.jclepro.2020.124921.

[59] *A framework for enabling circular business models in Europe — European Environment Agency*. URL: https://www.eea.europa.eu/publications/a-framework-for-enabling-circular.
[60] *How to Build a Circular Economy | Ellen MacArthur Foundation*. URL: https://ellenmacarthurfoundation.org/.
[61] Joan Manuel F. Mendoza et al. "Integrating Backcasting and Eco-Design for the Circular Economy: The BECE Framework". In: *Journal of Industrial Ecology* 21.3 (2017), pp. 526–544. ISSN: 15309290. DOI: 10.1111/jiec.12590.
[62] Michael Saidani et al. *A taxonomy of circular economy indicators*. Jan. 2019. DOI: 10.1016/j.jclepro.2018.10.014.
[63] *EASAC - Science Advice for the Benefit of Europe*. URL: https://easac.eu/.
[64] Author Ben Cartwright et al. *Recommendations on circularity indicators for WP8*. Tech. rep. 2021, pp. 1–71.
[65] Nouman Khadim et al. "Critical review of nano and micro-level building circularity indicators and frameworks". In: *Journal of Cleaner Production* 357.October 2021 (2022), p. 131859. ISSN: 09596526. DOI: 10.1016/j.jclepro.2022.131859. URL: https://doi.org/10.1016/j.jclepro.2022.131859.
[66] Alejandro Padilla-Rivera et al. "Social circular economy indicators: Selection through fuzzy delphi method". In: *Sustainable Production and Consumption* 26 (2021), pp. 101–110. ISSN: 23525509. DOI: 10.1016/j.spc.2020.09.015. URL: https://doi.org/10.1016/j.spc.2020.09.015.
[67] *Social Cities Index — IFHP*. URL: https://www.ifhp.org/social-cities-index.
[68] Linda Braakman, Silu Bhochhibhoya, and Robin de Graaf. "Exploring the relationship between the level of circularity and the life cycle costs of a one-family house". In: *Resources, Conservation and Recycling* 164.September 2020 (2021), p. 105149. ISSN: 18790658. DOI: 10.1016/j.resconrec.2020.105149. URL: https://doi.org/10.1016/j.resconrec.2020.105149.
[69] Verberne Joachim Hermanus Jacobus. "Building circularity indicators-An approach for measuring circularity of a building". 2016.
[70] *Material Circularity Indicator (MCI)*. URL: https://ellenmacarthurfoundation.org/material-circularity-indicator.
[71] Durmisevic Elma. "Transformable building structures: design for disassembly as a way to introduce sustainable engineering to building design & construction". 2006.
[72] IDEAL & CO Explore. *Circularity Calculator*. URL: http://www.circularitycalculator.com/#us.
[73] Nevin Cohen and Paul Robbins. "Social Return on Investment". In: *Green Business: An A-to-Z Guide* January (2012). DOI: 10.4135/9781412973793.n132.
[74] Erwan Mouazan and Clive Peckham. "CESME Circular Economy & Return On Investment Toolbox". In: ().
[75] Roberto Carvallo. "Cálculo del Retorno Social de la Inversión". In:
[76] Claudia Peña et al. "Using life cycle assessment to achieve a circular economy". In: *International Journal of Life Cycle Assessment* 26.2 (2021), pp. 215–220. ISSN: 16147502. DOI: 10.1007/s11367-020-01856-z. URL: https://doi.org/10.1007/s11367-020-01856-z.
[77] Michael Z Hauschild, Ralph K Rosenbaum, and Stig Irving Olsen. *Life Cycle Assessment*. Tech. rep.
[78] Maria Saridaki and Kim Haugbølle. "Towards sustainable design: Integrating data from operation of buildings in design practices". In: *IOP Conference Series: Earth and Environmental Science* 588.5 (2020). ISSN: 17551315. DOI: 10.1088/1755-1315/588/5/052051.

[79] *¿Qué es Balanced Scoredcard o cuadro de mando integral?* URL: https://www.globalsuitesolutions.com/es/que-es-balanced-scorecard/.

[80] Andrea Charlson. *D7.2 Template business cases for built environment - Circular Construction In Regenerative Cities*. 2021.

[81] Katrine Hauge Smith et al. "Ressource Blokken Ressource Blokken". In: ().

[82] Vaerdibyg. "Totaløkonomiske metoder". In: ().

[83] Gambale. "EPD of CONCRETE ROOF TILE "COPPO MEDITERRANEO WITH GROUT SURFACE"". In: (2010), pp. 1–11.

[84] EPD Denmark. *Epd - Dobbelt-S, Vinge Økonomi - IBF*. Tech. rep. 2021, pp. 1–10. URL: www.epddanmark.dk.

[85] *Tejas de barro vs Tejas de hormigón - Pros y contras*. URL: https://tejasverea.com/tejas-de-barro-vs-tejas-de-hormigon-pros-y-contras/.

[86] *How Long Does Concrete Tile Roofs Last? - Behmer Roofing*. URL: https://behmerroofing.com/how-long-does-concrete-tile-roofs-last/.

[87] *Pros and Cons Concrete Roof Tiles*. URL: https://www.roofcalc.com/pros-and-cons-concrete-roof-tiles/.

[88] EPD Denmark. "3rd Party Verified EPD Clay Tiles - Randers Tegl". In: (2018), pp. 1–12.

[89] *Have You Heard? Clay Roof Tiles Have A Lifespan Of Up To 150 Years | Go Smart Bricks*. URL: https://gosmartbricks.com/clay-roof-tiles-lifespan-150-years/.

[90] *Molio Prisdatabaser - Introduktion - Hjælp og træning - Community | Sigma Estimates A/S*. URL: https://wpstagingcommunitydk.sigmatest.dk/support_artikel/molio-prisdatabaser-introduktion/.

[91] *IBF Dobbelt-S teglrød tagsten*. URL: https://www.ibf.dk/professionel/Dobbelt-S-sort-b2b-Kopier/SW10275.

[92] *Generador de precios de la construcción. CYPE Ingenieros, S.A.* URL: http://www.generadordeprecios.info.

[93] Heidi Simone Kristensen and Mette Alberg Mosgaard. "A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability?" In: *Journal of Cleaner Production* 243 (2020), p. 118531. ISSN: 09596526. DOI: 10.1016/j.jclepro.2019.118531. URL: https://doi.org/10.1016/j.jclepro.2019.118531.

[94] Pedro Nuñez-Cacho et al. "What gets measured, gets done: Development of a Circular Economy measurement scale for building industry". In: *Sustainability (Switzerland)* 10.7 (July 2018). ISSN: 20711050. DOI: 10.3390/su10072340.

[95] *¿Qué son los métodos de costes direct costing y full costing?* URL: https://www.unir.net/empresa/revista/direct-costing-full/.

[96] *Contabilidad analítica: Full cost y direct cost. - Business ControllerBusiness Controller*. URL: https://comunidad.iebschool.com/jordirodriguez/2020/05/14/contabilidad-analitica-full-cost-y-direct-cost/.

[97] Dansk Standard Danish Standards Association. "Betontagsten og tilbehør til tag- og vægbeklædning – Prøvningsmetode Concrete roofing tiles and fittings for roof covering". In: (2022).

[98] Dansk Standard Danish Standards Association. "Dansk standard Betontagsten og tilbehør til tag- og vægbeklædning – Produktspecifikationer Concrete roofing tiles and fittings for roof covering and". In: (2022).

[99] BP. *Full report – Statistical Review of World Energy 2021*. Tech. rep.

[100] Piero Morseletto. "Targets for a circular economy". In: *Resources, Conservation and Recycling* 153.October 2019 (2020), p. 104553. ISSN: 18790658. DOI: 10.

1016/j.resconrec.2019.104553. URL: https://doi.org/10.1016/j.resconrec.2019.104553.

[101] *Building a Circular Supply Chain for a Circular Economy*. URL: https://news.ewmfg.com/blog/building-a-circular-supply-chain-for-a-circular-economy.

[102] Żaneta Muranko et al. “Characterisation and environmental value proposition of reuse models for fast-moving consumer goods: Reusable packaging and products”. In: *Sustainability (Switzerland)* 13.5 (2021), pp. 1–35. ISSN: 20711050. DOI: 10.3390/su13052609.

A Appendix

A.1 Not included sections. For support

A.1.1 Layered Design

Layering can be done according to the cycles of use of the building. The primary key to the layered design is to ensure that layers do not overlap, thus preventing separation, disassembly and reuse [14], on the other hand, the aim is to extend the lifetime of each layer.

Besides, in a practical sense, the fewer the layers and the simpler the solutions, the better we are at designing for separation.

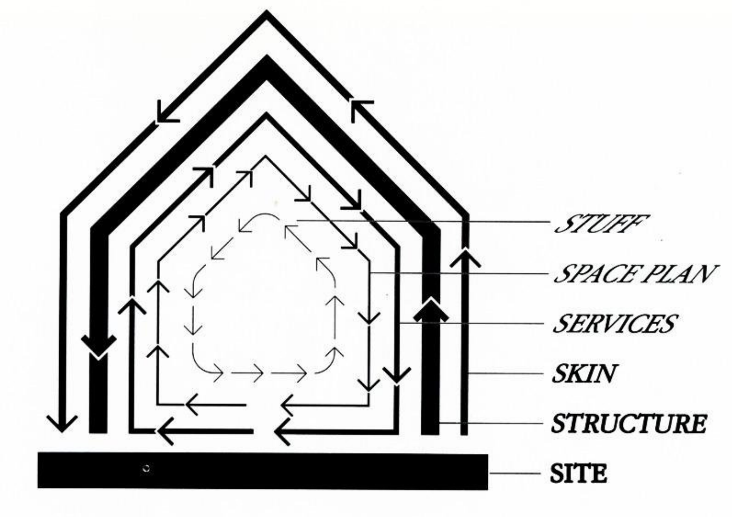


Figure A.1: Layers of a building

As seen in the picture, there is a consensus in the industry on the different coatings according to their service life. The definition and characteristics of each layer are as follows [14]:

- **Stuff:** This refers to all furniture, household appliances, utensils, etc., found in buildings. Although a life span of 5 to 10 years is established, historically their life span has generally been much longer. The current problem that the circular economy faces is the increasingly prevalent problem of fast consumption, driven by fashion, low quality and imminent obsolescence. It is essential to take stuff as a part of the total resources consumed in the building and consider it in its circularity.
- **Space plan:** These are the interior walls that divide the spaces and superficies. It is one of the components that is replaced the most, and it will try to optimise and facilitate versatility and adaptability without affecting the rest of the layers.
- **Services:** Historically, they have been designed to be inaccessible and not fully integrated, making maintenance and replacement difficult. The idea is to prepare them to be quickly accessible and uninstallable.
- **Skin**: The strategy for the skin would be to design it to be easily reformable, repairable and reusable. In other words, it can be disassembled without loss of value.

- **Structure:** Design along the same lines so that it can be easily disassembled and used for other buildings.

A.1.2 Innovative Examples of Selective Demolition projects

Almere, The Netherlands - HISER project: Demonstrates that selective demolition and recycling of concrete into new concrete is economically and environmentally efficient. The project has carried out life cycle analyses and cost calculations and identified what best practice in selective demolition entails. According to the study, the precondition for economic and environmental benefits is that the recycling of resources takes place locally.

Hong Kong - ChinaSe: They have created computer models at Kai Tak airport in Hong Kong to simulate the work processes involved in the selective demolition of the airport. This simulation has made it possible to evaluate the cost-effectiveness of the processes.

A.1.3 *Other Relevant Studies*

Other relevant reviews or studies have been found, which we will not go into in depth, either because they are not focused on the construction sector or because they do not have a direct approach to decision making at the model design stage, but from which interesting indicators or ideas could also be drawn that could be applied in the sector.

The first of these [93] (not focused in the building sector), performs a review of indicators at product level, and also determines whether the indicator is a single quantitative indicator from applying an analytical tool or whether they are composite indicator sets. After this, it makes a division by categories and according to whether they are single or split focus indicators and determines which categories or sustainable dimensions each indicator covers, presenting a final graphic map where all the indicators are presented framed according to the dimensions they cover, as can be seen in the appendix A.2.22.

The second study [94] makes a selection of indicators both from the academic world and from different companies in the building sector, with which to measure the implementation of CE in the company (using a delphy approach[1] and CFA[2]). This study is not aimed at direct decision making, but rather focuses on a circular audit tool. However, many of the indicators may be relevant for application at other stages or levels [3].

The third study [62] makes a selection of 55 indicators and in addition, proposes a semi-automatic tool developed as an excel macro to make it easier to choose the proper indicators depending on several aspects, as the level, objectives or stage of implementation. This 55 indicators are not particularly focused in the building sector but some of the indicators could be interesting as well as the tool idea and classification. The list of indicators is attached in appendix A.2.24.

A.1.4 Traditional Costing Concepts

Cost accounting is the first step before other types of economic evaluation to determine the actual viability of a project. It is an analytical or internal accounting, which allows knowing

[1]By surveying a panel of experts.

[2]A statistical technique that verifies the factor structure of a set of observed variables.

[3]Use of the tool: With the group of indicators, a survey is carried out to evaluate the perceived relevance of each indicator in the company (from 1 to 7, with 1 being very low relevance and 7 being very high relevance). Afterwards, the results for each dimension are added up and weighted by the established weight of each indicator. After this, the new values are weighted again according to the weight of each section. The sum of all weighted dimensions describes the final value of the degree of implementation of the CB. The final weighted score will be between 1 and 7, where 1 means that a company does not implement CE at all and 7 is a company where CE is fully implemented [94].

the margins that will be available, pricing or analytical capacity for decision making (as in the case study). It can be applied to any project phase, as in this case in the design phase, for planning, although it is based on estimates and not on actual costs.

It is essential to decide which costs to take into account, as this will determine to a large extent, the results. Therefore, the existing costs and different models of traditional cost analysis are explained in the following.

Costs can be classified according to their degree of allocation as direct or indirect costs and their relation to the volume of activity as fixed and variable.

This depends on different variables such as the type of company, management criteria, depending on the volume (fixed), and behaving in other ways such as increasing, decreasing, constant, semi-variable, etc. (variable).

1. **Direct and indirect costs**
    - Direct: Cost of resource or activity that is required or used for a single cost object.
    - Indirect: Cost of a resource acquired for more than a single cost object.
2. **Fixed and variable costs**
    - Fixed: These are costs incurred in those that are acquired in anticipation of the work to be carried out by the company as a whole.
    - Variables: Costs proportional to the amount of resources used or consumed.

It should be noted that both variable and fixed costs can be direct or indirect. When a cost varies with an activity that supports different products, it is an indirect cost.

It should be noted that in cost analysis, direct costs are always incorporated and the difference between models will come from indirect costs.

Depending on this degree of incorporation of indirect costs into cost analysis, we can talk about different models, which are listed below and a brief mention of each one, explaining their advantages and limitations:

1. **Functional costing:** This system allocates only objective costs, combining financial and analytical accounting, in this system the semi-direct or indirect costs of general company functions are not distributed (overhead costs).
2. **Full Costing:** This system allocates all costs, both fixed (overhead and administration costs) and variable costs.
    - Usefulness: can be used for price calculation. It is useful when manufacturing under budget (for projects with an almost fixed price), or to compare companies in the same sector [95].
    - Disadvantages: It does not offer adequate information to make decisions about the real interest of undertaking or not undertaking a work. Difficult to allocate indirect costs (there is no objective criterion). And it does not provide accurate information for pricing policy (estimation of industrial benefits to be applied) [95].
3. **Direct Costing:** Only variable costs (e.g. raw materials, salaries of employees involved in the production process or direct labour) are allocated, while fixed costs are

considered as structural or period costs, as they represent the burden of maintaining the permanent structure of the company.

- Usefulness: Useful when the direct costs represent a large part of the total costs of the company, to know and compare different business models to be applied in the same project by recognising the costs directly associated with each business model in a clean and pure way without adulteration of the data with costs of the company or companies that will execute the project. Very useful for decision making.
- Advantages: Allows estimation of the profitability threshold and orientation of the pricing policy, helps to determine more accurately the minimum prices below which it is not interesting to undertake a project. It facilitates the selection of the most profitable projects.
- Disadvantages: Complicates the problem of allocating joint costs. It does not take into account the structural costs, with the danger that this implies in the event that these have a great weight in the company.

4. **Evolved Direct Costing:** Combines the classification of costs used in the Direct Costing model with the direct or indirect nature of the costs [96]. It allocates variable costs together with fixed costs directly attributable to the project (all direct costs). It is also a method for decision making.

All these models are systems used for traditional cost analysis, which are essential to know as a basis for more advanced models for decision-making in cost management.

This knowledge can be used and taken into account for elaborating the LCC by adapting it to the essence of a product life cycle cost analysis.

A.1.5 How to Assess the Remaining Lifespan of the Current Tiles

To carry out this study of the tiles and to have a more accurate estimation of the remaining years of the life of the tiles compared to the previous estimate of 28 years, specific tests can be carried out for verification, following the Danish standards [97] [98], using destructive testing by taking random samples of the coatings as indicated in the standard without entailing a significant loss of the final product. This method is recommendable in this case, as the product is supposed to be in large quantities, and conventional testing does not have a significant impact compared to non-destructive testing. It would be much simpler and cheaper to carry out.

A.1.6 Assessment at a Different Level (Component) - ROOF

For this LCC, the roof as a whole has been taken into account. The objective is to observe the impact of applying the different models when the rest of the roof materials are considered.

The procedure, although somewhat different from the previous ones on the reference LCC and mainly analysed (LCC for the tiles from the client's perspective taking Direct-Costing assumptions), will not go into as much detail in obtaining data.

The models analysed are the same as for the rest of the LCC. In the Molio calculations, several reference roofs have been selected depending on the selected tiles and materials, correction factors have been applied to correct the differences in tiles per m2 and correction factors have also been applied to the number of battens per square metre. It is verified that the rest of the materials and layers coincide.

On the other hand, in this case, the demolition prices are taken as dkk/m2 for the whole roof (not in the previous case where the price/m2 has been shelled out and obtained for the tiles only).

One of the significant differences, in this case, is that the demolition and consequently its cost is applied to the whole roof, not only to the part with tiles, as the study is not isolated to the product of the tiles but tries to obtain the costs of the roof refurbishment completely. Therefore the demolition will be applied to the 1197m2 of the existing roof at 60.77dkk/m2 in case of normal demolition and 117.46dkk/m2 in case of selective demolition, according to the data provided by Enemaerk and Petersen.

Base Case

A normal demolition is applied to the 1197m2 roof and the final roof of 962m2 is renovated at 550.1dkk/m2, with cement tiles.

Business Model 1

In this case the costs for demolition are estimated differently when taking into account the whole roof, on the one hand the costs for selective demolition of the tiled part of the roof, on the other hand the costs for demolition of the vaulted part, and finally the associated costs for the application of selective demolition on other roofs to obtain sufficient tiles for the renovation.

	Code			Quantity	Unit	Unit price (DKK)	Sum (DKK)	Description	
			Demolitions (Roof With tiles)	619	m2	117.46	72,708		
			Demolitions (Roof without tiles)	578	m2	60.77	35,125		
			Demolitions (Other roofs)	756	m2	56.69	42,858		
			Storage		m3				

Figure A.2

After this, two solutions have been developed as in the rest of the LCC, one with cement tiles and one with clay tiles. In both cases the costs of the first renovation are the same as they refer to the life-span of the reused cement tiles, as well as the demolition costs of these tiles from the first refurbishment.

To estimate the costs of the first renovation where the life-span of the current tiles is extended, Molio Prisdata has been used. First of all, the price of renovation of the complete roof has been estimated without taking into account the roof tiles, to which the cost of renovation of the part of the roof tiles has been added after estimating separately, but without taking into account the material cost of the roof tiles. That is:

- Cost of roof without tiles: 329427dkk
- Cost of the assembly of the tiles: 66323dkk
- Total cost: 395750dkk
- Cost per square metre: 411,38dkk/m2

The maintenance cost is estimated at 5,291dkk, which would be 1% of the cost of a complete renovation with concrete roof tiles, and the useful life for this first renovation is 28 years and is carried out in year 2.

For the second refurbishment, only the dismantling of the roof tiles is taken into account, which will be demolished using a shelled demolition for the roof tiles, so the demolition cost of 45dkk/m2 is used.

The differences between the two cases can be seen in the second renovation carried out in year 30.

For the costs of the second renovation, only the refurbishment costs for roof tiles are taken into account, as the rest of the roofing materials will be maintained. For cement, it will be 207.65dkk/m2 (50 years life span), while for clay tiles, it will be 216.46dkk/m2 (100 years life span) (reference all).

The maintenance costs will be 5.291dkk/m2*year for the concrete tile roof. In contrast, for the clay tile roof, it will be slightly higher, 5.829dkk/m2, taking into account that it refers to 1% of the total cost of a renovation to the use of concrete tiles for the first case and clay tiles for the second case, the second case being more expensive (the material has a higher cost).

- Concrete:

Code			Quantity	Unit	Unit price (DKK)	Sum (DKK)	Description
4.47		Roofs, surfaces *Primarily concrete, terrazzo and cement mortar*	962	m2	372.77	358,605	
		Demolition	962		45	43,290	Just for tiles
4.47		Roofs, surfaces *Primarily bricks and tiles*	962	m2	207.65	199,759	Just for tiles

Figure A.3

- Clay:

Code			Quantity	Unit	Unit price (DKK)	Sum (DKK)	Description
4.47		Roofs, surfaces *Primarily concrete, terrazzo and cement mortar*	962	m2	372.77	358,605	
		Demolition	962		45	43,290	Just for tiles
4.47		Roofs, surfaces *Primarily bricks and tiles*	962	m2	216.46	208,235	Just for tiles

Figure A.4

Business Model 2

The costs for roof demolition will be the same as in the previous model, but in this case no extra costs for demolition of other roofs have to be accounted for as the tiles will not be used for re-roofing but the recovered tiles will be sold, the income is the same as estimated in the LCC where only the tiles are taken into account.

Code			Quantity	Unit	Unit price (DKK)	Sum (DKK)	Description
		Demolitions	578	m2	60.77	35,125	
		Demolitions	619	m2	117.46	72,708	
		Income from tiles	433	m2	70.56	30,552	

Figure A.5

As in the case of the tile-only LCC, 3 possible solutions are presented. For each case the costs are estimated with Molio taking into account the complete renovation of the roofs and applying the corresponding factors.

- Concrete: 550.1ddk/m2
- Clay: 582.95dkk/m2
- Clay 2: 635,17dkk/m2

Results

With concrete tile reform:

- Initial costs:
  - 0 : 77,281 dkk
  - 2: 529,196 dkk (627,163 dkk Present Value)
- Maintenance: 128,345 dkk
- Net Present Value: 704,443 dkk

With clay tile reform:

- Initial costs:
  - 0: 77,281 dkk
  - 2: 560,798 dkk (604,325 dkk Present Value)
- Maintenance: 136,009 dkk
- Net Present Value: 681,606 dkk

With refurbishment of plain cladding clay roof tiles:

- Initial costs:
  - 0: 77,281 dkk
  - 2: 611,034 dkk (658,460 dkk Present Value)
- Maintenance: 148,193 dkk
- Net Present Value: 735,741 dkk

LCC-roof	Client pers.	Full-cost					
		BC	BM1-1	BM1-2	BM2-1	BM2-2	BM2-3
Initial co	0	72742	150691	150691	77281	77281	77281
	2	529196	395748	395748	529196	560798	611034
	NPV	699881	728123	724276	704433	681606	735741

Figure A.6

A.2 Graphic Documentation

A.2.1 Global and European Primary Energy Consumption

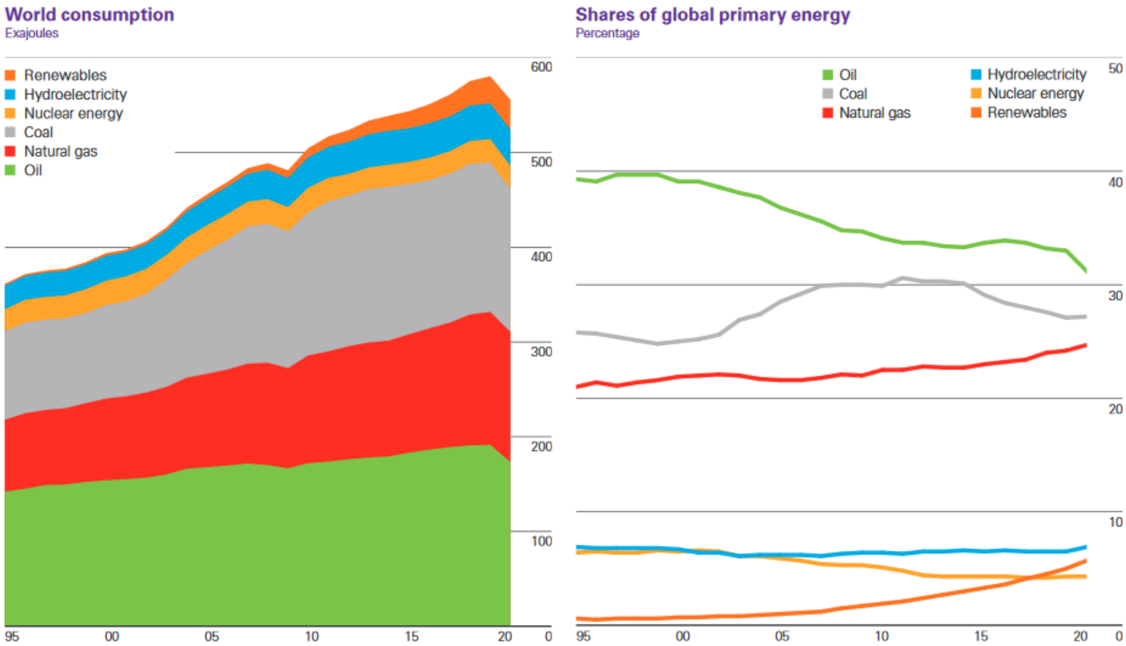


Figure A.7: Primary energy consumption and shares of GPE. Source:BP [99]

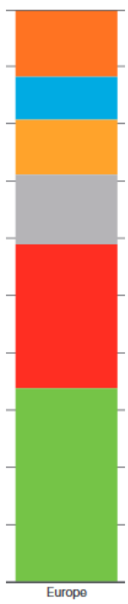


Figure A.8: European share of GPE. Source:BP [99]

A.2.2 Targets for 9r’s

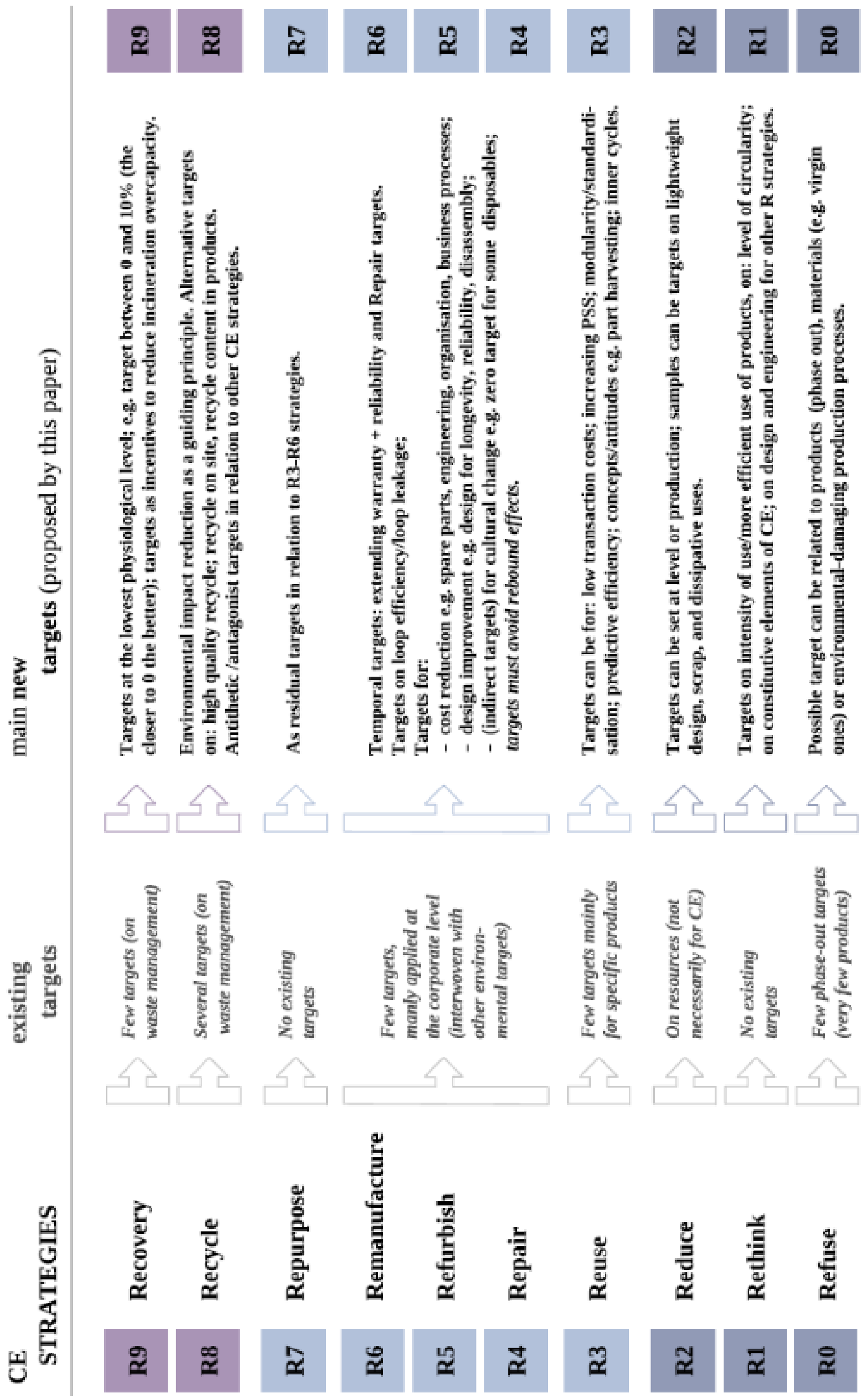
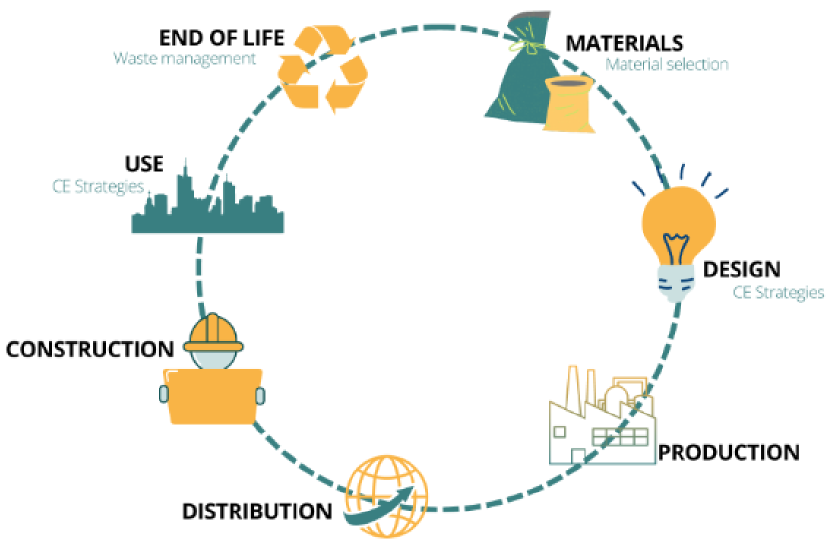


Figure A.9: 9r’s [100]

A.2.3 Stages of Construction Sector as a CE diagram



A.2.4 Needs for the supply chain in CE

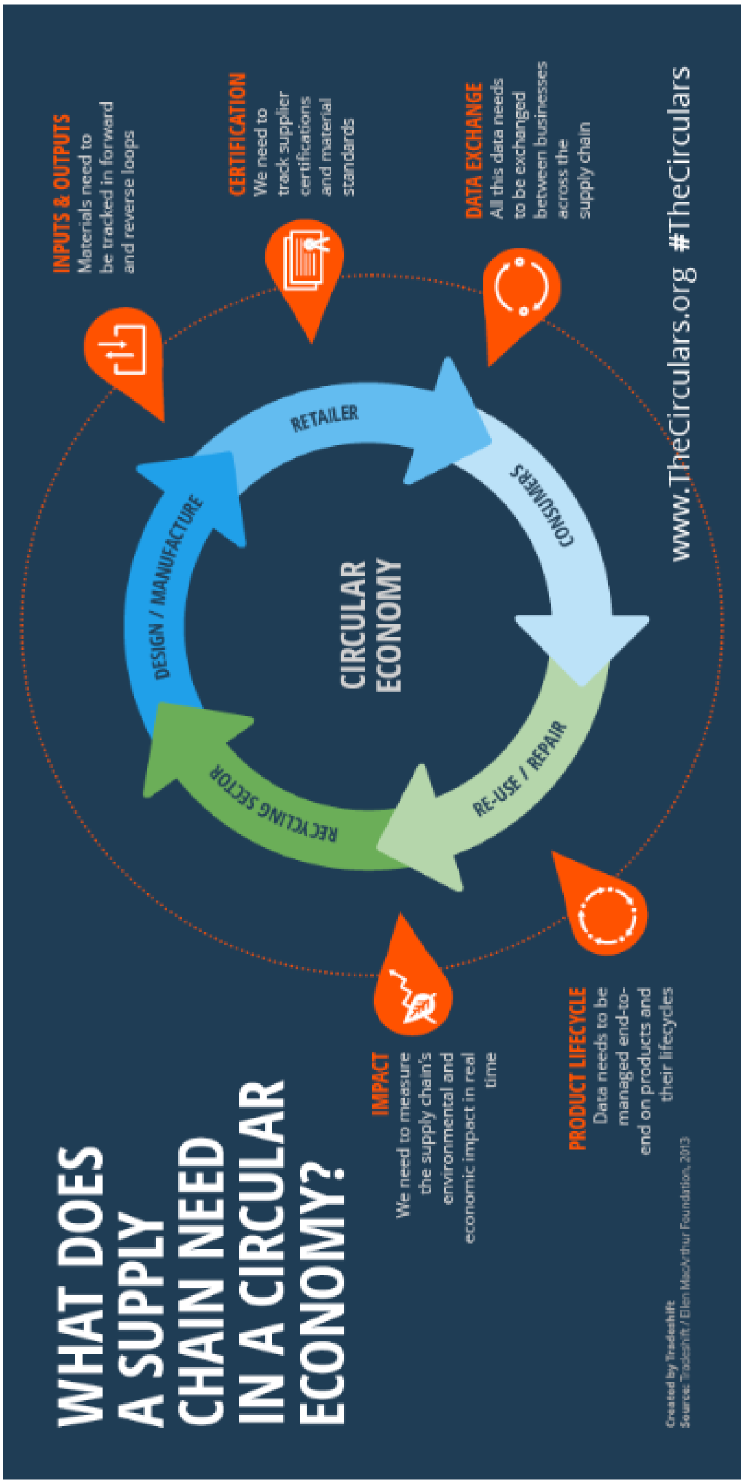


Figure A.10: [101]

A.2.5 Strategic Framework

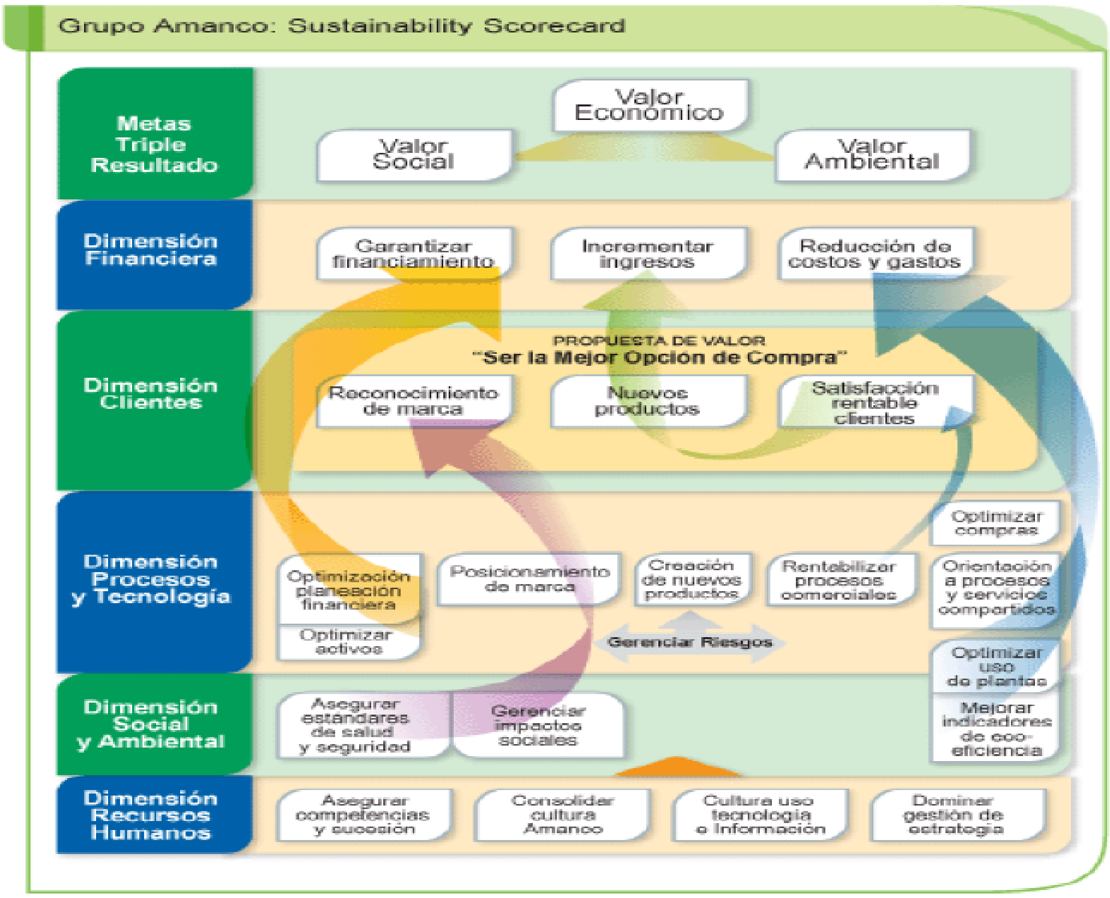


Figure A.11: Visual example of a strategy map of a Sustainable BSC model

A.2.6 SCI

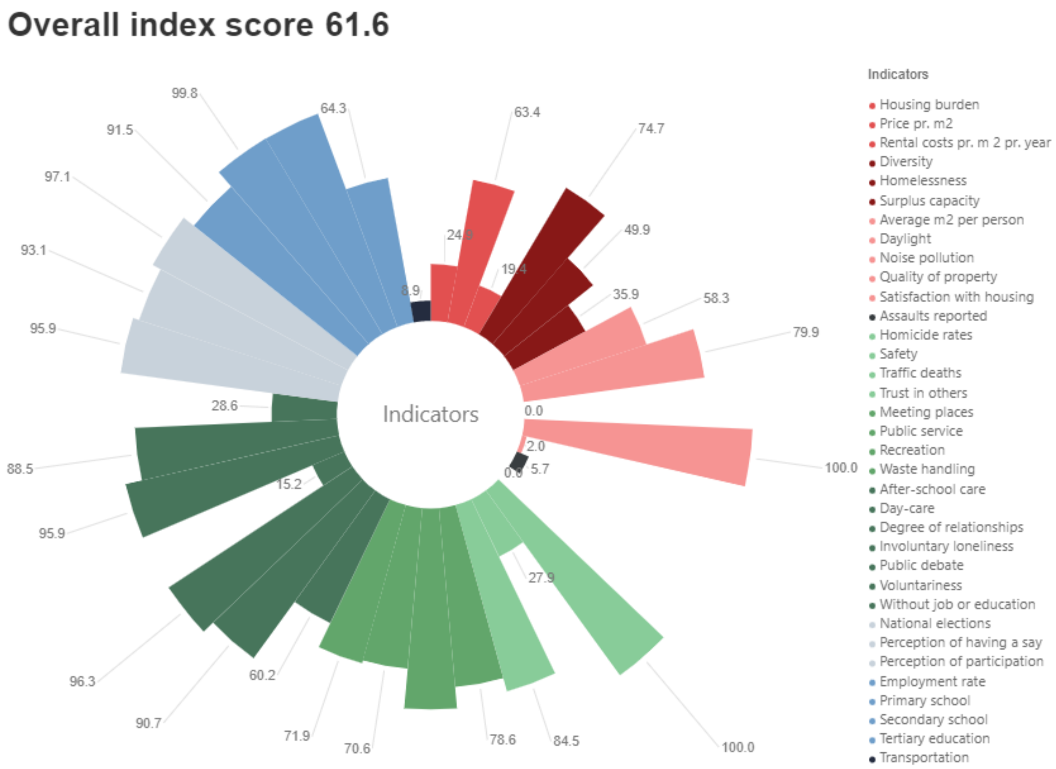


Figure A.12: Overall Index and the 35 indicators[64]

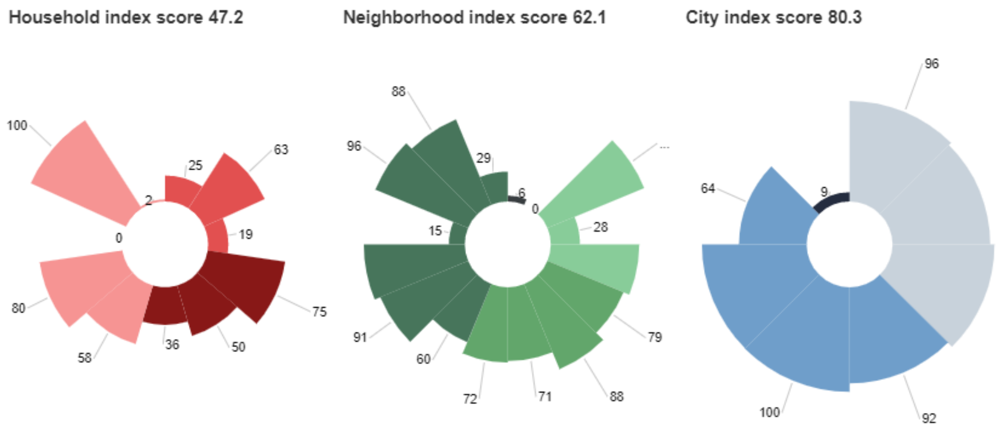


Figure A.13: Unaggregated Overall Index in household, neighbourhood and city[64]

A.2.7 Valuation techniques for indicators

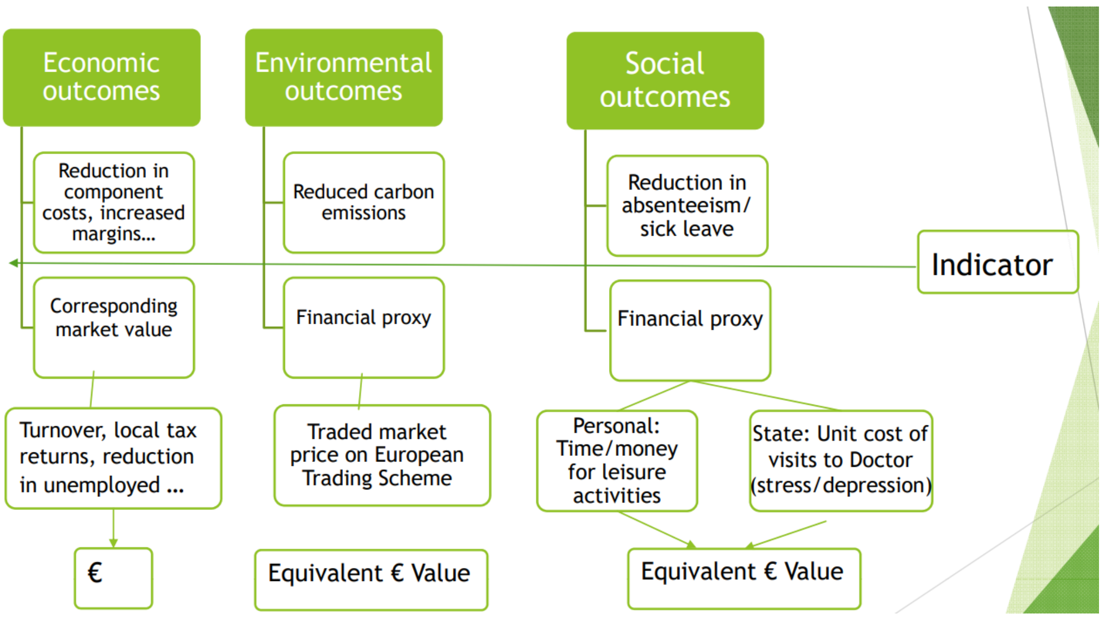


Figure A.14

A.2.8 Business Model Canvas for 21st century

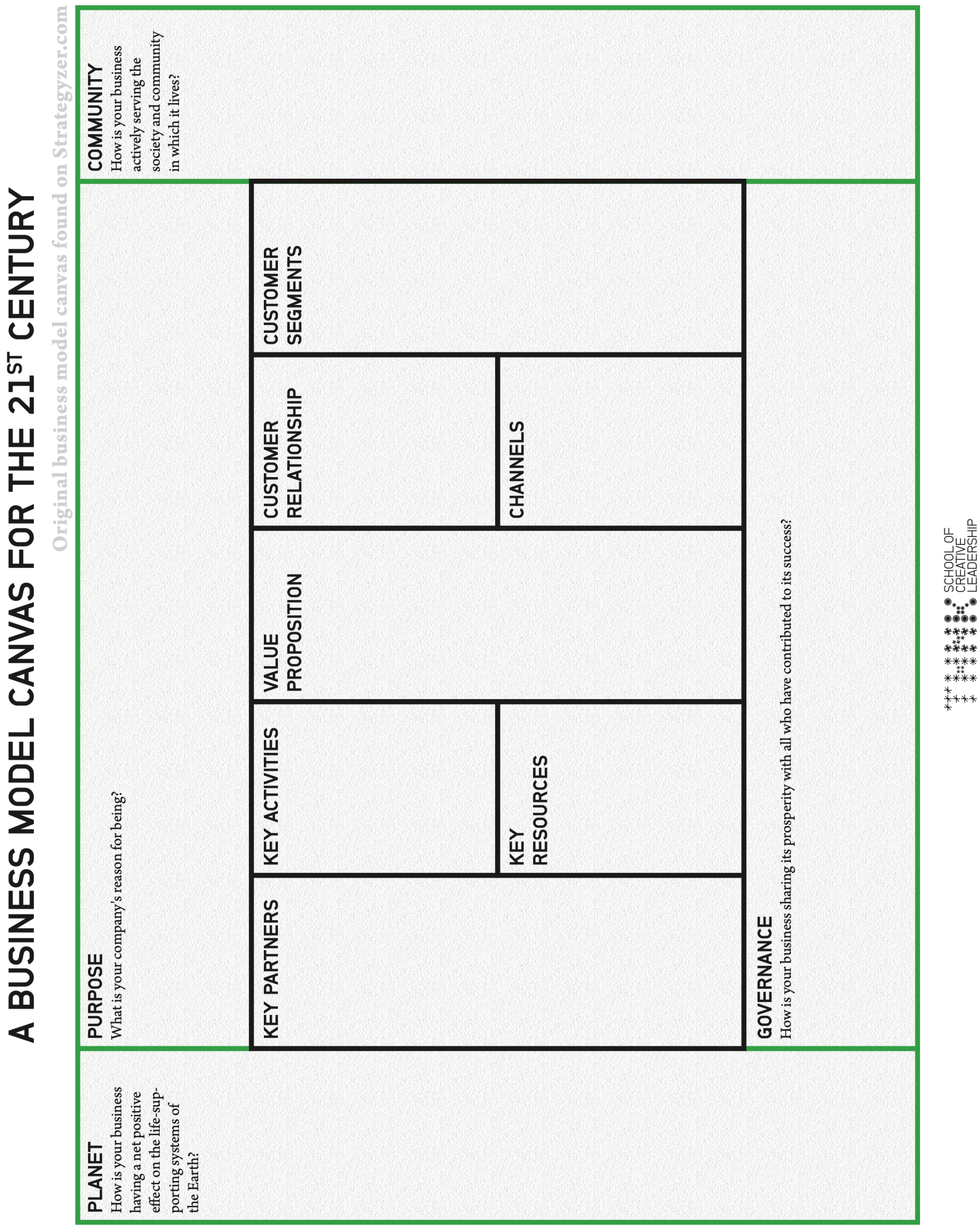
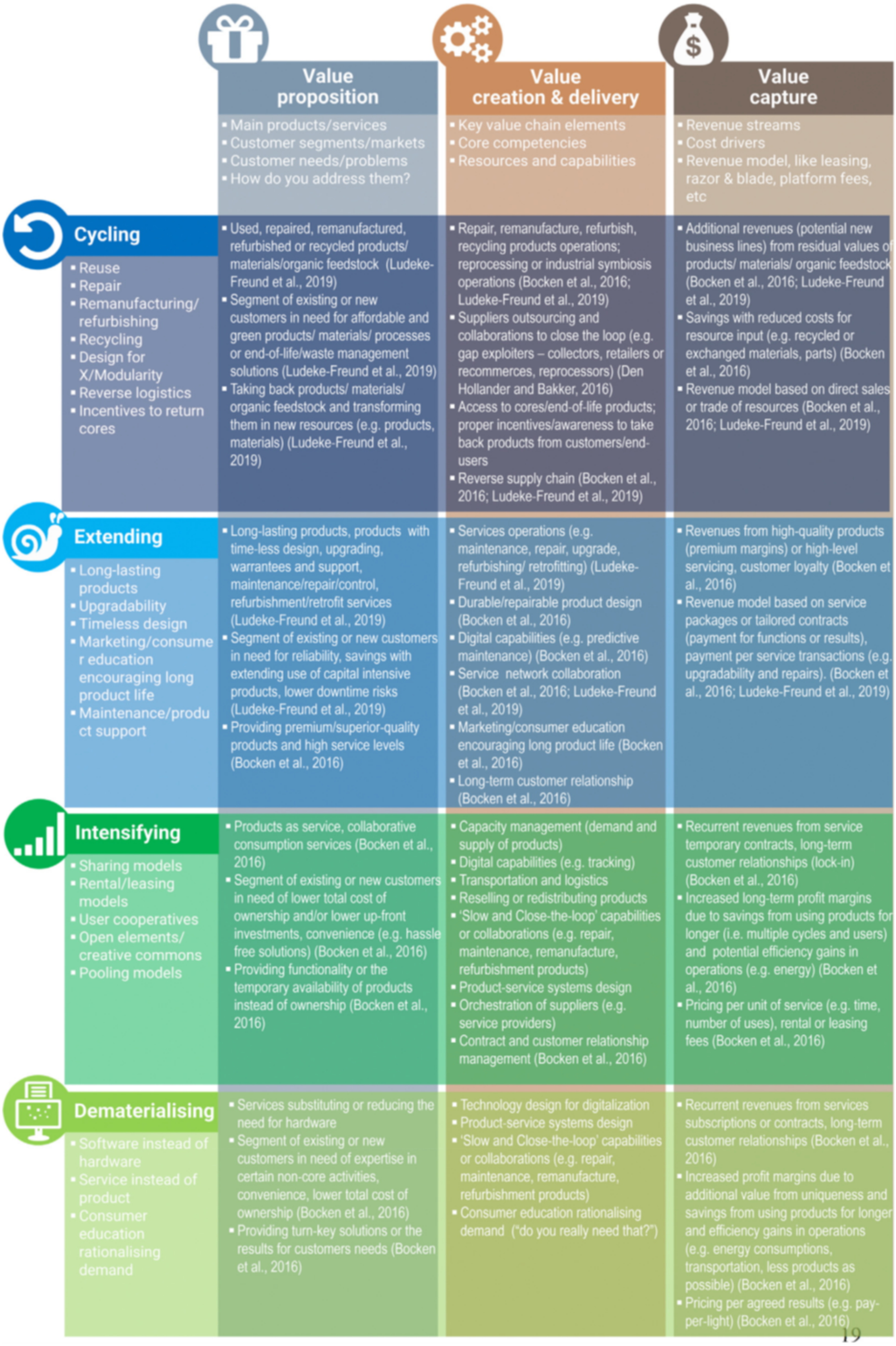


Figure A.15

A.2.9 Circular Business Model Tool



	Value proposition	Value creation & delivery	Value capture
	▪ Main products/services ▪ Customer segments/markets ▪ Customer needs/problems ▪ How do you address them?	▪ Key value chain elements ▪ Core competencies ▪ Resources and capabilities	▪ Revenue streams ▪ Cost drivers ▪ Revenue model, like leasing, razor & blade, platform fees, etc
Cycling ▪ Reuse ▪ Repair ▪ Remanufacturing/ refurbishing ▪ Recycling ▪ Design for X/Modularity ▪ Reverse logistics ▪ Incentives to return cores	▪ Used, repaired, remanufactured, refurbished or recycled products/ materials/organic feedstock (Ludeke-Freund et al., 2019) ▪ Segment of existing or new customers in need for affordable and green products/ materials/ processes or end-of-life/waste management solutions (Ludeke-Freund et al., 2019) ▪ Taking back products/ materials/ organic feedstock and transforming them in new resources (e.g. products, materials) (Ludeke-Freund et al., 2019)	▪ Repair, remanufacture, refurbish, recycling products operations; reprocessing or industrial symbiosis operations (Bocken et al., 2016; Ludeke-Freund et al., 2019) ▪ Suppliers outsourcing and collaborations to close the loop (e.g. gap exploiters – collectors, retailers or recommerces, reprocessors) (Den Hollander and Bakker, 2016) ▪ Access to cores/end-of-life products; proper incentives/awareness to take back products from customers/end-users ▪ Reverse supply chain (Bocken et al., 2016; Ludeke-Freund et al., 2019)	▪ Additional revenues (potential new business lines) from residual values o products/ materials/ organic feedstock (Bocken et al., 2016; Ludeke-Freund et al., 2019) ▪ Savings with reduced costs for resource input (e.g. recycled or exchanged materials, parts) (Bocken et al., 2016) ▪ Revenue model based on direct sales or trade of resources (Bocken et al., 2016; Ludeke-Freund et al., 2019)
Extending ▪ Long-lasting products ▪ Upgradability ▪ Timeless design ▪ Marketing/consumer education encouraging long product life ▪ Maintenance/product support	▪ Long-lasting products, products with time-less design, upgrading, warrantees and support, maintenance/repair/control, refurbishment/retrofit services (Ludeke-Freund et al., 2019) ▪ Segment of existing or new customers in need for reliability, savings with extending use of capital intensive products, lower downtime risks (Ludeke-Freund et al., 2019) ▪ Providing premium/superior-quality products and high service levels (Bocken et al., 2016)	▪ Services operations (e.g. maintenance, repair, upgrade, refurbishing/ retrofitting) (Ludeke-Freund et al., 2019) ▪ Durable/repairable product design (Bocken et al., 2016) ▪ Digital capabilities (e.g. predictive maintenance) (Bocken et al., 2016) ▪ Service network collaboration (Bocken et al., 2016; Ludeke-Freund et al., 2019) ▪ Marketing/consumer education encouraging long product life (Bocken et al., 2016) ▪ Long-term customer relationship (Bocken et al., 2016)	▪ Revenues from high-quality products (premium margins) or high-level servicing, customer loyalty (Bocken et al., 2016) ▪ Revenue model based on service packages or tailored contracts (payment for functions or results), payment per service transactions (e.g. upgradability and repairs). (Bocken et al., 2016; Ludeke-Freund et al., 2019)
Intensifying ▪ Sharing models ▪ Rental/leasing models ▪ User cooperatives ▪ Open elements/ creative commons ▪ Pooling models	▪ Products as service, collaborative consumption services (Bocken et al., 2016) ▪ Segment of existing or new customers in need of lower total cost of ownership and/or lower up-front investments, convenience (e.g. hassle free solutions) (Bocken et al., 2016) ▪ Providing functionality or the temporary availability of products instead of ownership (Bocken et al., 2016)	▪ Capacity management (demand and supply of products) ▪ Digital capabilities (e.g. tracking) ▪ Transportation and logistics ▪ Reselling or redistributing products ▪ 'Slow and Close-the-loop' capabilities or collaborations (e.g. repair, maintenance, remanufacture, refurbishment products) ▪ Product-service systems design ▪ Orchestration of suppliers (e.g. service providers) ▪ Contract and customer relationship management (Bocken et al., 2016)	▪ Recurrent revenues from service temporary contracts, long-term customer relationships (lock-in) (Bocken et al., 2016) ▪ Increased long-term profit margins due to savings from using products for longer (i.e. multiple cycles and users) and potential efficiency gains in operations (e.g. energy) (Bocken et al., 2016) ▪ Pricing per unit of service (e.g. time, number of uses), rental or leasing fees (Bocken et al., 2016)
Dematerialising ▪ Software instead of hardware ▪ Service instead of product ▪ Consumer education rationalising demand	▪ Services substituting or reducing the need for hardware ▪ Segment of existing or new customers in need of expertise in certain non-core activities, convenience, lower total cost of ownership (Bocken et al., 2016) ▪ Providing turn-key solutions or the results for customers needs (Bocken et al., 2016)	▪ Technology design for digitalization ▪ Product-service systems design ▪ 'Slow and Close-the-loop' capabilities or collaborations (e.g. repair, maintenance, remanufacture, refurbishment products) ▪ Consumer education rationalising demand ("do you really need that?")	▪ Recurrent revenues from services subscriptions or contracts, long-term customer relationships (Bocken et al., 2016) ▪ Increased profit margins due to additional value from uniqueness and savings from using products for longer and efficiency gains in operations (e.g. energy consumptions, transportation, less products as possible) (Bocken et al., 2016) ▪ Pricing per agreed results (e.g. pay-per-light) (Bocken et al., 2016)

19

Figure A.16: Combines the main strategies with Value proposition model

A.2.10 EEA example

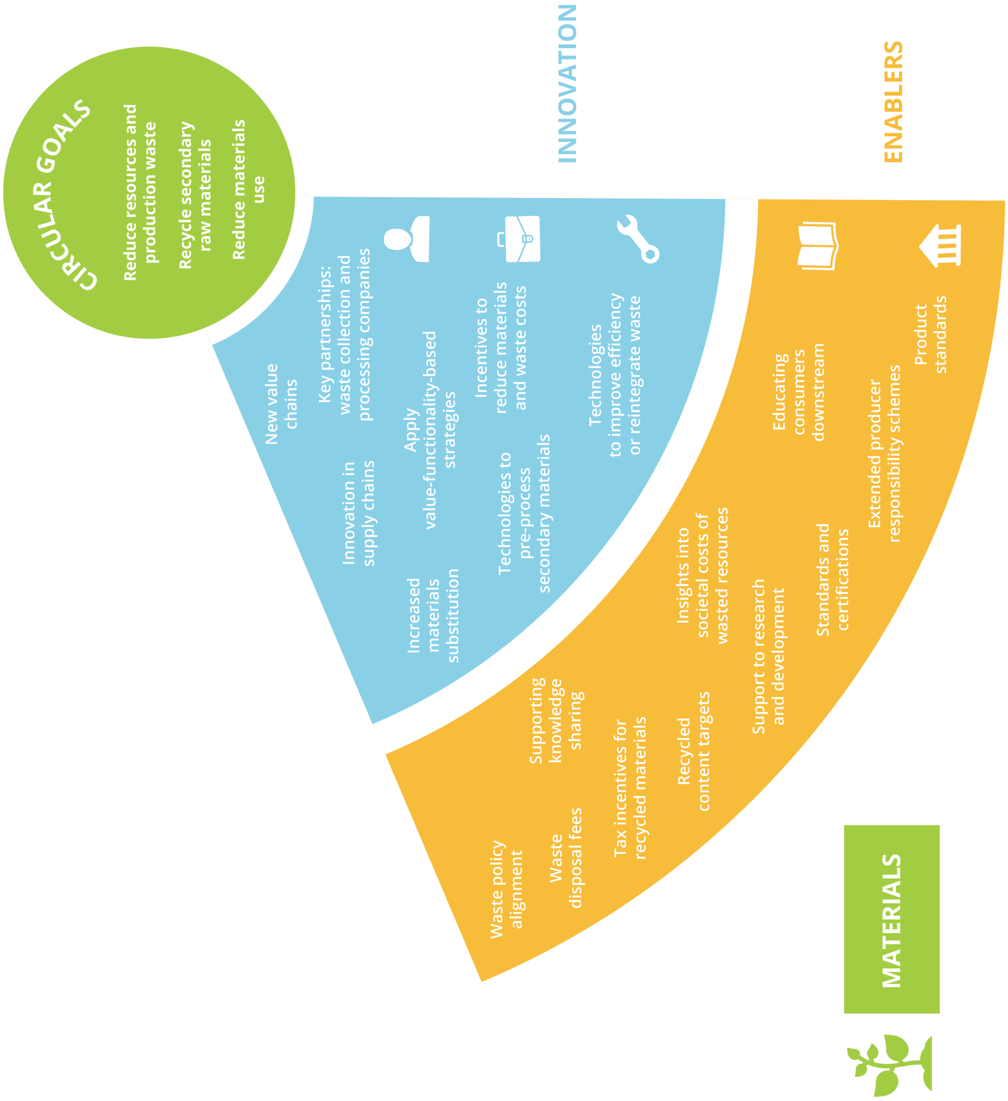


Figure A.17

A.2.11 BECE Framework

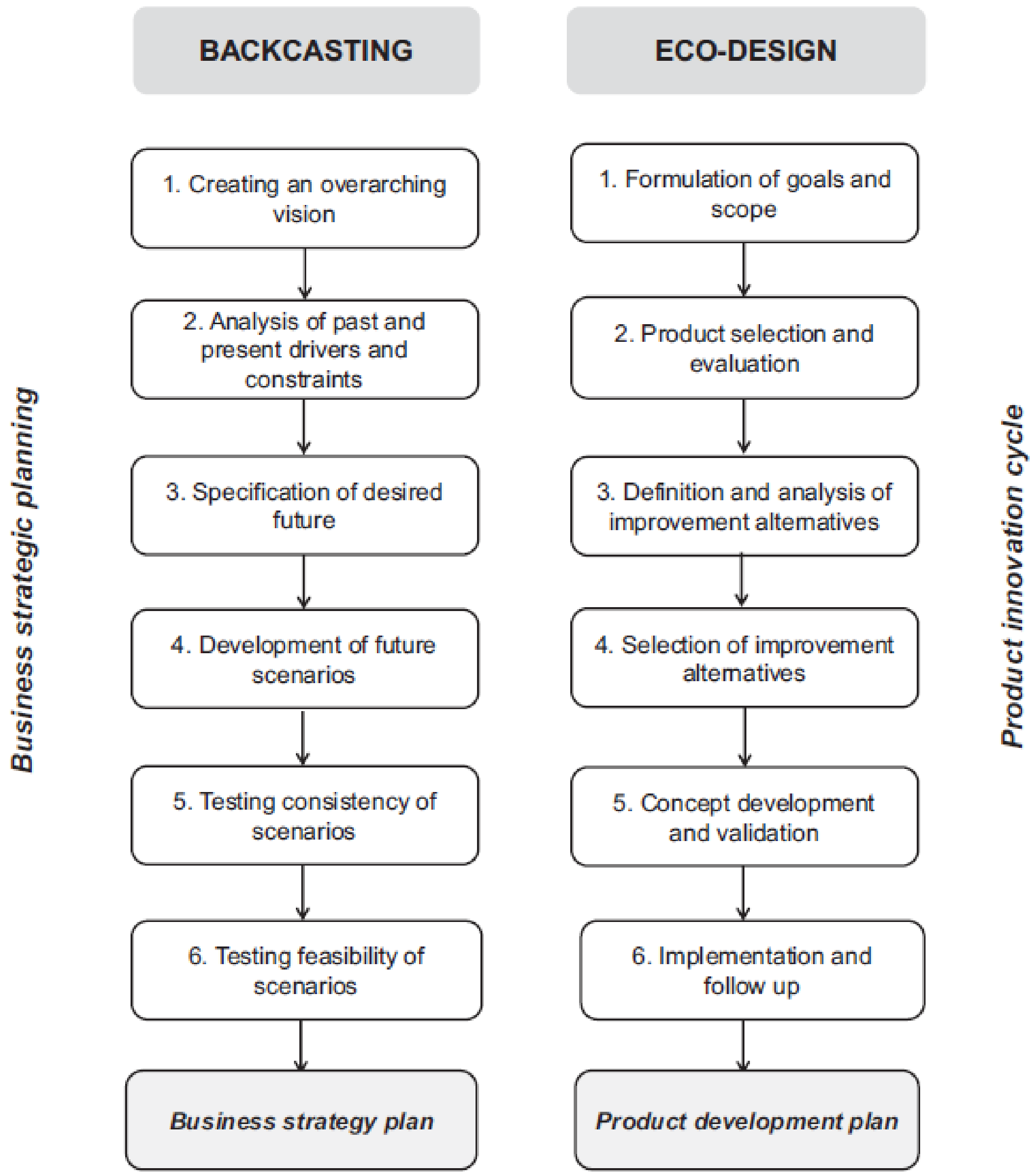
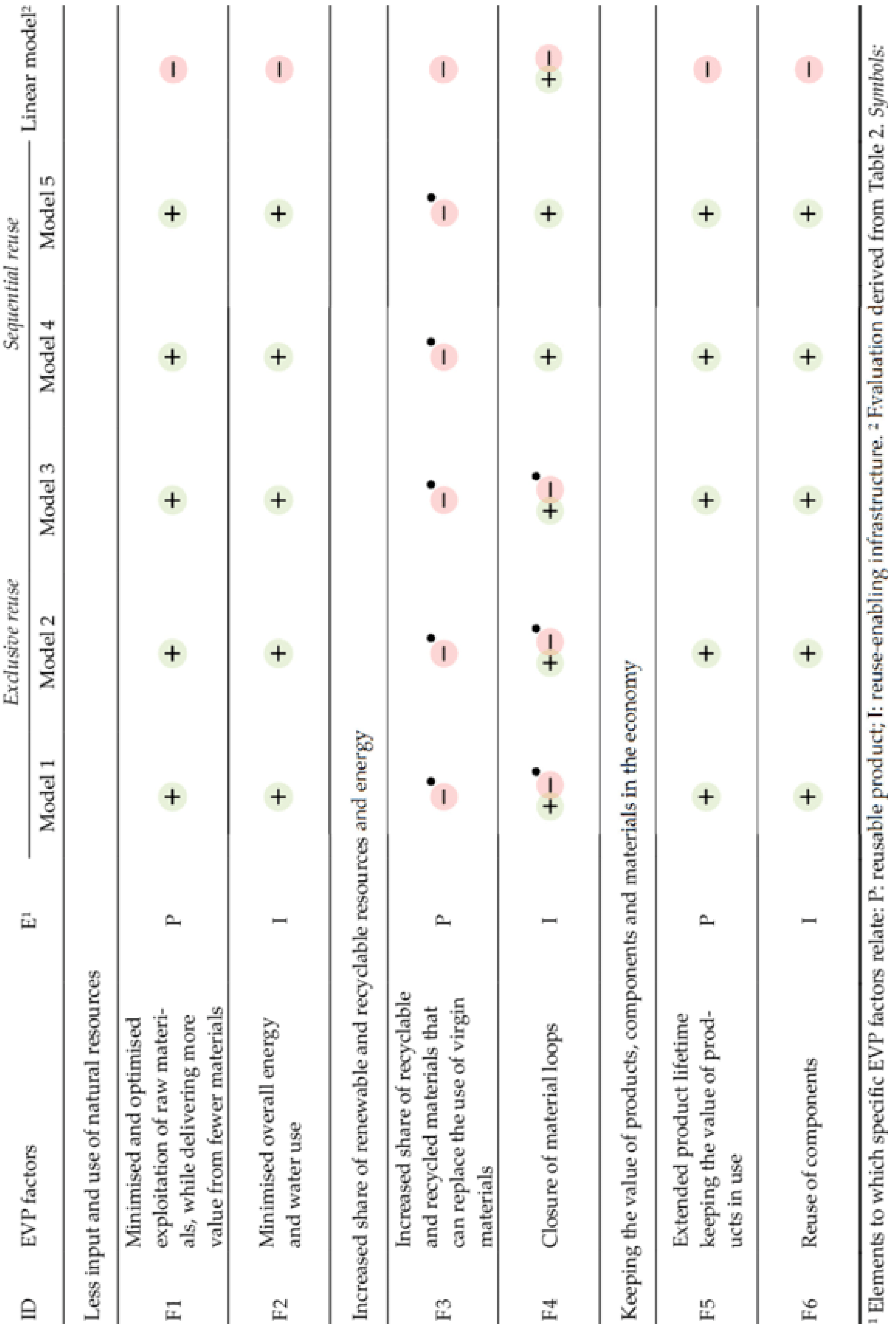


Figure A.18: Outline of the backcasting and eco-design methodologies

A.2.12 EVPT example

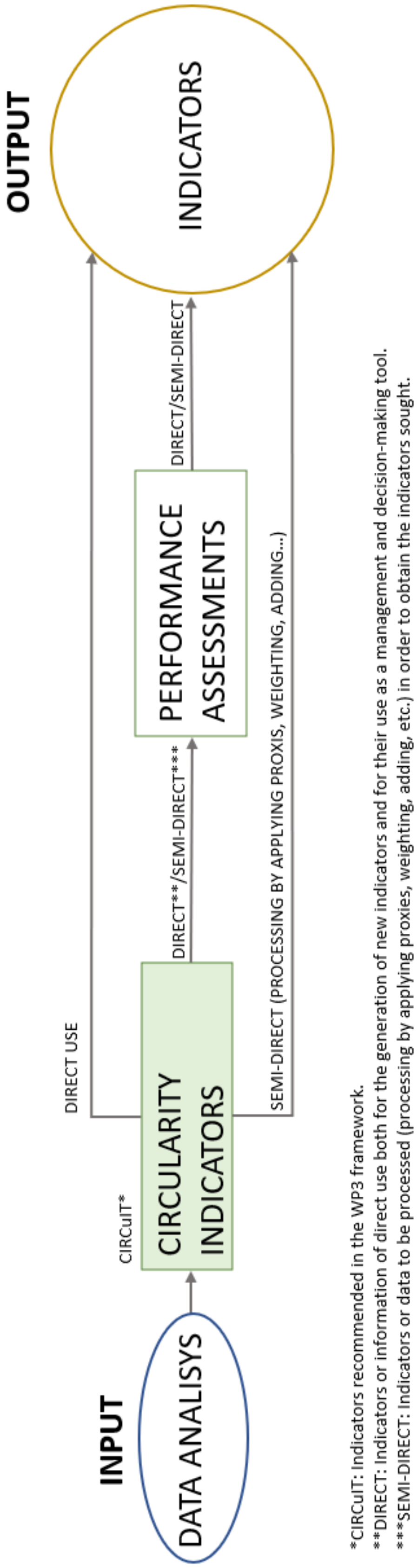


ID	EVP factors	E[1]	*Exclusive reuse* Model 1	Model 2	Model 3	*Sequential reuse* Model 4	Model 5	Linear model[2]
Less input and use of natural resources								
F1	Minimised and optimised exploitation of raw materials, while delivering more value from fewer materials	P	+	+	+	+	+	–
F2	Minimised overall energy and water use	I	+	+	+	+	+	–
Increased share of renewable and recyclable resources and energy								
F3	Increased share of recyclable and recycled materials that can replace the use of virgin materials	P	• –	• –	• –	• –	• –	–
F4	Closure of material loops	I	• +/–	• +/–	• +/–	+	+	+/–
Keeping the value of products, components and materials in the economy								
F5	Extended product lifetime keeping the value of products in use	P	+	+	+	+	+	–
F6	Reuse of components	I	+	+	+	+	+	–

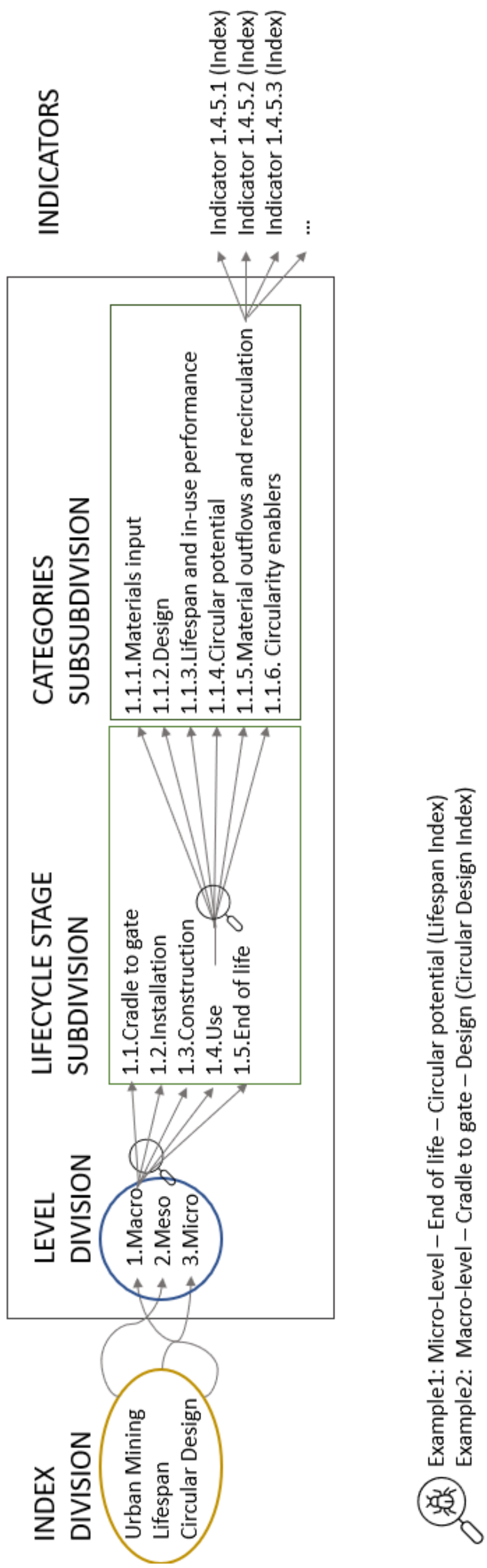
[1] Elements to which specific EVP factors relate: P: reusable product; I: reuse-enabling infrastructure. [2] Evaluation derived from Table 2. *Symbols:*

Figure A.19: [102]

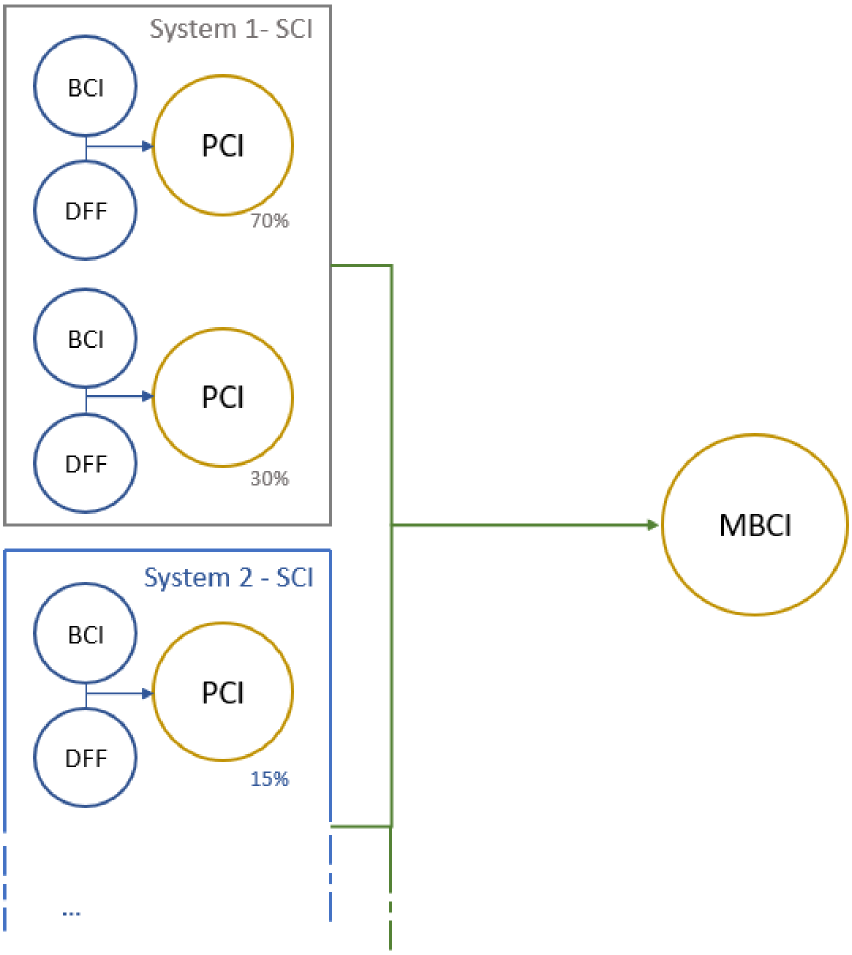
A.2.13 Possible applications of circularity indicators



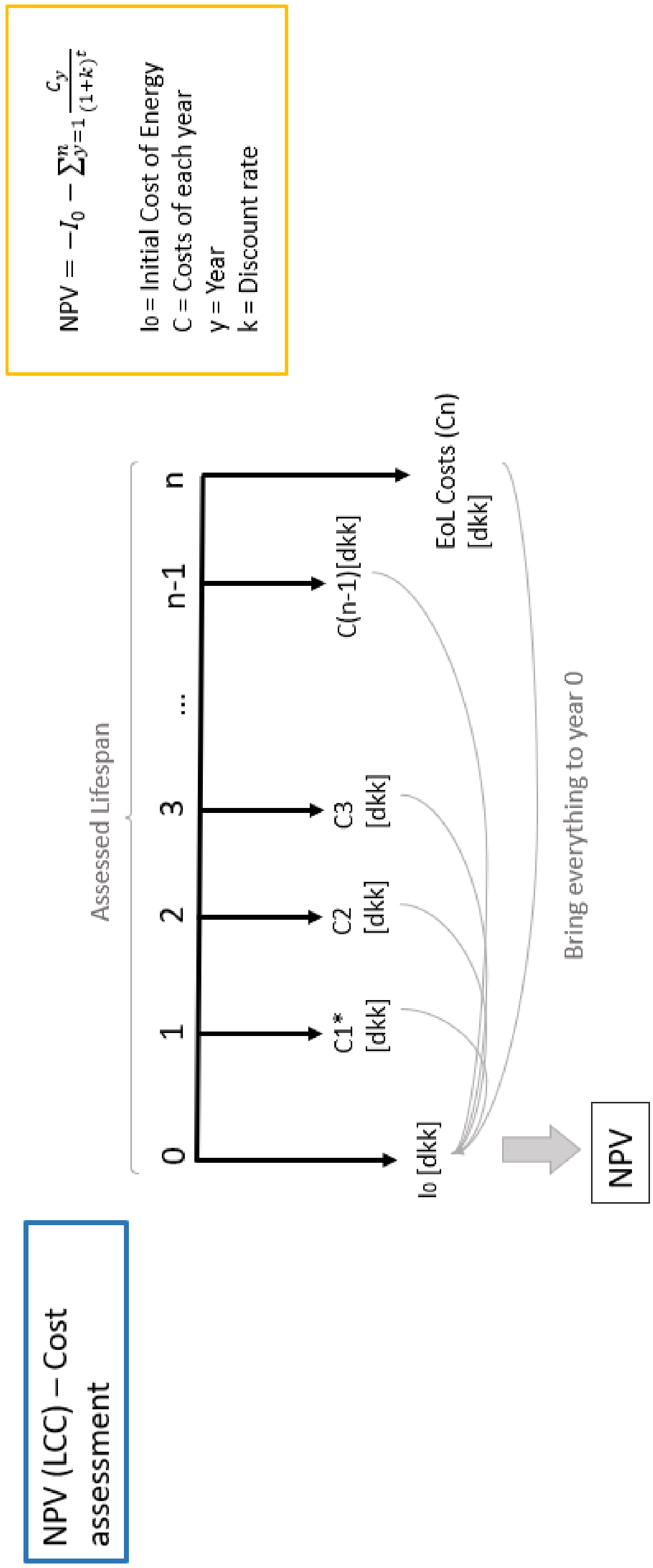
A.2.14 Proposal for the classification of indicators

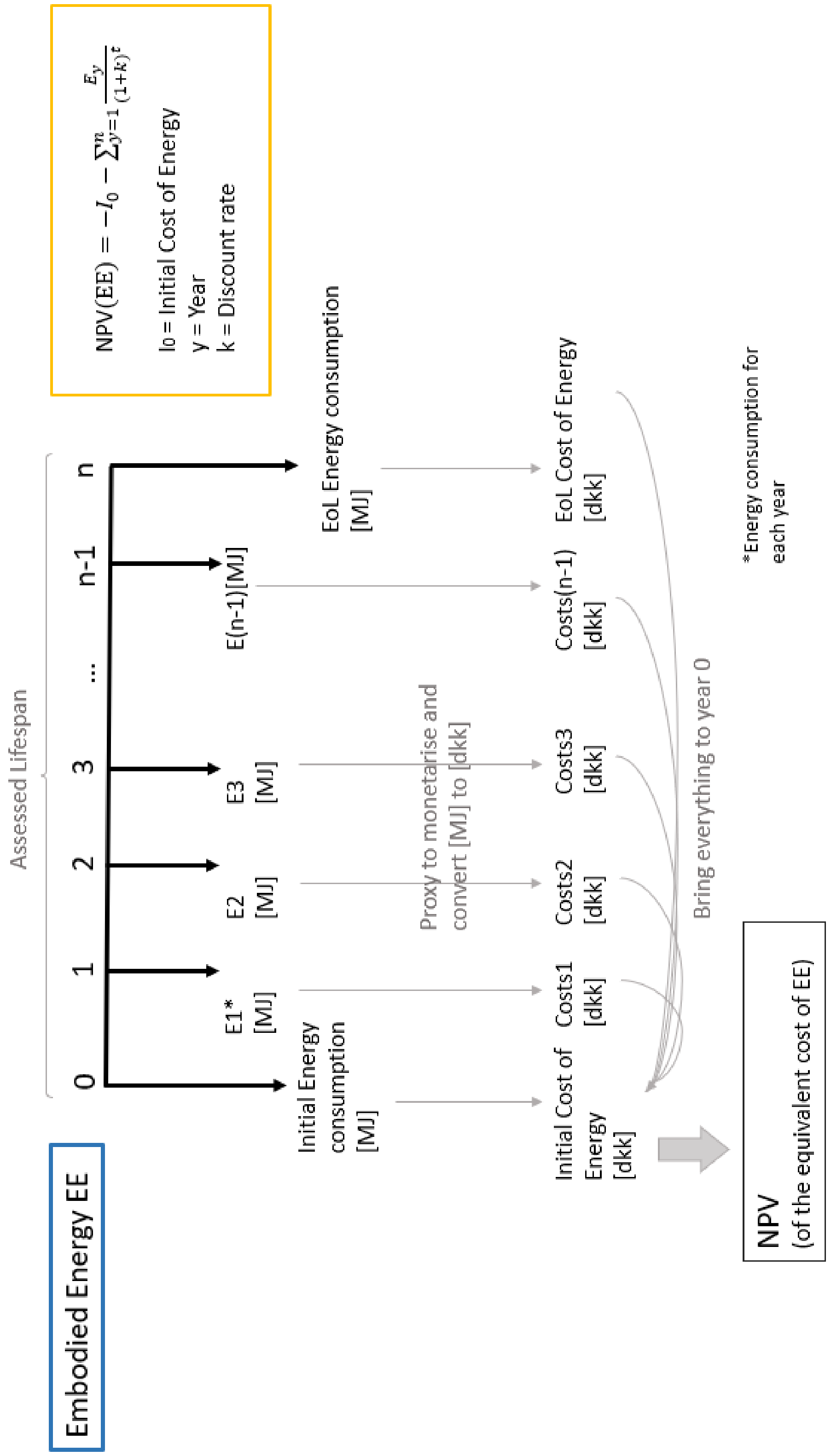


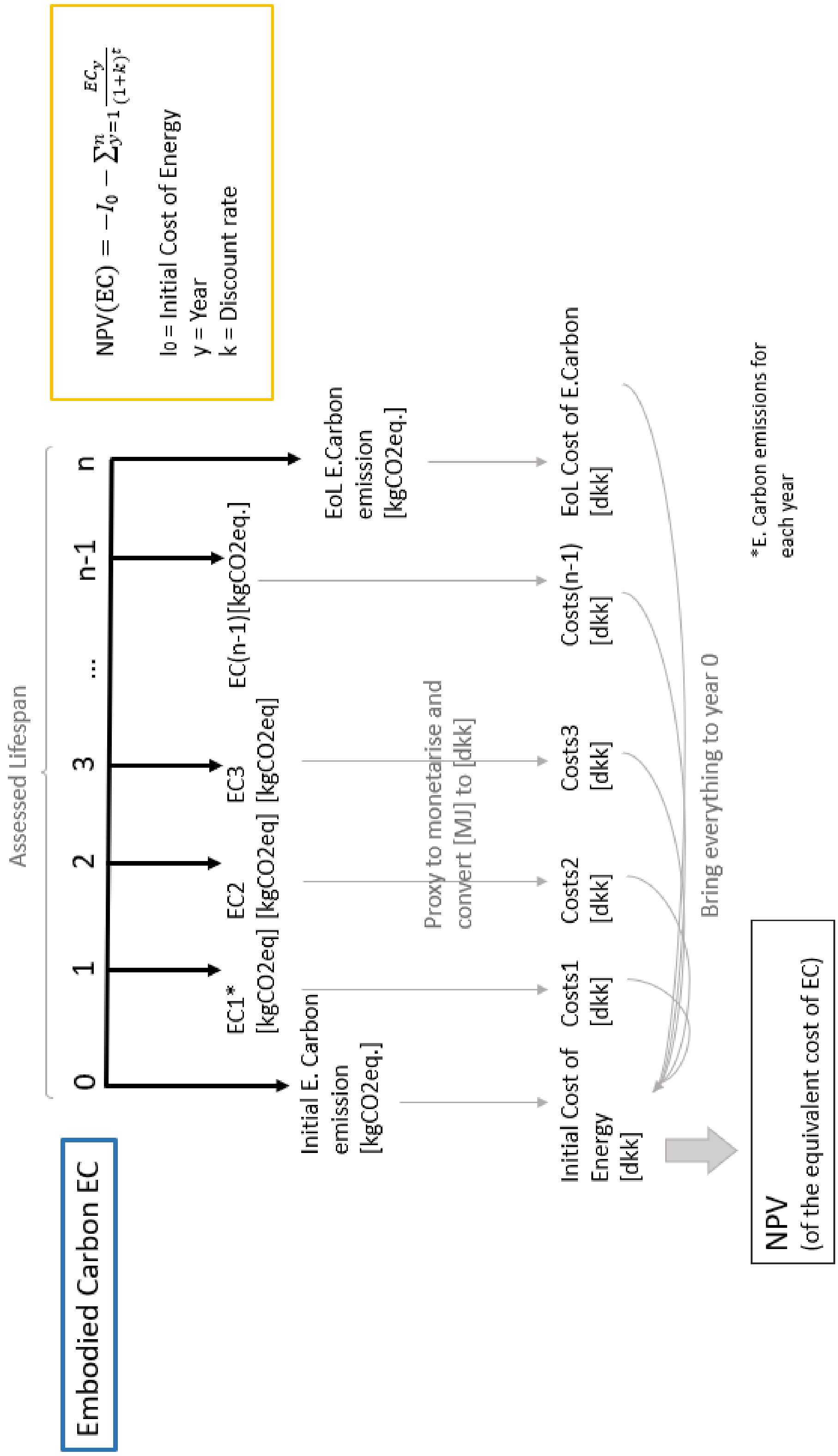
A.2.15 MBCI

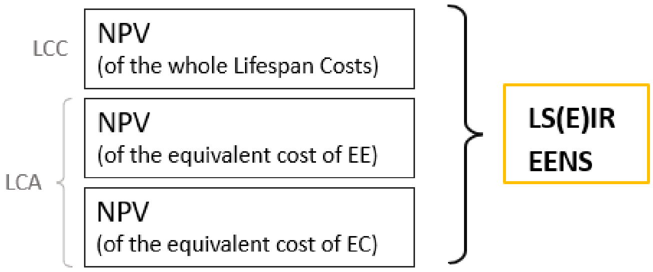

System 1- SCI
BCI
DFF
PCI
70%
BCI
DFF
PCI
30%
System 2 - SCI
BCI
DFF
PCI
15%
...
MBCI

A.2.16 NPV's for LS(E)IR and EENS




Embodied Energy EE
Assessed Lifespan
0
1
2
3
...
n-1
n
E1* [MJ]
E2 [MJ]
E3 [MJ]
E(n-1)[MJ]
EoL Energy consumption [MJ]
Initial Energy consumption [MJ]
Proxy to monetarise and convert [MJ] to [dkk]
Initial Cost of Energy [dkk]
Costs1 [dkk]
Costs2 [dkk]
Costs3 [dkk]
Costs(n-1) [dkk]
EoL Cost of Energy [dkk]
Bring everything to year 0
*Energy consumption for each year
NPV (of the equivalent cost of EE)
$NPV(EE) = -I_0 - \sum_{y=1}^{n} \frac{E_y}{(1+k)^t}$
I0 = Initial Cost of Energy
y = Year
k = Discount rate


Embodied Carbon EC
Assessed Lifespan
0
1
2
3
...
n-1
n
Initial E. Carbon emission [kgCO2eq.]
EC1* [kgCO2eq]
EC2 [kgCO2eq]
EC3 [kgCO2eq]
EC(n-1)[kgCO2eq.]
EoL E.Carbon emission [kgCO2eq.]
Proxy to monetarise and convert [MJ] to [dkk]
Initial Cost of Energy [dkk]
Costs1 [dkk]
Costs2 [dkk]
Costs3 [dkk]
Costs(n-1) [dkk]
EoL Cost of E.Carbon [dkk]
Bring everything to year 0
*E. Carbon emissions for each year
NPV (of the equivalent cost of EC)
NPV(EC) = −I0 − Σ EC_y / (1+k)^t
I0 = Initial Cost of Energy
y = Year
k = Discount rate



A.2.17 Strategy plan

Type	Existing unit type										New unit types after merging					
	A	B	C	D	E	F	G	H	J	I alt	A+A	A + D	C+F	G+H	G+J	
M²	82	75	49	45	94	27	85	32	31	M²	128	127	76	117	116	M²
Social housing (family units) 2020	380	84	119	111	174	8	40	40	30	986 units						
Demolished units	94	15	35	33	37	2	16	16	12	260 units						
Merged units	89		6	73		6	13	3	10	200 units	8	73	6	3	10	100 units
Sold units	36	9	3	3	24					75 units						
Re-branded units			75	1				21	8	105 units						
Social housing (accessibility units) 2030	60	35			18		1									114 units
Social housing (family units) 2030	101	25	-	1	95	-	10	-	-		8	73	6	3	10	332 units

Figure A.20

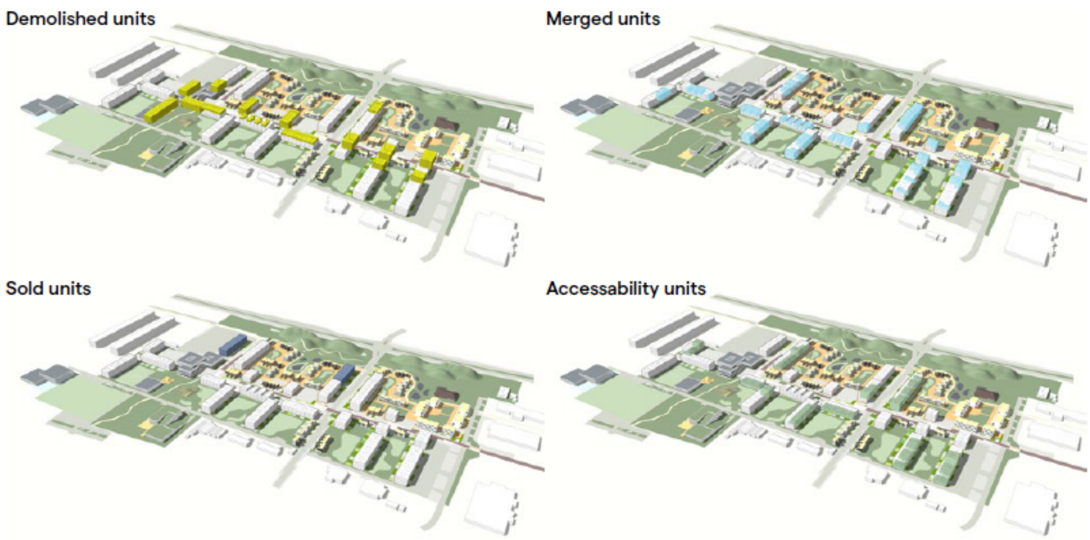
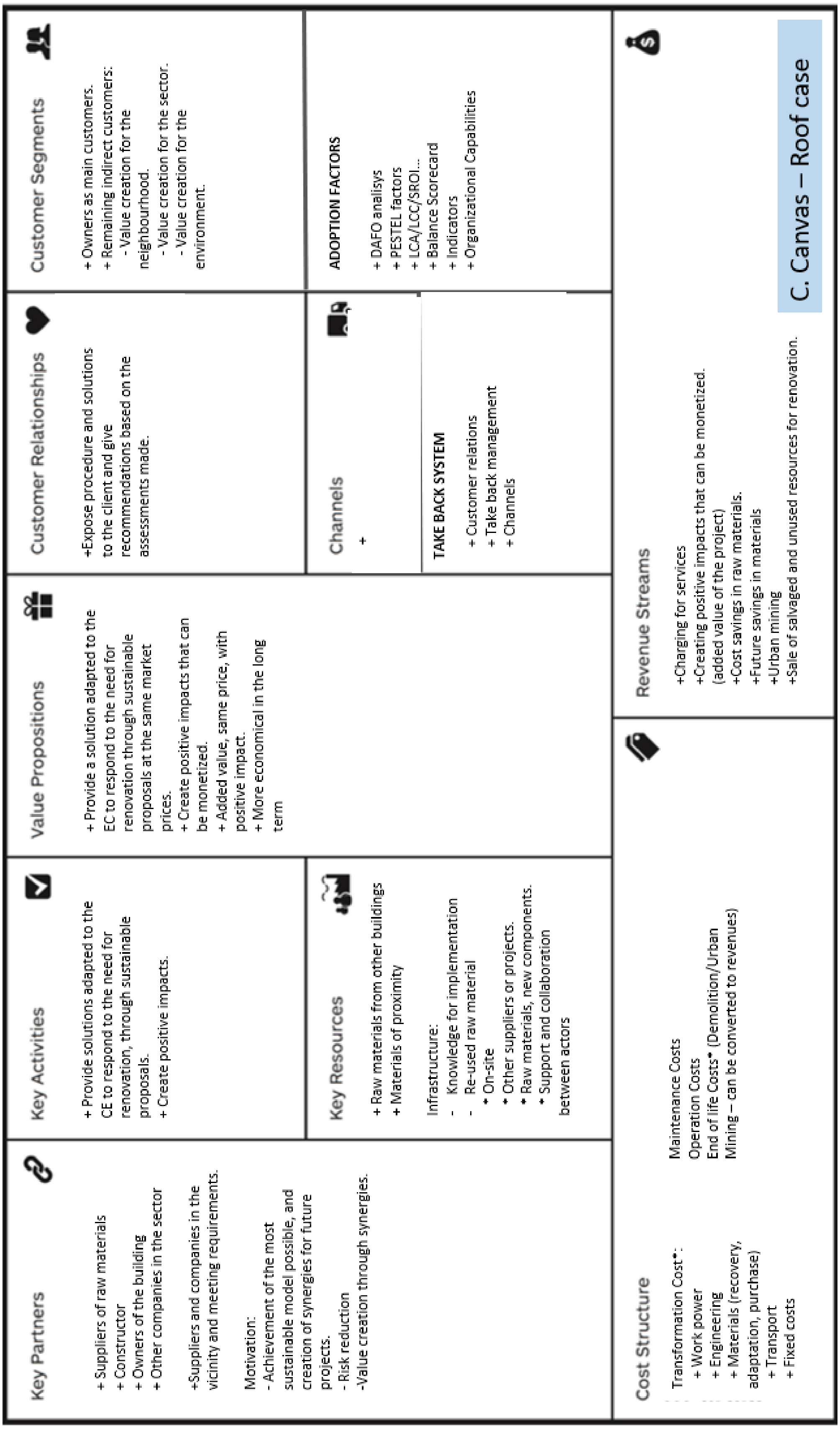


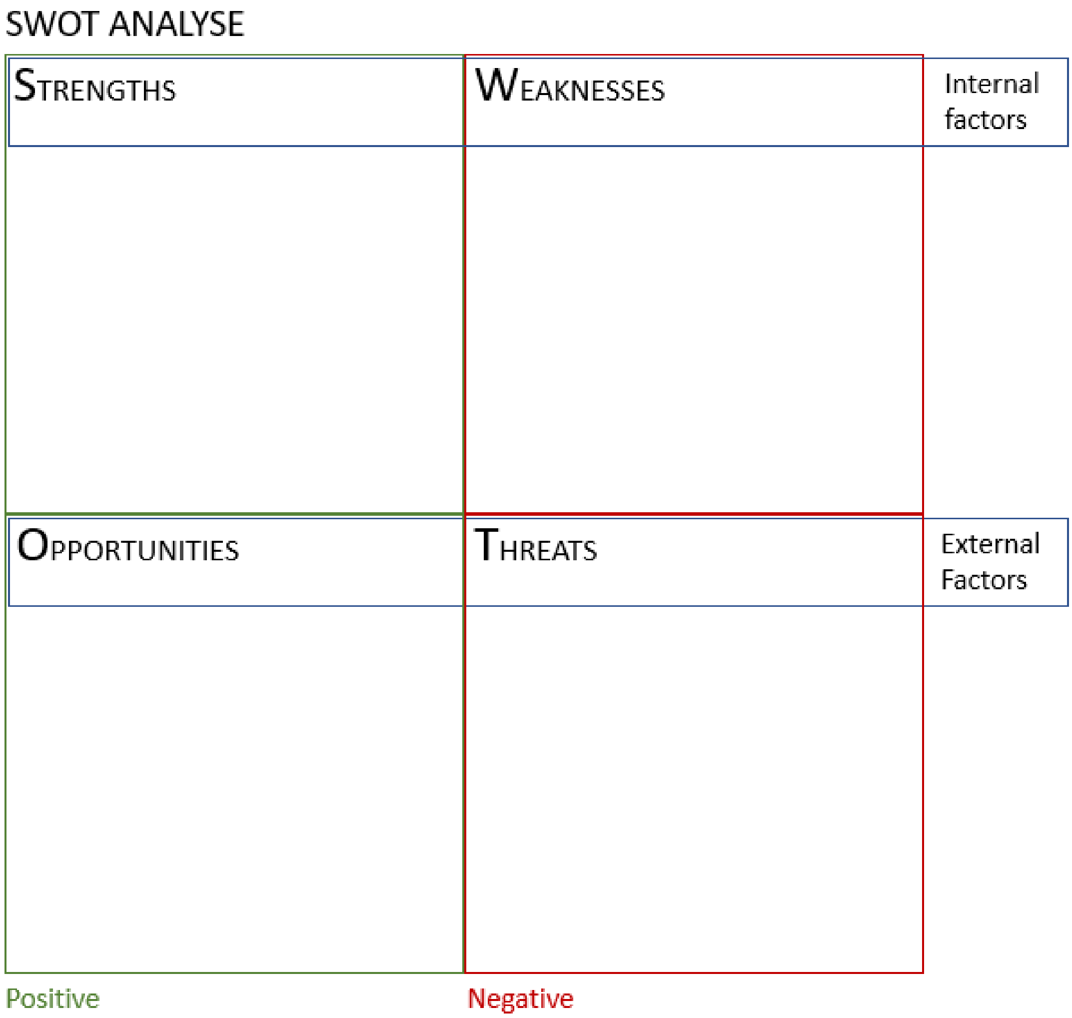
Figure A.21

Figure A.22

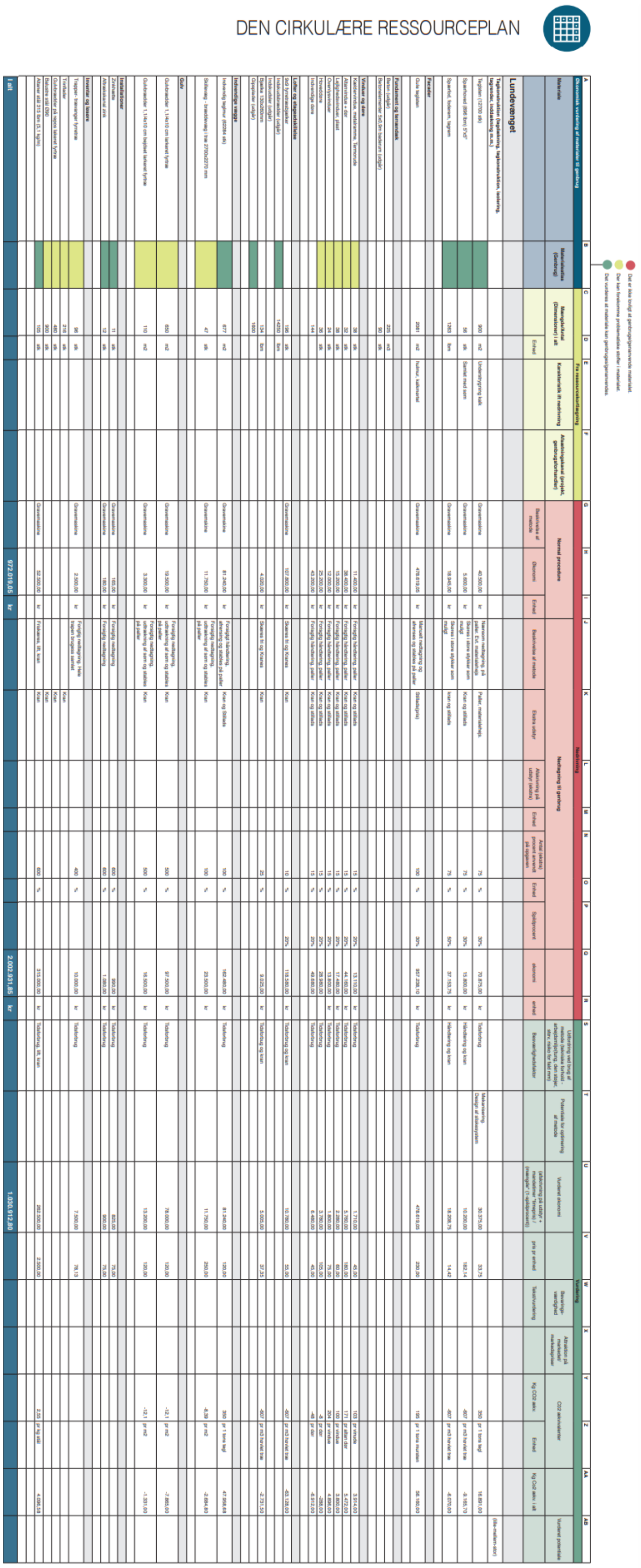
A.2.18 Circular Canvas - Iteration prior to model development



A.2.19 SWOT


SWOT ANALYSE
STRENGTHS
WEAKNESSES
Internal factors
OPPORTUNITIES
THREATS
External Factors
Positive
Negative

A.2.20 Demolition Costs Lundevænget



DEN CIRKULÆRE RESSOURCEPLAN

Lundevænget

Materiale	Mængde/Antal (Dimensioner) i alt	Enhed	Karakteristik ift nedrivning	Beskrivelse af metode	Økonomi
Tagkonstruktion (tagdækning, tagkonstruktion, isolering, lægter, inddækning m.m.)					
Tegltag (12700 stk)	900	m2	Understrygning kalk	Gravemaskine	40.500,00
Spærhoved (896 lbm) 5"x5"	56	stk	Samlet med søm	Gravemaskine	5.600,00
Spærfod, fodrem, lægter	1263	lbm		Gravemaskine	18.945,00
Facader					
Gule teglsten	2081	m2	hulmur, kalkmørtel	Gravemaskine	478.619,05
Fundament og terrændæk					
Beton (udgår)	225	m3			
Betonelementer 5x0,3m badeværelse (udgår)	90	stk			
Vinduer og døre					
Kældervindue, metalramme, Termorude	38	stk			11.400,00
Altanvindue + dør	32	stk			38.400,00
Lejlighedsvinduer, plast	38	stk			15.200,00
Ovenlysvinduer	24	stk			12.000,00
Hoveddøre	36	stk			25.200,00
Indvendige døre	144	stk			43.200,00
Lofter og etageadskillelse					
Stål fyrretræsbjælker	196	stk		Gravemaskine	107.800,00
Indskudsbrædder (udgår)	14250	lbm			
Indskudsler (udgår)					
Bjælke 130x280mm	134	lbm			4.020,00
Gipsplader (udgår)	1650				
Indvendige vægge					
Indvendig teglmur (62264 stk)	677	m2		Gravemaskine	81.240,00
Skillevæg - brædde/væg i træ 2700x2270 mm	47	stk		Gravemaskine	11.750,00
Gulv					
Gulvbrædder 1,1/4x10 cm lakeret fyrtræ	650	m2		Gravemaskine	19.500,00
Gulvbrædder 1,1/4x10 cm bejdset lakeret fyrtræ	110	m2		Gravemaskine	3.300,00
Installationer					
Zinkhætte	11	stk		Gravemaskine	165,00
Afføkaskanal zink	12	stk		Gravemaskine	180,00
Inventar og løsøre					
Trapper- trævanger fyrretræ	96	stk		Gravemaskine	2.500,00
Trinflader	216	stk			
Gulvbrædder på repos lakeret fyrtræ	480	stk			
Balustre stål Ø20	900	stk			
Altaner stål 315 lbm (5,1 kg/m)	105	stk		Gravemaskine	52.500,00
I alt					972.019,05 kr

A.2.21 Comparison of scenarios

1-CASE STUDY (CONSERVATIVE)

Name	BC	BM1 - -Concrete-	BM1 - -Clay-	BM2 - -Concrete Double-S-	BM2 - -Clay Double-S-	BM2 - -Cladding Clay-
Net present value	-264,580	-280,047	-273,224	-263,362	-251,026	-308,912

2-10 EXTRA YEARS OF USEFUL LIFE FOR REUSED TILES (REALISTIC)

Name	BC	BM1 - -Concrete-	BM1 - -Clay-	BM2 - -Concrete Double-S-	BM2 - -Clay Double-S-	BM2 - -Cladding Clay-
Net present value	-264,580	-245,832	-241,931	-259,361	-247,025	-304,911

3-WITHOUT EXTRA CLEANING COSTS (OPTIMISTIC)

Name	BC	BM1 -Concrete-	BM1 -Clay-	BM2 -Concrete Double-S-	BM2 -Clay Double-S-	BM2 -Cladding Clay-
Net present value	-264,580	-261,288	-254,465	-254,919	-242,583	-300,468

4-HIGHER LIFESPAN 1 (OPTIMISTIC)

Name	BC	BM1	BM2 - -Concrete-	BM2 - -Clay Double-S-	BM2 - -Cladding clay-
Net present value	-243,105	-201,999	-232,885	-234,562	-290,523

5-HIGHER LIFESPAN 2 (REALISTIC)

Name	BC	BM1 - -Concrete-	BM1 - -Clay-	BM2 - -Concrete Double-S-	BM2 - -Clay Double-S-	BM2 - -Cladding Clay-
Net present value	-243,105	-240,678	-240,140	-237,886	-239,563	-295,524

6-NO EXTRA CLEANING COSTS+HIGHER LIFESPAN (VERY OPTIMISTIC)

Name	BC	BM1	BM2 -Concrete Double-S-	BM2 -Clay Double-S-	BM2 -Cladding Clay-
Net present value	-243,105	-183,240	-224,441	-226,118	-282,079

A.2.21.1 Details of KPI covered by indicators

References	Technical Cycle	Biological/ Renewable	Recycling Efficiency	Functional Lifetime	Disassembly	Reusability Index	Adaptability	Energy	Emission	Water	Heritage	Economy
MCIC	✓		✓									✓
MCI	✓		✓									
BCI	✓				✓							
BCIDR	✓				✓							
BBCA	✓	✓		✓	✓							
MBCI	✓	✓	✓		✓							✓
PBCI	✓				✓			✓				
ACBCI	✓	✓		✓	✓	✓						
MAC	✓	✓		✓		✓	✓					
CIPB	✓				✓	✓						
Level(s)	✓				✓		✓		✓	✓		
MAD-CI	✓	✓	✓			✓						
ARCHCEIF	✓	✓				✓		✓	✓	✓	✓	
FLEX					✓		✓					
CEMS	✓							✓	✓	✓		
CBMCI	✓					✓			✓			
MCI'	✓	✓			✓	✓						
IEPC	✓				✓	✓		✓	✓			
BBWPE	✓					✓						
BCAF	✓				✓	✓	✓					
SEEI	✓		✓		✓			✓	✓			✓
GEOLMI	✓				✓	✓						✓
RIPAT 1.0											✓	
FCB	✓	✓			✓	✓	✓	✓		✓		
PCB	✓	✓	✓				✓					
CC	✓											✓
CBAP	✓				✓	✓	✓					✓
C-CALC	✓	✓					✓		✓			
Cirulytics	✓	✓								✓		
CCEF		✓			✓	✓	✓					

A.2.22 A review of micro level indicators for a circular economy e moving away from the three dimensions of sustainability?

Table 3
Overview of indicators included in review. A/P: A = academic contribution; P = practical contribution. Type: 1) single quantitative indicators; 2) analytical tools; 3) composite indicator sets.

Indicator	Abbreviation	Year	Source	A/P	Type
Disassembly Effort Index	DEI	2000	Das et al. (2000)	A	3
Remanufacturing Product Profiles	$REPRO^2$	2006	Zwolinski et al. (2006)	A	2
Circular Economy Toolkit	CET	2013	Evans and Bocken (2013)	P	2
End-of-life Index	EOLI	2014	Lee et al. (2014)	A	3
Reuse Potential Indicator	RPI	2014	Park and Chertow (2014)	A	1
Circular Economy Index	CEI	2015	Di Maio and Rem (2015)	A	1
Material Circularity Indicator	MCI	2015	(Ellen MacArthur Foundation and Granta Design, 2015)	P	1
Circularity Calculator	CC	2016	(IDEAL&CO Explore, 2016)	P	2
Eco-cost/Value Ratio	EVR	2016	Scheepens et al. (2016)	A	1
Longevity Indicator (resource duration)	LI	2016	Franklin-Johnson et al. (2016)	A	1
Material Reutilization Score (C2C certification framework)	MRS	2016	(Cradle to Cradle Products Innovation Institute, 2016)	P	1
Recycling Indices	RI	2016	Van Schaik and Reuter (2016)	A	3
Circular Economy Indicator Prototype	CEIP	2017	Cayzer et al. (2017)	A	3
Eco-efficient Value Creation	EEVC	2017	Vogtlander et al. (2017)	A	3
End-of-life Indices (Design Methodology)	EOLI-DM	2017	Favi et al. (2017)	A	3
Model of Expanded Zero Waste Practice	EZWP	2017	Veleva et al. (2017)	A	2
Product-level Circularity Metric	PLCM	2017	Linder et al. (2017)	A	1
Recycling Desirability Index	RDI	2017	Mohamed Sultan et al. (2017)	A	1
Value-based Resource Efficiency Indicator	VRE	2017	Di Maio et al. (2017)	A	1
Circularity Design Guidelines	CDG	2018	Bovea and Pérez-Belis (2018)	A	2
Combination Matrix	CM	2018	Figge et al. (2018)	A	3
Decision Support Tool for Remanufacturing	DSTR	2018	van Loon and Van Wassenhove (2018)	A	2
Ease of Disassembly Metric	eDiM	2018	Vanegas et al. (2018)	A	1
Effective Disassembly Time	EDT	2018	Marconi et al. (2018) Mandolini et al. (2018)	A	1
Product Recovery Multi-criteria Decision Tool	PR-MCDT	2018	Alamerew and Brissaud (2018)	A	2
Sustainability Indicators in CE	SICE	2018	Mesa et al. (2018)	A	3
Design Method for End-of-use Product Value Recovery	EPVR	2019	Cong et al. (2019)	A	2
Multi-criteria Decision Analysis Combining Material Circularity Indicators & Life-cycle based Indicators	MCDA-ML	2019	Niero and Kalbar (2019)	A	2
Mathematical Model to Assess Sustainable Design and End-of-life Options	SDEO	2019	Ameli et al. (2019)	A	2
Typology for Quality Properties	TQP	2019	Iacovidou et al. (2019)	A	2

Figure A.23: [93]

H.S. Kristensen, M.A. Mosgaard / Journal of Cleaner Production 243 (2020) 118531 15

Table 12
Main CE categories of micro level indicators. Indicator abbreviations can be found in Table 3.

Category	Description	Single focus indicators	Split focus indicators	Most used measure
Recycling	Recycled content in new or remanufactured products and potential to recycle materials after use of products	*RDI; RI; CEI; MRS; RPI*	*PLCM; CM; SICE; MCI; CC*	Ratio
Remanufacturing	Remanufacturing of products or components through work done and addition of new or used product parts, components etc. Refurbishment and recondition are included in this category	*EEVC; DSTR; REPRO*[2]	*PLCM; CM*	Ratio or value/cost
Reuse	Reuse of whole product with no or minor adaptations and/or work, or reuse of components/modules in a new product	–	*SICE; CC*	Ratio or percentage
Resource-efficiency	Traditional resource-efficiency; optimizing resource use in products	*VRE; EVR; TQP*	–	Ratio
Disassembly	Disassembly of products to enable other CE strategies. This category includes disassembly sequence, tools, time, work flow etc.	*eDiM; EDT; DEI*	–	Time
Lifetime extension	Lifetime extension through considerations of durability and use of products, including repair of products	*LI*	*CM; MCI*	Time
Waste management	Different waste management strategies, including zero waste, waste generation, linear flow (virgin mat.) and unrecoverable waste from production	*EZWP*	*SICE; MCI*	Ratio
End-of-life management	Methods of comparing different end-of-life management options such as recycling, reuse and disposal.	*EOLI; EOLI-DM; SDEO; PR-MCDT; EPVR*	–	Value/cost
Multidimensional indicators	Indicators that combine different parameters and measures, which demonstrates the diversity of CE	*CEIP; CDG; MCDA-ML; CET*	–	–

Figure A.24: [93]

Table 1
Categorization of reviewed indicators.

Source	Indicator abbreviation	Academic or practice	Type	CE categories	Sustainability		
					Eco	Env	Soc
(Alamerew and Brissaud, 2018)	PR-MCDT	A	2	End-of-life management	x	x	x
(Ameli et al., 2019)	SDEO	A	2	End-of-life management	x	x	x
(Bovea and Pérez-Belis, 2018)	CDG	A	2	Multidimensional		x	
(Cayzer et al., 2017)	CEIP	A	3	Multidimensional		(x)	
(Cong et al., 2019)	EPVR	A	2	End-of-life management	x		
(Cradle to Cradle Products Innovation Institute, 2016)	MRS	P	1	Recycling		(x)	
(Das et al., 2000)	DEI	A	3	Disassembly	x		x
(Di Maio et al., 2017)	VRE	A	1	Resource-efficiency	x		
(Di Maio and Rem, 2015)	CEI	A	1	Recycling	x		
(Ellen MacArthur Foundation and Granta Design, 2015)	MCI	P	1	Recycling; waste management; lifetime extension		(x)	
(Evans and Bocken, 2013)	CET	P	2	Multidimensional	x	x	
(Favi et al., 2017)	EOLI-DM	A	3	End-of-life management	x	x	
(Figge et al., 2018)	CM	A	3	Lifetime extension; recycling; remanufacturing		(x)	
(Franklin-Johnson et al., 2016)	LI	A	1	Lifetime extension		(x)	
(Iacovidou et al., 2019)	TQP	A	2	Resource-efficiency		(x)	
(IDEAL&CO Explore, 2016)	CC	P	2	Recycling; reuse	x		
(Lee et al., 2014)	EOLI	A	3	End-of-life management	x	x	
(Linder et al., 2017)	PLCM	A	1	Recycling; remanufacturing	x		
(Mandolini et al., 2018; Marconi et al., 2018)	EDT	A	1	Disassembly	(x)		
(Mesa et al., 2018)	SICE	A	3	Waste management; recycling; reuse		(x)	
(Mohamed Sultan et al., 2017)	RDI	A	1	Recycling		x	
(Niero and Kalbar, 2019)	MCDA-ML	A	2	Multidimensional		x	
(Park and Chertow, 2014)	RPI	A	1	Recycling	x		
(Scheepens et al., 2016)	EVR	A	1	Resource-efficiency	x	x	
(van Loon and Van Wassenhove, 2018)	DSTR	A	1	Remanufacturing	x	x	
(Van Schaik and Reuter, 2016)	RI	A	3	Recycling		(x)	
(Vanegas et al., 2018)	eDiM	A	1	Disassembly	(x)		
(Veleva et al., 2017)	EZWP	A	2	Waste management	x	x	x
(Vogtlander et al., 2017)	EEVC	A	3	Remanufacturing	x	x	
(Zwolinski et al., 2006)	REPRO[2]	A	2	Remanufacturing	x		

Figure A.25: [93]

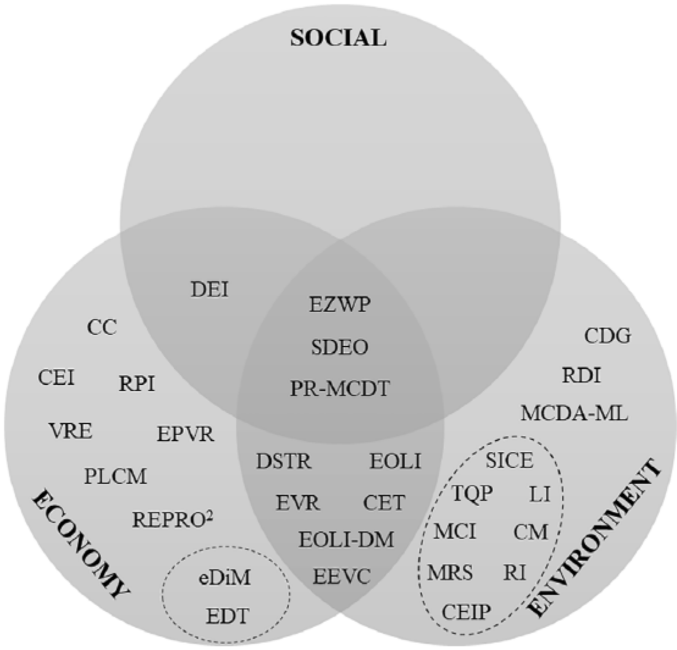


Fig. 6. Mapping of micro level indicators in sustainability dimensions. Dotted circle within economy: time-based indicators, and dotted circle within environment: resource-efficiency and longevity indicators.

Figure A.26: [93]

A.2.23 Terms

Table 3. Circular economy (CE) key definitions and terms in the literature review.

Author (Year)	Key Definition	Key Terms
[28]	"Circular economy is described as a scientific development model where resources become products, and the products are designed in such a way that they can be fully recycled" (p. 13)	Emphasize on recycling
[30]	"Circular economy defines its mission as solving the problems from the perspective of reducing the material flux and making the material flow balanced between the ecosystem and the socioeconomic system" (p. 265)	Reduction of material use
[31]	"Circular economy (CE) focuses on resource-productivity and eco-efficiency improvement in a comprehensive way, especially on the industrial structure optimization of new technology development and application, equipment renewal and management renovation" (p. 221)	Eco-efficiency and resource productivity
[29]	"A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" (p. 07)	Regenerative and restorative of resources
[35]	"A circular economy is an industrial system focused on closing the loop for material and energy flows and contributing to long-term sustainability" (p. 1256)	Closing the loop for material
[36]	"A circular economy is one that is restorative by design, and which aims to keep products, components and materials at their highest utility and value, at all times" (p. 16)	Restorative by design
[37]	"The circular economy is what seeks to stretch the economic life of goods and materials by retrieving them from post-production consumer phases. This approach too valorizes closing loops but does so by imagining object ends in their design and by seeing ends as beginnings for new objects." (p. 9)	CE prolongs product's life
[42]	"Circular economy means to reuse, repair, refurbishing, and recycling of the existing materials and products; what was earlier considered to be waste becomes a resource" (p. 2)	Transform waste into a resource
[43]	"The circular economy (CE) is viewed as a promising approach to help reduce our global sustainability pressures according to Ellen MacArthur Foundation and European Commission" (p. 300)	CE promotes sustainability
[46]	"circular economy is defined as one in which the value of products, materials, and resources is maintained for as long as possible, minimizing waste and resource use". (p. 2014)	Sustainability development
[26]	"The concept of closing material loops to preserve products, parts, and materials in the industrial system and extract their maximum utility" (p. 1)	Products are sustained by the closed-material flow
[13]	"CE is an economic model wherein planning, resourcing, procurement, production, and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well-being" (377)	Maximize ecosystem functioning
[14]	"Circular economy as a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling" (p. 759)	Regenerative system

Table 3. *Cont.*

Author (Year)	Key Definition	Key Terms
[48]	"A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times" (p. 483)	Restorative and regenerative by design
[13]	"An economy is envisaged as having no net effect on the environment; rather it restores any damage done in resource acquisition, while ensuring little waste is generated throughout the production process and in the life history of the product" (p. 371)	Restoration by design
[16]	"A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro-level (products, companies, consumers), meso level (eco-industrial parks) and macro-level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations." (pp. 224–225)	Creating environmental quality
[49]	"Circular economy is an economy constructed from societal production-consumption systems that maximize the service produced from the linear nature-society-nature material and energy throughput flow. Circular economy limits the throughput flow to a level that nature tolerates and utilizes ecosystem cycles in economic cycles by respecting their natural reproduction rates" (p. 39)	Maximizes the service produced
[1]	"Circular Economy (CE) is an activity, set of process for reducing the material used in production and consumption, promoting material resilience, closing loops and exchange sustainability offering in such a way that maximize the ecological system" (p. 30)	Reducing the environmental burden with an ecological system theory approach

4. Overarching Themes for Future Research

A.2.24 Circular and Environmental indicators

Table 3. Summary table of environmental indicators in end-of-life stage and relative cost items.

Environmental Indicators in End-Of-Life	Unit	Cost Items
Level of disassembly of building systems	points	Dismantling costs
Recycled materials quantity	%	Disposal costs (waste disposal
Wastes production quantity	kg	costs—Value of recycled materials)

Analogously, Embodied Energy and Embodied Carbon indices and related costs are summarized in the following Table 4.

Table 4. Summary table of Embodied Energy and Embodied Carbon indices and relative cost items.

Environmental Indicators	Unit	Cost Items
Embodied Energy	MJ	Cost of electric power
Embodied Carbon	kg CO_2 eq (100 years)	Cost of Carbon tax in Europe

All these costs items are summed to Global Cost, as in the following equation:

$$C_{GEnEc} = C_I + C_{EE} + C_{EC} + \sum (C_m + C_r)/(1+r)^t + (C_{dm} + C_{dp} - V_r)/(1+r)^N \quad (7)$$

Figure A.27

A.2.25 ”What gets measured, gets done: Development of a Circular Economy measurement scale for building industry”

Table 6. Final dimension, statistics, scores, weight of the scale after Delphi round and confirmatory factor analysis (CFA).

			Number of Expert with Rating					
Final Dimension of the Scale	$\overline{X}$	δ	**1**	**2**	**3**	**4**	**5**	**POSITION**
Energy	1.273	0.626	25	7	1	0	0	1°
3R, Reduce, Reuse and Recycle	1.394	0.556	22	10	1	0	0	2°
Water management	1.394	0.747	25	6	1	1	0	3°
Waste Management	1.424	0.830	24	7	1	0	1	4°
Management of materials	1.455	0.869	20	10	1	0	1	5°
Emissions generated	1.576	0.902	19	10	2	0	1	6°
Transition to Circular Economy	1.636	0.783	17	11	4	0	0	7°
Indicators of dimension Transition to CE	$\overline{X}$	δ	**1**	**2**	**3**	**4**	**5**	**POSITION**
Our company design according to Circular economy principles	1.394	0.609	22	9	2	0	0	1°
Our company aims the transformation to Circular economy model	1.424	0.792	19	9	4	1	1	2°
Our company take into account environmental issues	1.545	0.564	16	16	1	0	0	3°
There is an environmental awareness in our society	1.636	0.783	17	12	3	1	1	4°
Our company use the Building Information Modelling (BIM)	1.727	0.719	14	14	5	0	0	5°
We dispone of a board indicators for management of materials	1.879	0.696	9	20	3	1	1	6°
Indicators that composed the dimension: *Material management*	$\overline{X}$	δ	**1**	**2**	**3**	**4**	**5**	**POSITION**
We disponse of a Indicators of Improvement of use of materials	1.515	0.712	17	12	4	0	**0**	1°
Are the product's materials passed back into the supply chain?	1.606	0.827	19	9	4	1	**0**	2°
Extensive use of environmentally responsible in materials	1.758	0.830	14	15	2	2	**0**	3°
We use asphalt pavement recycled in order to reclaim bitumen	1.939	0.659	5	22	5	1	**0**	4°
We dispose of a lead indicator for resource productivity	2.121	0.696	6	17	10	0	**0**	5°
We reduce the direct Material Input	2.061	0.966	5	19	8	1	**0**	6°
Is there a complete bill of materials and substances for the product?	2.273	0.944	3	19	10	1	**0**	7°
Our crude steel production is very high	2.333	0.692	3	17	12	1	**0**	8°
We reduce the output of main mineral resource	2.364	0.822	2	21	7	2	**1**	9°
Our company analyze the iron resource efficiency	2.394	0.788	3	17	10	3	**0**	10°
Indicators that composed the dimension: Energy	$\overline{X}$	δ	**1**	**2**	**3**	**4**	**5**	**POSITION**
We increase the consumption of new, renewable or clean energy	1.273	0.517	25	7	1	0	0	1°
We raise the energy saving amount	1.424	0.663	19	12	2	0	0	2°
We dispose of Indicators of energy eficciency improvement	1.515	0.755	20	10	2	0	0	3°
We have a lower fuel consumption on a trial mode	1.939	0.747	9	18	5	1	0	4°
We use agroindustrial energy (sugar, ethanol biomass	1.939	0.864	12	14	7	0	0	5°
We are diminising the energy used per tonne of asphalt mix produced	1.970	0.951	12	15	6	0	0	6°
Indicators that compose the dimension Water	$\overline{X}$	δ	**1**	**2**	**3**	**4**	**5**	**POSITION**
Our company recycle and reused water	1.212	0.6	23	9	1	0	0	1°
We dispose of Indicators of Industrial water reuse ratio	1.424	0.792	19	10	4	0	0	2°
We dispose of Indicators of Improvement of Water efficiency	1.485	0.755	21	9	2	1	0	3°
Environmental Chemicals is used in the process of treating water.	1.939	0.864	12	15	4	2	0	4°
Indicator that composed the dimension 3 R´s, reduce, reuse and recycle	$\overline{X}$	δ	**1**	**2**	**3**	**4**	**5**	**POSITION**
Our company improves the recycling rate of solid waste	1.394	0.659	20	11	2	0	0	1°
Our products/service can be reused	1.424	0.614	18	14	1	0	0	2°
Our products/service can be redesign	1.485	0.834	18	10	5	0	0	3°

Figure A.28: [94]

Table 6. *Cont.*

Final Dimension of the Scale	Number of Expert with Rating							
	$\overline{X}$	δ	1	2	3	4	5	POSITION
Our company uses efficient technologies for the recovery of materials	1.576	0.663	14	17	2	0	0	4°
Our products/service can be repaired	1.606	0.899	19	10	2	2	0	5°
Our company disposes of a material recovery scheme	1.606	0.899	16	11	6	0	0	6°
Our company improves the ratio: use of recycled materials/production	1.697	0.810	14	13	6	0	0	7°
Indicators of dimensión Emissions	$\overline{X}$	δ	1	2	3	4	5	POSITION
We reduce our carbon footprint	1.333	0.816	22	8	2	1	0	1°
We reduce our CO2 emissions level	1.364	0.962	25	6	1	1	0	2°
We reduce the energy indirect greenhouse gas emissions level	1.515	0.755	18	11	4	0	0	3°
We reduce our energy environmental Footprints	1.576	0.792	16	14	2	1	0	4°
Indicators of dimension Waste Management	$\overline{X}$	δ	1	2	3	4	5	POSITION
Does the product reduce waste through its use?	1.364	0.699	19	12	2	0	0	1°
We improve our recycling rate of solid waste	1.485	0.619	16	15	1	1	0	2°
We diminish our hazardous waste	1.515	0.795	12	15	4	2	0	3°
We manage efficiently the waste	1.515	0.795	21	8	3	1	0	4°
We employ measures to prevent, recycle and eliminate waste	1.576	0.792	17	11	5	0	0	5°
We reduce the non-hazardous waste that is recycled	1.636	0.895	16	14	3	0	0	6°
We use a complete bill of solid waste for the manufacturing process	1.758	0.751	11	17	5	0	0	7°

Source: authors. Ii: Indicator i.; $\overline{X}$ = Average of the evaluation by the experts, where 1 is very important and 5 very little important; δ = standard deviation of the valuation made, and position order the importance of highest to lowest of each indicator.

Figure A.29: [94]

Table 7. Scale after Delphi rounds and CFA.

Weight	Indicator	1: Fully Disagree–7: Fully Agree						
	General CE Indicators (Weight: 13.54%)	1	2	3	4	5	6	7
17.68	Our company design according to Circular economy principles							
17.53	There is an environmental awareness in our society							
16.94	Our company take into account environmental issues							
16.49	We dispone of a board indicators for management of materials							
16.05	Our company aims the transformation to Circular economy model							
15.30	Our company use the Building Information Modelling (BIM)							
	Material Indicators (Weight: 14.27%)							
11.76	Are the product's materials passed back into the supply chain?							
11.45	We use asphalt pavement recycled in order to reclaim bitumen							
10.94	Our crude steel production is very high							
10.33	We reduce the direct Material Input							
9.71	Our company analyze the iron resource efficiency							
9.92	Is there a complete bill of materials and substances for the product?							
9.20	We dispose of a lead indicator for resource productivity							
9.00	Extensive use of environmentally responsible in materials							
8.89	We disponse of a Indicators of Improvement of use of materials							
8.79	We reduce the output of main mineral resource							
	Energy Indicators (Weight: 15%)							
18.69	We increase the consumption of new, renewable or clean energy							
17.93	We raise the energy saving amount							
17.48	We are diminising the energy used per tonne of asphalt mix produced							
15.35	We have a lower fuel consumption on a trial mode							
15.35	We dispose of Indicators of energy eficciency improvement							
15.20	We use agroindustrial energy (sugar, ethanol biomass)							
	Water Indicators (Weight: 14.51%)							
27.17	We dispose of Indicators of Improvement of Water eficciency							
25.65	Environmental Chemicals is used in the process of treating water							
25.22	We dispose of Indicators of Industrial water reuse ratio							
21.96	Our company recycle and reused water							
	3R's Indicators (Weight: 14.51%)							
14.89	Our products/services can be repaired							
14.77	Our products/services can be reused							
14.52	Our products/services can be redesign							
14.14	We dispose of a material recovery scheme							
14.02	We use efficient technologies for recovery of materials							
14.02	We increase ratio use of recycled materials/production							
13.64	We improve the recycling rate of solid waste							

Figure A.30: [94]

Table 7. *Cont.*

Weight	Indicator	1: Fully Disagree–7: Fully Agree
	Indicators of emissions (Weight: 13.78%)	
25.80	We reduce the energy indirect greenhouse gas emissions level	
25.58	We reduce our carbon footprint	
24.52	We reduce our CO_2 emissions level	
24.09	We reduce our energy environmental Footprints	
	Indicators of Waste (Weight: 14.39%)	
15.06	Does the product reduce waste through its use?	
14.55	We diminish our hazardous waste (metric ton)	
14.43	We use a complete bill of solid waste for the manufacturing process	
14.43	We employ measures to prevent, recycle and eliminate waste	
14.18	we reduce the non-hazardous waste that is recycled	
13.93	We improve our recycling rate of solid waste	
13.42	We manage efficiently the waste	

Figure A.31: [94]

A.2.26 CIRCuIT CE Indicators

A.2.26.1 CE Indicators(1)

City level indicators					
Category	**Indicator name (index)**	**Indicator description**	**Suggested unit**	**Stakeholder relevance/benefit**	**Core or Aspirational**
Material inputs Existing stock	Total material inputs to building stock (UM)	Indicates the quantity of material inputs (virgin and secondary) to the city's built environment. Calculated as an absolute quantity of materials used.	Tonnes of materials	Urban planners will be able to set targets on how much materials is needed and what type	Aspirational
	Secondary inputs to building stock – recycled materials (UM)	Indicates the proportion of raw material inputs to the city's built environment that are recycled (excluding downcycling) following a previous use cycle. Calculated as a percentage of recycled materials compared to virgin materials used.	% of recycled materials versus virgin materials	Planning officers will be able to set targets for amount of recycled materials to be used in future buildings	Aspirational
	Secondary inputs to building stock – reused materials (UM)	Indicates the proportion of raw material inputs to the city's built environment that are reused) following a previous use cycle. Calculated as a percentage of reused compared to virgin materials used.	% of reused materials versus virgin materials	Planning officers will be able to set targets for amount of reused materials to be used in future buildings	Aspirational
Lifespan and in-use performance	Ratio of building transformation to new construction (CD)	Ratio of refurbishment/transformation to new construction	% of buildings that are refurbished rather than demolished	Urban planners will be able to set targets for buildings to be refurbished rather than demolished	Core
	Intensiveness of use (L)	The average intensiveness of use of the building stock relative to the average potential intensiveness of use. This indicator is only suitable for buildings such as schools, offices or community centres.	% hours actually occupied versus potential	Planning officers will be able to validate the need for new buildings to be added or if they could more efficiently use existing ones	Aspirational

Figure A.32: [64]

A.2.26.2 CE Indicators(2)

		Number of hours the building is occupied versus the amount of hours it has the capacity to be occupied in average			
	Proportion of different materials in building stock mapped (additional one) (UM)	Map of materials available in the current building stock Tonnes of materials of different types in different building types. This will be calculated using pre-demolition audits	Tonnes of materials	Demolition industry/contractors will be able to evaluate faster what material is available where for more efficient reuse	Aspirational
Circular potential of existing building stock	Reuse/recycling potential of existing building stock (UM)	The amount of materials which are available for reuse/recycling in the building stock.	Tonnes of materials that has the potential for reuse/recycling	Policy makers will be able to set targets for recycling and reuse	Aspirational
Material outflows and recirculation – based on actual current activities	Total materials/wastes arising from construction and buildings sector and end of life reporting (UM)	The total amount of materials and wastes emerging from the construction and buildings sector.	Tonnes of wastes generated	Policy makers will be able to understand quantities of wastes generated	Core
	Recirculated materials (UM)	The proportion of total materials arisings at end-of-use in buildings within the city/region (see above), that enter new use cycles within the city/region (reuse/recycle) % per tonnes of the city's construction and demolition waste that is recycled or reused	% per tonnes of the city's solid waste that is recycled or reused	Policy makers will be able to validate their targets for recycling and reuse against those numbers	Aspirational
	Quantity of materials that is reused/recycled through dedicated centres (UM)	Quantity of materials that is reused/recycled through as a material outflow Tonnes of materials reused/recycled in the city	Tonnes of materials reused/recycled	Policy makers will be able to understand the efficiency of reuse/recycling ability at city level	Core

Figure A.33: [64]

A.2.26.3 CE Indicators(3)

Building level indicators					
Category	**Indicator name**	**Indicator description**	**Suggested unit**	**Stakeholder relevance/benefit**	**Core or aspirational**
Building design	Dematerialisation (linked to total material inputs to building stock) (CD)	Building has been designed so that the minimum material inputs are required to achieve the same whole life functionality, without compromising on durability, resilience, other technical performance requirements or health and safety. % of material that has not been used as a result of redesigning and as a function of the total amount of material used	% of material not used	Designers demonstrate that they have designed the asset with material optimisation. This will support building level assessments, such as BREEAM. This information will also inform LCA and LCC studies	Aspirational
	Design for disassembly (CD)	Proportion of building components that are reversible from the wider building without significant damage to either the removed component or its wider assembly. This indicator should be linked to BIM and guidelines to ensure stakeholder down the supply chain can optimise the building end of life. This indicator is measured using ISO20887. % of the building that can be disassembled at end of life	% of the building that can be disassembled	Designers can demonstrate to urban planners that the building can be disassembled at the end of its life. This will support building level assessments, such as DGNB. This information will also inform LCA and LCC studies	Core
	Design for adaptability (transformation capacity) (CD	The spatial and technical aspects of building design allow for adaptation to another function (as designed). This indicator is measured using ISO20887.	% of the building that can be adapted at end of life	Designers can demonstrate to urban planners that the building can be disassembled at the end of its life. This will support building	Core

Figure A.34: [64]

A.2.26.4 CE Indicators(4)

		% of the building that can be adapted at end of life		level assessments, such as DGNB. This information will also inform LCA and LCC studies	
Material inputs to building	Reused content (UM)	Proportion of the building that is formed of reused products and product components % reused content	% reused content	These will enable contractors to demonstrate compliance with local requirements, such as the GLA circular economy statement. This indicator will also inform policy makers to set future targets. This information will also inform LCA studies	Core
	Recycled content (UM)	Proportion of the building that is formed of recycled/upcycled products and product components (exclude downcycling). % recycled content	% recycled content		Core
Circular potential (as built)	Transformation capacity (CD)	The spatial and technical aspects of building design allow for adaptation to another function (for existing buildings)	Monofunctional (score 3-6) Transfunctional (score 6-8) Fully transformable (score >8)[62]	This enables building owners/ managers or developers to understand the potential to transform their building to deliver greater value and function with lower resource inputs.	Aspirational
	Reuse potential (UM)	The percentage (by mass) of products which can be reused at the end of the life of the building	% by mass of products that can be reused	These will enable contractors to demonstrate compliance with	Core

Figure A.35: [64]

A.2.26.5 CE Indicators(5)

	Recycling potential (UM)	The percentage (by mass) of products which can be recycled at the end of the life of the building	% by mass of products that can be recycled	local requirements, such as the GLA circular economy statement.	Core
Lifespan & in-use performance	Intensiveness of use (L)	The average intensiveness of use of the building stock relative to the average potential intensiveness of use. This indicator is only suitable for buildings such as schools, offices or community centres. Number of hours the building is occupied versus the amount of hours it has the capacity to be occupied in average	% hours actually occupied versus potential	Clients will be able to understand whether the use of their asset is optimised. Planning officers will also be able to validate the need for new buildings to be added or if they could more efficiently use existing ones	Aspirational
Material outflows and recirculation	Residual value (all materials in building) (L)	The forecasted total value obtained from material recirculation of materials within the building	£ or euro that can be extracted from the reuse of components in the building	Demolition companies and contractors will be able to quantify the benefits of maximising reuse and recycling. Investors will understand the value of their portfolio	Aspirational
	Total material arisings (whole life) (UM)	The amount of waste materials from the building across its lifetime, including during future refurbishment, repair phases.	Tonnes of waste arising	Policy makers will be able to understand quantities of wastes generated. This information will also inform LCA and LCC studies	Core
	% reused, remanufactured, recycled (CD)	The percentage of materials which were reused, remanufactured or recycled at the end of the life of the building	% reused, remanufactured, recycled	Policy makers will be able to validate their targets for recycling and reuse against those numbers. This information will also inform LCA studies	Core

Figure A.36: [64]

A.2.26.6 CE Indicators(6)

	End of Life reference scenario (UM)	Mapping of material history and recycling potential, before it reaches a material bank/storing site.	Typical % recycled or reused at end of life	Policy makers will be able to validate their targets for recycling and reuse against those numbers. This information will also inform LCA studies	Aspirational
Materials/product/components level indicators					
Category	**Indicator name (index)**	**Indicator description**	**Suggested unit**	**Stakeholder relevance/benefit**	**Core or aspirational**
Product design	Dematerialisation (linked to total material inputs to building stock) (CD)	Product has been designed so that the minimum material inputs are required to achieve the same whole life functionality, without compromising on durability, resilience, other technical performance requirements or health and safety. % of material that has not been used as a result of redesigning the product and as a function of the total amount of material used	% of material not used	Product manufacturers demonstrate that they have designed the product with material optimisation. This will support scheme such as the cradle to cradle certification scheme. This information will also inform LCA and LCC studies	Core
	Design for repairability (CD)	Product has been designed to enable future repair of key components of the product. This is not applicable to all products. % by mass of components of the product that can be easily removed and repaired or replaced.	% by mass of components of the product that can be easily removed and repaired or replaced.	Product manufacturers demonstrate that they have designed the product for future repairability. This will support scheme such as the cradle to cradle certification scheme. This information will also inform LCA and LCC studies	Core
Material inputs (as	Reused content (UM)	Proportion of the product/component that is formed of reused materials/products	% reused content	These will enable products manufacturers to demonstrate to	Core

Figure A.37: [64]

A.2.26.7 CE Indicators(7)

manufactured)		% by mass of the product that consists of components that have been reused		contractors' compliance with local requirements, such as the GLA circular economy statement. This indicator will also inform policy makers to set future targets. This will also support product certification schemes like EPD or cradle to cradle	
	Recycled content (UM)	Proportion of the product/component that is formed of recycled materials/products (exclude downcycling). % by mass of the product that consists of components that have been recycled	% recycled content	This will support schemes such as the cradle to cradle certification scheme. This information will also inform LCA and LCC studies	Core
Material inputs (as installed in building)	Product is reused after it has been used in a building (CD)	The product has previously been used for the same function in another building % of similar products/components that are reused at the end of their life based on actual waste analysis.	% reuse	This informs the product manufacturers on the end of life potential of their product/component. This can also inform policy makers on whether there is a further need for recycling facilities. This will support scheme such as the cradle to cradle certification scheme. This information will also inform LCA and LCC studies	Core
	Product is recycled after it has been used in a building (CD)	The product has previously been used for the same value function in another building and has been through some processing. % of similar products/components that are recycled at the end of their life based on actual waste analysis. Excludes downcycling	% recycled		Core
Circular potential (as installed)	Reuse potential (UM)	Product is designed and installed so that it can be easily demounted from the wider assembly with no loss of value to itself or the assembly	% potential reuse	This will support scheme such as the cradle to cradle certification scheme. This information will also inform LCA and LCC studies	Core

Figure A.38: [64]

A.2.26.8 CE Indicators(8)

		% of the product/component that has the potential to be reused			
	Part of an extended producer responsibility scheme (CD)	The product is covered by an Extended Producer Responsibility scheme by the manufacturer (e.g. a take-back scheme) This is a yes/no answer	Yes/no	This will enable policy makers to identify where more EPR schemes may need to be implemented. This will affect product manufacturers & suppliers	Core
	Repairability potential (L)	The amount of components of the product that can be easily removed and replaced (once installed)	% of the essential components of the product that can be repaired	This will enable the replacement of core components of units without the need to replace whole units. This will enable facility managers to manage better the buildings	Aspirational
Lifespan and in-use performance	Service life (L)	The number of years the material or product has been used for its intended function.	Number of years	This will enable the demolition industry to understand whether the product/component can be reused. It will also inform contractors on when the product needs to be considered for further testing to ensure it is fit for purpose	Core
Material outflows and recirculati on	Residual value (L)	Financial value obtained by actor with duty of care of product at building end of life	£ or euro that can be made from the reuse of a product	Demolition companies and contractors will be able to quantify the benefits of maximising reuse and recycling. Investors will understand the value of their portfolio	Aspirational

Figure A.39: [64]

A.2.26.9 Enablers(1)

City level enablers		
Indicator	**Description**	**Stakeholder**
Promotion of circular design incentives	Number of initiatives, regulations, taxes for new materials and incentives promoting circular design (e.g. lean principles, design for disassembly and adaptability)/ building lifespan extension over replacement/ looping at building end of life	Policy makers need to develop the right incentives to the whole construction industry to enable more circular decisions to be made. Those could be at planning stage for example.
Circular economy included in public procurement strategies	Proportion of value procurement in which Circular economy requirements are included in public procurement strategies	Government department, local authorities, public bodies need to set procurement rules to enable more circular economy decisions to be made
'City circularity database' exists for aggregation and analysis of data on building stocks and material flows	A database is present in the city to analyse the circular economy practices in buildings	The database would be populated and used by contractors and demolition companies (demand/supply), facility managers (during refurbishment and repair cycles). It would also be useful to policy makers to establish targets for reuse/repair and recycling.
Educational courses/skills	Number of participants enrolled in University courses/ apprenticeship/ upskilling on the topic of circular economy	Universities and professional bodies can set up course to upskill professionals and students to make them aware of the importance of circular economy
Proportion of building stock mapped (ie: materials with building known)	Amount of material required for a typical building in the building stock, across its whole life.	A better understanding of the building stock in a given city will support planning officers in their decision to award permission to build as they would understand the building stock better.
Building level enablers		
Indicator	**Description**	**Comment**

Figure A.40: [64]

A.2.26.10 Enablers(2)

Building passport / Bill of Materials	The data set that describes the characteristics of the products in the building which give them value for recovery, recycling and reuse	Building on materials passport this enable information on the building to be passed on to facility managers, landlords.
Guidelines available for repair, maintenance, transformation and material looping	Data is available for the repair, maintenance, transformation and material looping of the building	Information on the efficient repair/maintenance/replacement schedule of components will enable facility managers/ landlords to manage their facility more efficiently. It will also ensure the end of life of components/products is optimised. Product manufacturers could therefore benefit from materials/products re-entering the manufacturing loop
BIM	Has a Building Information Model with relevant circularity data.	The BIM model should be used by the whole building supply chain from designers to facility managers and need to be kept up to date throughout the building life
'City circularity database'	Relevant data routinely shared with a 'city circularity database' throughout lifetime	A database that enables communication across the whole supply chain and support the supply/demand of recycled/reused materials
Screening of existing buildings (added)	Resource and environmental pre-demolition audit	Contracted by the client or contractor, this will enable the policy makers to inform recycling/reuse targets
Logistic centre	Logistic centre to store and transport recycled/reuse materials in an efficient way. Linked to "number of reuse/recycling centres created" at city level/	Client with large portfolio would benefits for setting hubs to support a better supply/demand approach. Those could also be set up at city level.
Material/product/component enablers		
Indicator	**Description**	**Comment**
Material passport	The data set that describes the characteristics of the products in the building which give them value for recovery, recycling and reuse	This must be in place to support any re-use or potential re-use in future life cycles. Really important to know what is going into buildings today to avoid the same issues we currently face with

Figure A.41: [64]

A.2.26.11 Enablers(3)

		existing building stock i.e. don't know what's in them so how do we reuse? Screening/mappings of the potential hazardous substances in buildings should be part of the materials passport. Long use of buildings, components and materials can be promoted by equipping buildings with a deconstruction/disassembly/adaptability plan
Guidelines available for repair, maintenance and material looping	Data is available for the repair, maintenance, transformation and material looping of the building	This is not always the right incentive for all products. Could be part of material passport
Taxes	Taxes on new products	Important to ensure that the tax will drive the right incentive and not promote the wrong behaviour. Tax relief on high recycling/reuse rate could be an option
Affordability of reused and leased products (additional)	Price of reused and leased products compared to linear products	This is calculated as part of a whole life costing approach

Figure A.42: [64]

A.2.27 Social indicators

Table 3. *Cont.*

Author (Year)	Key Definition	Key Terms
[48]	"A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times" (p. 483)	Restorative and regenerative by design
[13]	"An economy is envisaged as having no net effect on the environment; rather it restores any damage done in resource acquisition, while ensuring little waste is generated throughout the production process and in the life history of the product" (p. 371)	Restoration by design
[16]	"A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro-level (products, companies, consumers), meso level (eco-industrial parks) and macro-level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations." (pp. 224–225)	Creating environmental quality
[49]	"Circular economy is an economy constructed from societal production-consumption systems that maximize the service produced from the linear nature-society-nature material and energy throughput flow. Circular economy limits the throughput flow to a level that nature tolerates and utilizes ecosystem cycles in economic cycles by respecting their natural reproduction rates" (p. 39)	Maximizes the service produced
[1]	"Circular Economy (CE) is an activity, set of process for reducing the material used in production and consumption, promoting material resilience, closing loops and exchange sustainability offering in such a way that maximize the ecological system" (p. 30)	Reducing the environmental burden with an ecological system theory approach

4. Overarching Themes for Future Research

A.2.28 Indicators and KPI covered by them in the "Critical review of nano and micro-level building circularity indicators and frameworks" [65]

A.2.28.1 Identified circular indicators

Acronyms	Method	References	Sector	Publisher	Applicable
Level(s)	Level(s)	(Dodd et al., 2021a, b, c; Donatello et al., 2021a, b) (Díaz-López et al., 2021)	Government Agency	European Commission	Residential and office buildings
BCI	Building Circularity Indicator	Verberne (2016)	Academia, Consulting Company	University of Twente	All kinds of buildings, foundations, bridges
BCIDR	Building Circularity Indicator (Disassembly Reconsidered)	Van Vliet (2018)		Eindhoven University of Technology	
BBCA	BIM Based Building Circularity Assessment	Zhai (2020)			
MAC	Modified Alba Concept (For Foundations)	van Schaik (2019)		Delft University of Technology	
ACBCI	Alba Concepts BCI	(Alba, 2018)		Alba Concepts	
MBCI	Modified Building Circularity Indicator	Braakman et al. (2021)		Resources, Conservation and Recycling	
PBCI	Predictive Building Circularity Model	Cottafava and Ritzen (2021)			
CIPB	Circularity Indicator for Pedestrian Bridges	Anastasiades et al. (2020)		International Winter Conferences 2020, Tignes, France	
ARCHCEIF	ARCH Circular Environmental Indicator Framework	Foster et al. (2020)	Academia	Environmental Sciences Europe	Existing ARCH buildings
MAD-CI	MADASTER Circularity Indicator	(Heisel and Rau-Oberhuber, 2020; Madaster, 2018)	Consulting Company	MADASTER, Netherlands	All kinds of buildings
FLEX	FLEX (Ver 1.0, 2.0, 3.0 & 4.0)	(Geraedts, 2016; Geraedts and Prins, 2016; Geraedts et al., 2014; Prins and Geraedts, 2015)	Academia	Delft University of Technology	General and office, school
MCI	Material Circularity Indicator	Ellen MacArthur Foundation and Granta Design (2015)	Consulting Company, Registered Charity	EMF and Granta Design, United Kingdom	Materials
MCIC					Companies
CEMS	Circular Economy Measurement Scale	Nuñez-Cacho et al. (2018)	Academia	Sustainability (Switzerland)	Construction companies
CES	Circular Economy Scale	Núñez-Cacho et al. (2018)		Journal of EU Research in Business	
CBMCI	Circular Business Models (CBM) Based Circularity Indicator	Di Biccari et al. (2019)	Academia	IOP Conference Series: Earth and Environmental Science	All kinds of buildings
MCI	Material Circularity Indicator for Construction	Jiang (2020)	Academia	University of Twente	Products (Construction)
IEPC	Integrated Energy Performance and Circularity	Sreekumar (2019)	Academia	Delft University of Technology	New buildings
BBWPE	BIM-based Whole-life Performance Estimator (BWPE)	Akanbi et al. (2018)	Academia	Resources, Conservation and Recycling	Structure of building
BCAF	Bridge Circularity Assessment Framework	Coenen et al. (2021)	Academia	Journal of Industrial Ecology	Bridges
SEEI	Synthetic Economic Environmental Indicator	Fregonara et al. (2017)	Academia	Buildings	Existing buildings
GEOLMI	Gypsum End of Life Measurement Indicator	Jimenez-Rivero and Garcia-Navarro (2016)	Academia	Waste and Biomass Valorization	Material (Gypsum)
RIPAT 1.0	RIPAT 1.0	Valdebenito et al. (2021)	Academia	Arquitetura Revista	Heritage buildings
FCB	Framework for Circular Buildings	Kubbinga et al. (2018)	Consulting Company	Circle-Economy.Com	All kinds of buildings
PCB	Platform CB' 23	(Platform CB'23, 2020a, b)	Consulting Company	Platform CB23, Netherlands	All kinds of buildings
CC	Circularity Calculator	(IDEAL & CO Explore, 2017)	Consulting Company	IDEAL & CO Explore, Netherlands	Generic
CBAP	Circular Building Assessment Prototype	BAMB (2012)	EU Funded Project	BAMB, EU Funded Horizon 2020	All kinds of buildings
C-CALC	C-CALC	CENERGIE (2020)	Consulting Company	CENERGIE, Netherlands	All kinds of buildings
Cirulytics	Cirulytics	Ellen Macarthur Foundation (2020)	Registered Charity	EMF, United Kingdom	Company
CACE	Circular Assessment Criteria for Envelope	Finch et al. (2021)	Academia	Sustainable Cities and Society	Building envelope
CCEF	Circular Construction Evaluation Framework	Dams et al. (2021)	Academia	Journal of Cleaner Production	All kinds of buildings

Technical
University of
Denmark

Brovej, Building 118
2800 Kgs. Lyngby
Tlf. 4525 1700

www.byg.dtu.dk