Systems Analysis for Assessing Impacts of a Circular Economy on the Construction Sector

A Case Study on Urban Construction Waste Management in the Netherlands

Master Thesis

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by

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to obtain the degree of Master of Science in Engineering and Policy Analysis at the Delft University of Technology. This thesis will be defended publicly on Tuesday September 27, 2022 at 13:00.

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Place:	Faculty of Technology, Policy and Management, Delft
Project Duration:	February, 2022 - August, 2022
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TU Delft

Preface

This journey actually started some three odd years ago when I was working in Bangalore as a software engineer. I liked programming, but I wanted to use my skills for something more. Fast forward to today, and here I am, finishing my master's in EPA and it is everything I dreamt of doing and more. I stumbled upon circularity accidentally a year back. It was as if a whole new world opened up for me. I knew then, that I wanted to do my thesis on circularity.

Thank you Dr. Filippos Zisopoulos for allowing me to do this thesis with the Inclusive Wise Waste Cities and for your valuable insights. I remember the first time we met, you allowed me to take this research in whichever direction I liked and for that I'm grateful. I hope I've done justice to your vision. It has been a rich experience working as part of the IWWC team with like-minded researchers who are also as passionate about the topic. I'd also like to thank Dr. Amineh Ghorbani for her unwavering support and encouragement throughout the process. Dr. Els van Daalen, as my first supervisor, you were there every second of the way. You've been my anchor, my lighthouse, and my lifeguard. I really couldn't have done this thesis without you.

I'd like to thank my parents, Rajeev and Beena, for their immense love and support and for having faith in me. You're both my inspiration! My father is an engineer, and my mother a social researcher. Being a product of these two amazing people, I'd like to think I've imbibed the best of these two fields as well and made them my own. To my brother, Nikhil, you're my constant. Our never-ending bickering made sure I felt right at home even millions of miles away. And to my partner Arvind who is my biggest cheerleader, thank you for always pushing me. Special mention to Jeebu, my team lead at Dell who's belief in me was the push I needed to leave my career and take this leap of faith. Lastly, big shoutout to my Netherlands family, especially Anmol and Qin, I'm forever grateful to have you by my side and I cannot imagine surviving masters without you all.

It wasn't the easiest thing to leave home and come halfway across the world during a pandemic to follow a passion. But I'm so glad I made this decision - it is easily one of the most rewarding experiences. I have learnt so much in the last two years, and especially in the last six months. There were times where I felt like this research had a mind of it's own and I was merely helping steer it. "It's an iterative process" took a whole new meaning for me during this phase. But I learnt to trust the process and I'm a better researcher today because of this experience.

I am proud of this report and I hope you enjoy reading!

Lekha Nambiar
Delft, September 2022

Summary

As a systems change framework, the circular economy aims to gradually decouple economic activity from the consumption of finite resources. The Dutch Government has prioritized the construction sector for a circular economy transition as part of implementing the Circular Economy Action Plan and the Waste Framework Directive. The Dutch construction sector consumes around 250 million tons of raw materials each year and produces around 25 million tons of construction and demolition waste. The Netherlands has an advanced CDW recovery of more than 90% but this figure includes recovery through incineration and downcycling. Only a mere 3-4% of recycled CDW is used in new construction, thus limiting actual closed-loop recycling. According to the Dutch Government, this cannot be called circular. This research aims to understand the circular transition in the context of construction and demolition waste management system in the Netherlands - what it means, how it could be improved and how might it evolve, while at the same time exploring potential barriers and unintended consequences.

Existing policy studies done for construction and demolition waste management only cover preliminary policies such as effects of landfill bans, taxes and disposal charges which are not applicable to the Netherlands. Impact studies done for the Netherlands cover bottom up initiatives on a smaller scale. This leaves a gap where a top down systems analysis is undertaken to compare policies to study their individual or combined impacts. This would help in understanding the difficulties in implementing circular economy and help provide a strategic focus for the future. This research focuses on evaluating the role of policy measures on the construction waste sector. The main research is formulated as -*What policies can the Dutch Ministry of Infrastructure and Water Management use to stimulate a circular economy transition in the construction and demolition waste management sector?*.

Research Approach

The research approach used is based on systems analysis/policy analysis adapted from Enserink et al. (2022). A consequential research methodology was used based on three phases - problem formulation, system diagram and model building. The data collection methods used were desk research and semi-structured interviews. Assuming the client as the Dutch Ministry of Infrastructure and Water Management, the study started with a means-ends analysis which allowed to list out all the possible solutions to achieve circularity throughout the value chain. Then an actor analysis was done to identify the gaps in the system according to different actors and objectives they considered most important, and possible actions they can take. The output from actor analysis formed the gaps, barriers and opportunities in the current construction and demolition waste management system in the Netherlands. The opportunities were converted into 7 policy measures that could be implemented by the 3 key actors identified - the Government, the recycling companies and demolishing companies. This was then followed by a system diagram and a multi-criteria analysis which helped identify factors affecting the CDW material flow. Finally, a model was built based on the CDW material flow to study the impacts of the policies.

Results

The 7 policy measures identified are - 1. Imposing certifications and standards for recycled aggregates, 2. Improve pricing for recycled aggregates, 3. Financial instruments: investments, tax incentives and subsidies, 4. Circular and sustainable material procurement, 5. Mandatory pre-demolition audits, 6. CDW identification, source separation and sorting obligations and 7. Technological advances in sorting and recycling.

The first run of the model involved simulating the impacts of each policy at a time. Results from this showed the policy of mandatory pre-demolition audits to be overall most effective. The policy that results in the highest upcycling and reuse rate and the highest carbon emissions reduction is Mandatory pre-demolition audits. It increases the recovery rate from the current 51% to 65% and the upcycling and reuse rate from 8% to 23% which was the highest among all policies tested. This is

because it not only focuses on source reduction, but also prioritizes reuse by redirecting the waste flow and ensuring there's enough time for components to be reused. It also has a positive effect on amount recovered (1500 kilotonnes/year) and total recovery rate (65%), second only to CDW identification and source separation.

CDW identification, separation and collection at source performed the best in total amount recovered and total recovery rate. It increased the total amount of CDW recovered by 7700 kilotonnes/year and the recovery rate from 51% to 83%. However, it only increased the upcycling and reuse rate to 10%. It was also the only policy that increased the amount of carbon emissions (by 5 million CO2ee kg/year). Financial instruments, improving price of recycled aggregates and imposing certifications and standards did increase the upcycling and reuse rate and reduce the carbon emissions. But they did not affect the material recovery criteria. The other policies did not perform as well as these.

In the next model run, scenarios were formed by clustering policies to provide a strategic focus and direction towards reducing consumption of primary materials and reducing carbon emissions. Three scenarios were formed - Efficient supply chain, Prioritizing closed-loop recycling and implementing all 7 policies. Efficient supply chain led to a significant increase in total recovery rate of 97% and carbon emissions reduction of 100 M kg CO2e. Prioritizing closed-loop recycling led to no change in material recovery or recovery rate, but led to carbon emissions reduction of 106 M CO2e. The scenario where all policies are implemented performs the best and led to a recovery rate of 97% and carbon emissions reduction of 206 M kg CO2e. Furthermore, it increased the upcycling and reuse rate from a previous under 6% to 65%.

A policy recommendation from this research is to implement pre-demolition audits and CDW identification and separation at source with sorting obligations. It was also found that recovering more waste on its own will not be helpful in the long run unless it's redirected towards low carbon destinations. A recommendation to policymakers would be to include not just material recovery indicators into assessing the effectiveness of circular policies, but to also include carbon emissions and upcycling and reuse rates as indicators.

Contributing to the scientific literature on CDWM, this research provides both a mix-method approach based on systems analysis and a material flow model to assess policy impacts. From an academic perspective, this study integrates a partial life-cycle assessment into a material flow analysis by adding carbon emissions to the material flow model. The mix-methods approach used can also be adapted to other value chains with a similar supply chain background. On the social side, by synthesizing and using a multi-criteria framework to calculate potential impacts, this research adds to a growing literature in policy design.

Contents

Nomenclature

Abbreviations

Abbreviations	
Aggregates	Granular materials used in construction which can be of different types such as sand, gravel (including marine aggregates), crushed rock, recycled and manufactured aggregates
CDW	Construction and Demolition Waste
CDWM	Construction and Demolition Waste Management
EC	European Comission
EoL	End-of-life
EIB	Economic Institute for Construction of the Netherlands C2CA and European Commission 7th Framework Program project “Advanced Technologies for the Production of Cement and Clean Aggregates from Construction and Demolition Waste”
EU	European Union
LAP2	Dutch Second Waste Management Plan for the period 2009–2021
MFA	Material flow analysis
VEEP	European Commission Horizon 2020 project “Cost-Effective Recycling of CDW in High Added Value Energy Efficient Prefabricated Concrete Components for Massive Retrofitting of our Built Environment”
WFD	Waste Framework Directive

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Introduction

As a systems change framework, the circular economy (CE) aims to gradually decouple economic activity from the consumption of finite resources based on three core principles - eliminating waste and pollution, circulating products and materials at their highest values and regenerating nature (Ellen MacArthur Foundation, 2019). The Dutch Government has prioritized the construction sector for a circular economy transition as part of implementing the Circular Economy Action Plan (CEAP) and the Waste Framework Directive (WFD) (Ministerie van Infrastructuur en Waterstaat, 2019).

The construction sector is important for the Dutch economy, as it accounts for almost 7% of the Gross Domestic Product (GDP) and provides employment to around 458,000 people (Schuttelaar and Partners, 2018a). Compassing residential and non-residential construction and civil engineering divisions, it is an innovative sector that proactively engages society, the market and consumer demand (Schuttelaar and Partners, 2018a). The construction sector is also responsible for a substantial share of adverse environmental impacts from materials usage, waste generation, energy use and greenhouse gas emissions (Fernandes et al., 2021). The Dutch construction sector consumes around 250 million tons of raw materials each year and produces around 25 million tons of construction and demolition waste (Circle Economy, 2017). Rapid economic development has led to a global environmental crisis driven partially by wasteful material usage and an accelerated pace of construction and demolition waste (CDW) generation around the world (Villoria Sáez & Osmani, 2019). Estimated carbon emissions from all construction and demolition activities in 2010 was 9.6 million tonnes CO2, which translates to 5% of the Netherlands' total carbon footprint (CE Delft, 2014).

The current economic systems provide very little incentives to value resources at the assumed end of their lives; they are not viewed as part of the revenue streams but are instead discarded as quickly as possible (EME, 2022). There is a need for a paradigm shift where waste isn't an afterthought. However, there are also concerns about using recycled CDW due to uncertainties about the potential health risk for workers using recycled CD materials (European Commission, 2018). To realise a fully circular construction and demolition sector, these bottlenecks need to be addressed. This research aims to understand the circular transition in the context of construction and demolition waste management system in the Netherlands - what it means, how it could be improved and how might it evolve, while at the same time exploring potential barriers and unintended consequences.

1.1. Background and current literature

1.1.1. Construction and demolition waste management in the Netherlands

Till the 1970's, all CDW in the Netherlands was put into landfills. However, with increasing environmental regulation and rising landfill taxes, this method of disposal became too expensive (Wildeboer & Savini, 2015). The landfill ban was a breakthrough policy and is the main reason for the high recovery rates in the country and the presence of well established recycling facilities (Wildeboer & Savini, 2015). Furthermore, CDW proved to be a good foundation for both residential and infrastructural development on the Dutch peaty soil, thereby resolving both waste management challenges and providing foundational feedstock (Wildeboer & Savini, 2015). Aside from the sheer volume, CDW differs from other wastes such as metals, plastics or textiles because it is a very local issue; the high weight and low value acutely limit the mobility of the material and thus management often needs to be done in proximity to the construction or demolition site or outside of densely inhabited areas (Pourkhorshidi et al., 2020).

The Netherlands has an advanced CDW recovery [1] rate of more than 90% (Deloitte, 2015). However, this figure includes recovery through incineration and downcycling to roadfilling or backfilling [2]. Only a mere 3-4% of recycled CDW is used in new construction, limiting actual closed-loop recycling (Rijkswaterstaat, 2015). The rest of it is used in civil works such as a base for road foundation or for landscaping purposes and according to the Dutch Government, this cannot be called circular (Rijkswaterstaat, 2015). The reasons for this mainly stem from conservative practices in current construction, a distrust of secondary aggregates quality (European Commission, 2018) and lobbying by primary aggregate producers (Wildeboer & Savini, 2015). This leads to stagnant market dynamics which may further discourage new ventures (or SME's) in waste management and recycling to come up (Wildeboer & Savini, 2015).

In 2016, the 'Betonakkoord' or the concrete agreement was formed by the actors in the concrete sector with support from the Ministry of Infrastructure and Water Management to pave the way for cooperation and joint action towards a sustainable construction sector (Betonakkoord, 2016). However, an inertia in the construction and demolition waste supply chain was found due to differences in perception and lack of trust between supply chain actors (Bukvic, 2018). With natural resources becoming scarce globally, and the demand for recycled CDW in road construction potentially reaching a saturation point in the future (Rijkswaterstaat, 2015), it becomes crucial to replace primary raw materials in construction work. In 2017, the Raw Materials Agreement was introduced which states that by 2030, 50% of all materials consumed need to be non-virgin, and by 2050, all the materials flowing through the Dutch economy will have to be from secondary sources (Waterstaat, 2019). But the current secondary material usage rate in construction is presumed to be around 13% (Metabolic, 2020) and the current recycled aggregates usage is presumed to be around 4% (Rijkswaterstaat, 2015), which is a long way away from achieving this goal.

It may be noted that given the increased focus on the construction waste management sector, there are upcoming projects which aim to accelerate a circular economy transition through joint cooper-

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[1] The EU definition of waste recovery according to Waste Framework Directive Article 3(15) is "waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy." (European Commission, 2010)

[2] According to the European Commission Decision 2011/753/EU, backfilling is defined as follows: "A recovery operation where suitable waste is used for reclamation purposes in excavated areas or for engineering purposes in landscaping and where the waste is a substitute for non-waste materials" (European Commission, 2010)

ation. The CityLoops project, for instance, plans to develop a series of innovative procedures, approaches and open access and open source tools to embed circularity within planning and decision-making processes for construction and demolition waste in seven European pilot cities and includes Apeldoorn from the Netherlands (City Loops, 2022). On retrieving value from waste, the concept of urban mining refers to the process of recovering and reusing a city's materials. To promote urban mining, new ventures and central database repositories are being set up so that customer and construction companies that want to start working with recycled building materials can offer or buy products (Oogstkaart, 2022) (EME, 2022). From a recycling and reuse perspective, a key enabler towards CE is Industrial Symbiosis (IS), which is when waste or byproducts of an industry or industrial process becomes the raw materials for another. Although IS has been widely applied in manufacturing industries, its implementation is unclear in the construction industry. A study by Yu et al. (2021) looks at IS through replacing primary concrete aggregates (PCA) with recycled concrete aggregates in the Netherlands. The Dutch Government in their report, 'Circular economy in the Dutch construction sector: a perspective for the market and government', also explore different routes to stimulating circularity in the sector that go beyond recycling (Rijkswaterstaat, 2015).

End-of-life (EoL) concrete is identified as an important stream for CDW recycling in most EU countries as CDW consists of about 80% concrete (Metabolic, 2021). The European projects of C2CA and VEEP have proposed several cost-effective technologies to recover EoL concrete to be used as substitute aggregates for new concrete manufacturing (C2CA (2011), EC (2016)). Another study by Zhang et al. (2020) to understand the potential effects of large-scale implementation of those recycling technologies on the circular construction found that they have the potential to improve the share of upcycling in the Netherlands from around 5% in 2015 up to 22%-32% in 2025. Based on the available data for CDW flows, Figure 1.1 is sketched. The previous collected data by Deloitte (2015) only includes the total CDW recycled, and information on the amount upcycled and downcycled is missing. To bring about a change in the situation of a low upcycling rate, policymakers need insights into the flow of materials as well as the climate impacts such as the CO2 footprint of different circular economy strategies when making strategic decisions (CE Delft, 2021). The figure was extended to include this distinction.

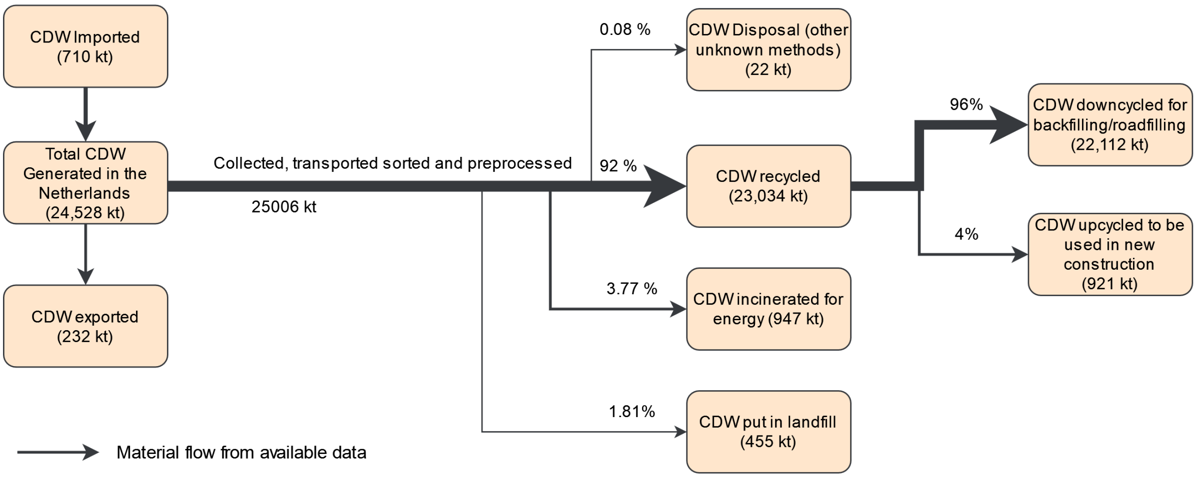


Figure 1.1: Material Flow of CDW data in 2010 based on the data collected by Deloitte (2015). Data table for the material flow can be found in Appendix 5.4. Additionally, CDW Recycled is extended to include both upcycling and downcycling flows since this research makes a distinction between the two. Thickness of the flows are for representation purposes only.

1.1.2. Complexity in Construction and Demolition Waste Management

Z. Ding et al. (2018) considers construction and demolition waste management (CDWM) a complex adaptive system (CAS), defined as "a system in which a perfect understanding of the individual parts do not automatically convey a perfect understanding of the whole systems behavior". A complex adaptive system consists of a collection of individual agents that are free to act in ways that are not totally predictable and may be looking out for their own interests (Holden, 2005). The entire construction supply chain not only involves various factors (e.g., social, economic, environmental) but also different stakeholders (such as builders, contractors, designers, collectors, recyclers and regulatory bodies) simultaneously. Moreover, as a functioning supply chain, the flow of materials keep changing hands at every stage. This makes studying the system complex and puts it in the midst of a multi-actor situation and subject to market dynamics.

Conversely, circular economy constitutes physical flows of materials, energy and information among the actors, organizations and communities affected by and affecting these physical flows. The flows can be inter-organizational, inter-sectoral or even international. They cross administrative, organizational and national boundaries and borders. A complex situation can be defined as one in which it is not possible to define the true state of the problem and in which case no such thing as the 'best' or 'optimal' solution can be found (Enserink et al., 2010). Going by this definition, CE in itself can be called a complex problem. Thus, it could be established that the policy problem of CE in construction is a complex situation that involve multiple layers of complexity.

Apart from this, complexities can also result from policies, which despite their best interests, are sometimes limiting. An example of this is the Waste Framework Directive (WFD). The Directive was amended in 2018 in order to facilitate the circular economy (EU, 2018), but even so, the changes have only produced a minimal improvement in practice. A policy analysis done by EME (2019) on Dutch waste legislation found that under the law, even valuable secondary materials may qualify as 'waste' regardless of if they have economic value, as long as the holder of these goods wants to get rid of them. This is attributed to the rather broad definition of waste which is defined as "any substance or object which the holder discards" (European Commission, 2006). As a result, the waste law has been quite unpredictable, which impacts new and upcoming ventures and SME's in recycling, as their business model operates on the borderline between waste and normal resources EME (2019). To get around this, new companies may have to comply with several legal obligations such as applying for permits for the processing of waste which can be expensive, keeping the authorities notified for every material transfer or registering the amount and composition of the CDW they treat EME (2019). Instead of risking non-compliance and enforcement, companies prefer to treat their secondary materials as waste, which means that they often take on unnecessary administrative burdens (EME, 2022).

1.1.3. Impact assessment of CDW management systems

According to the International Association of Impact Assessment (IAIA), an impact assessment refers to "a structured process of considering the implications of any proposed actions to people and their environment while still having an opportunity to modify" (IAIA, 2022). In the realm of policy analysis, it may also refer to finding out if a certain policy had the desired impact. Globally, a lot of studies dealing with impact assessment of CDW policies are focused on China, with a few in the rest of Europe. However, studies on the topic in the Netherlands are very few and scattered.

Tam et al. (2014) developed a system dynamics (SD) model for assessing the effectiveness of construction waste management in Shenzhen, mainland China through 5 subsystems, namely: construction waste generation, transportation, landfill, resource recovery, and illegal dumping. Then a simulation was run with policy options of landfill charges and penalties from illegal dumping to study the effectiveness of waste management through comprehensive waste minimization as a key performer indicator. This study presents a good overview of how the complexity of CDWM can be captured in a model. In line with the waste hierarchy, a study by Ding et al. (2016) on CDW reduction management and their environmental benefits, looks at the effects of source reduction at the construction phase, which was found to be effective in reducing 27.05% of waste. A study by Au et al. (2018) looked at both the environmental and financial implications of CD waste disposal charges in Hong Kong. Almost all studies on CDW impacts in China still study preliminary policies such as effects of landfill bans, landfill taxes and disposal charges, which are not applicable to the Netherlands as they already implemented these policies early in the 1970's and is already at an advanced stage.

Moving closer to Europe, a research by Coelho and de Brito (2013) focused on the operation of a large scale CDW recycling plant in Portugal to calculate the economic and environmental implications of managing CDW . They analysed the plant performance during a 60 year period, using primary energy consumption and CO2-eq emission as environmental impact performance indicators. The results found that the main environmental benefit came from replacing virgin materials. Conversely, the results from a life cycle assessment study done for Italy found that building waste recycling facilities is not only economically feasible and profitable, it is also sustainable from an energetic and environmental point of view (Blengini, 2009). In the Netherlands, an agent based modelling (ABM) study done by Yu et al. (2021) to investigate a bottom-up solution to upcycle concrete through industrial symbiosis found that a successful implementation requires collaboration of multiple actors across substantial temporal and spatial differences.

Factors that affect the context of CDW management in a country are varied, ranging from market, regulatory framework, available technologies as well as the social conditions that enable recycling businesses. In terms of environmental impacts of CDW, most assessments have focused on energy consumption and carbon emissions (operational, transportation and/or embodied) as an indicator. The general consensus is that results from studies are difficult to compare due to contextual differences and the different assumptions that are applied, even when following international standard methodologies.

Social impact assessments of CDW are even fewer and focus mainly on emerging economies (Duan et al., 2019; Mercader-Moyano et al., 2022). For the Netherlands, the social aspect of CDW may come from an instability in the workforce stemming from a shortage of qualified workers with circular skills across disciplines and education levels. Particularly for the built environment, skills needed for new design and assessment methods are critical. Coupled with the existing challenges faced by the Dutch labour market (PricewaterhouseCoopers, 2018), the need for a plan to manage the workforce, maximise employment opportunities and secure the human capital needed for the circular economy is required.

To benefit from the potential positive effects and mitigate any negative effects of a circular economy, a sound understanding of the existing, complex situation and challenges is required. This also calls for a clear perspective on what precautions are necessary to prevent unintended consequences. Combining circular economy policies with social protection measures will be important in order to ensure that the burden of efforts to promote circularity will not fall on a single actor and lead to worse working conditions and health impacts, reduced livelihoods, or job losses (Schroder, 2020). Identifying potential winners and losers can help shape effective cooperation mechanisms and partnerships nationally and internationally (Schroder, 2020).

1.1.4. Knowledge Gap

Reimagining the current linear system brings potential benefits beyond the environment such as employment and opportunities for workforce development. The construction sector in the Netherlands has been struggling with decreasing levels of productivity during the last decade as it is both labour-intensive, as well as volatile (CPB, 2014). A recent study on the effect of CE on the labour market has pointed to the evidence that sectors that offer virgin materials and those providing durable goods will suffer from lower demand for their products if the degree of circularity in the economy increases (Cambridge Econometrics, 2018). On the contrary, sectors engaging in recycling, maintenance and repair activities will grow rapidly and create new jobs. Companies that offer know-how and technology to enable material-efficiency will also benefit from the transition to a circular economy. This puts the construction sector which not only consumes a lot of primary materials, but also produces and recycles a lot of waste in an interesting position for a circular economy transition. According to Maio et al. (2017), to close the material loop and make the CDW management sector more sustainable, the following goals should be reached: 1. Widely replacing primary raw building materials through recycling end of life concrete, 2. Achieving a substantial reduction in road transport of building materials and 3. Creating a serious cut in carbon emissions from concrete production.

The policy impacts assessment done for CDWM covered in the literature review only cover preliminary policies such as effects of landfill bans, landfill taxes and disposal charges which are not applicable to the Netherlands. And the lifecycle impact assessments on CDWM cover mostly bottom up initiatives on a smaller scope - such as impacts of a single recycling facility, or effects of upcycling concrete through industrial symbiosis. This leaves a gap where multiple different policies are compared and contrasted to study their individual or combined impacts. This would help in understanding difficulties in CE implementation and help provide a strategic focus for implementing circularity in the future.

1.2. Research question

Based on the problem context and the knowledge gap regarding the impacts of circular economy on the construction sector, the following research question was formed:

What policies can the Dutch Ministry of Infrastructure and Water Management use to stimulate a circular economy transition in the construction and demolition waste management sector?

To help reach an answer to the main research question, the following sub-questions are formulated. Each sub-question elaborates a component of the main problem and helps contribute to the bigger puzzle piece.

SQ 1. What are the gaps, barriers, and opportunities in transitioning to a circular economy in the construction waste sector?

SQ 2. What are the key criteria that should be taken into account to design effective circular economy policies for CDW management?

SQ 3. What are the effects of potential policies on the key criteria?

1.3. Report structure

The remainder of this report is split into sections with each section addressing a specific aspect and is structured as follows. In Chapter 2, the research approach is outlined. Then, based on literature review and expert consultation, Chapter 3 explores the problem in detail through an actor analysis and identifies the gaps, barriers, opportunities and possible policy actions. Chapter 4 puts the problem in a dynamic context with the help of a multi-criteria analysis and a system diagram. Chapter 5 formulates a model to assess impacts of circular policies on the system based on the key-performance indicators identified through the multi-criteria analysis. Finally, the research is concluded in Chapter 6 and is followed by a discussion of limitations, recommendations and future work in Chapter **??**.

2

Methodology

In this chapter, a research methodology based on systems analysis is devised that enables a policy analysis of circular economy in the construction sector in a structured and systematic way. The research approach and the data collection methods used are described below.

2.1. Research Approach

The notion of the circular economy has two strands - the first relating to the flow of materials through an economy, and the second concerned with thinking about the systemic conditions that might bring about such a flow (OECD, 2020). Therefore, the approach chosen would gain from having both the ability to assess the flow of material, and allowing to zoom in to the factors that affect the flow of materials. An approach that is fitting is systems analysis. Systems analysis is an approach that evolved in the 1950s that applies scientific and mathematical approaches to investigate and solve complex problems in large systems (Enserink et al., 2010). The advantage of using systems analysis is that it provides structure to complex and often ill-defined policy fields (Enserink et al., 2010). The strength of the approach rests in the holistic analysis of structures, relationships, and emergent dynamics of complex situations.

2.1.1. Systems Analysis

In this part, a framework based on systems analysis/policy analysis is devised that enables analyzing the problem of designing circular economy policies and studying their impacts in a structured and organized way. The method chosen for system analysis in this research is based on and adapted from the steps defined in the book 'Policy Analysis of Multi-Actor Systems' (Enserink et al., 2022). The steps were adjusted to include the multi-actor perspective in the beginning of the problem formulation instead of defining the problem from a single-actor perspective first. This was done because from the literature review, it was established that actors in the CDW sector are quite motivated and are open to be more sustainable and are willing to cooperate with the other actors. The other change made was including a gaps, barriers and opportunities section. This is done because as Bukvic (2018) found there was inertia in the supply chain which still exists today in 2022. Thus, finding opportunities that fill these gaps and overcome the barriers would ensure that the policies will be more effective and more receptive to be accepted by all actors involved.

The approach is outlined as follows:

1. **Rich Problem Formulation**
    - Means-Ends Analysis
    - Actor Analysis
2. **System Diagram**
    - Establishing multi-criteria objectives
    - Integrated approach synthesizing causal relations between policies to objectives
3. **Model Building**
    - Model Conceptualization
    - Model Formulation
    - Model Validation
    - Model Implementation
4. **Evaluate the results and confront the trade-offs**

The approach and the framework used above can be applied to similar complex problems in a multi-actor situation. It's defined in more detail below.

Rich Problem Formulation

Although systems analysis has its benefits, it may also have risks such as over analysing a problem due to the scope being very big. The point of departure to a systems analysis is analyzing the problem and setting the scope. A poorly structured problem may create the risk of failure to recognize an urgent or impending problem in time, thus making it more difficult and more expensive to find a solution (Enserink et al., 2022). Incorrect structuring may also result in the selection of a wrong solution, which will not alleviate the problem. To aid a rich problem description, the analytical tools used are means-ends analysis and an actor analysis.

A means-ends analysis envisions the end goal and then determines multiple strategies for attaining the goal. There are multiple actors ('parties') who are organized in the Dutch construction network, which means that no single actor will be able to unilaterally impose their desired solution on others, but rather, that some form of cooperation between parties is required. An actor analysis improves insight into the field of forces (perceptions, interests, objectives, possible actions, etc.) and contributes to finding a solution. It reduces the chance that important values or risks are forgotten (due to systematic character) and increases the chance that different stakeholders are willing to lend their co-operation to solving the problem. Different perspectives will enrich the overall picture of what the situation or problem really is about.

The results from this section will results in finding the problem statement, the gaps and the barriers which prevent reaching the desired state. The barriers could be technical (relating to technology), institutional (relating to legislations) or social (relating to a lack of consensus or trust). Finally, opportunities are identified based on which potential solutions are explored further.

System Diagram

A big part of implementing solutions is identifying factors that can be influenced by the actors involved and acknowledging uncertainties, which cannot be influenced but still may affect the system. Furthermore, establishing relevant objectives and their evaluation criteria help to break down high levels goals to measurable goals. A system diagram is an integrated tool that summarizes results from the problem formulation and helps to map out the structure of the system, observe important factors and relationships and also provide a starting point to quantify the linkages between them. Thus, the next step in the analysis is to position the delineated problem formulation with the promising solutions and their effects in a dynamic context using a system diagram.

The system diagram helps present the information about the situation in a logical, coherent and transferable way while providing an overview by putting clear system boundaries, which define what part of the reality is being considered. The system diagram can then be updated and adjusted based on the outcomes of additional analyses. It also serves as a precursor to build a mathematical model. The system diagram could be both single-actor or multi-actor. In this study, a multi-actor system diagram will be formulated. To compare the different solutions, a qualitative multi-criteria consequences table will then be constructed following the system diagram. Additional care is taken to ensure that independent criteria are specified as it not only helps achieve determined objectives, but also eliminates the risk of double counting (Enserink et al., 2010). The output from the system diagram provides a conceptual model for the next phase of model building.

Model Building

In this phase, the complex situation as defined by the problem formulation phase and the system diagram phase will be converted into a simulation model. Modeling and simulation allows to capture structural and temporal dynamics of complex systems for which our mental models are not sufficient (Forrester, 1980). The model is used as a calculation tool which helps to calculate the impact of different policy interventions by comparing it to the baseline situation. The model building follows phases of model cycle adapted from (Forrester, 1980). It includes model conceptualization, model formulation, model validation and model implementation.

In model conceptualization, the problem is identified and the scope is defined. In this case, the results from Phase 1 and Phase 2 form the basis for model conceptualization. In model formulation, a computational model is built using a professional software package Vensim that quantifies the material flows and allows for simulation and subsequently analyze the simulation results. Model validation ensures that the model structure and simulation observations are aligned with real world data and principles. Finally, model implementation is the application phase which allows to use the model test the chosen policies and find their impacts. The next section identifies the data collection methods undertaken for the research approach.

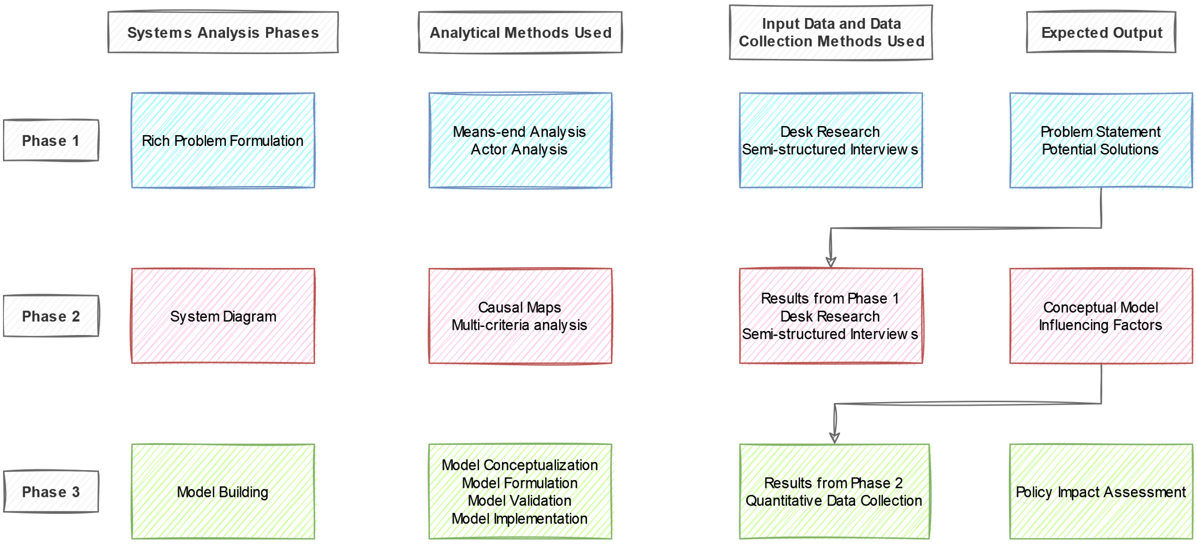


Figure 2.1: Research Flow Diagram

2.2. Data Collection Methods

This section outlines the mixed data collection methods needed for the research approach. Mixed methods are used that combines desk research, semi-structured interviews and quantitative data collection. Applying quantitative and qualitative methodologies to a research is viewed as being complementary to each other (Jick, 1979). The advantage of utilising a mixed methods approach is that by analysing a phenomenon from different perspectives a unique variance can be uncovered, providing insights that would be otherwise neglected when adopting a single method approach (Yu, 2009).

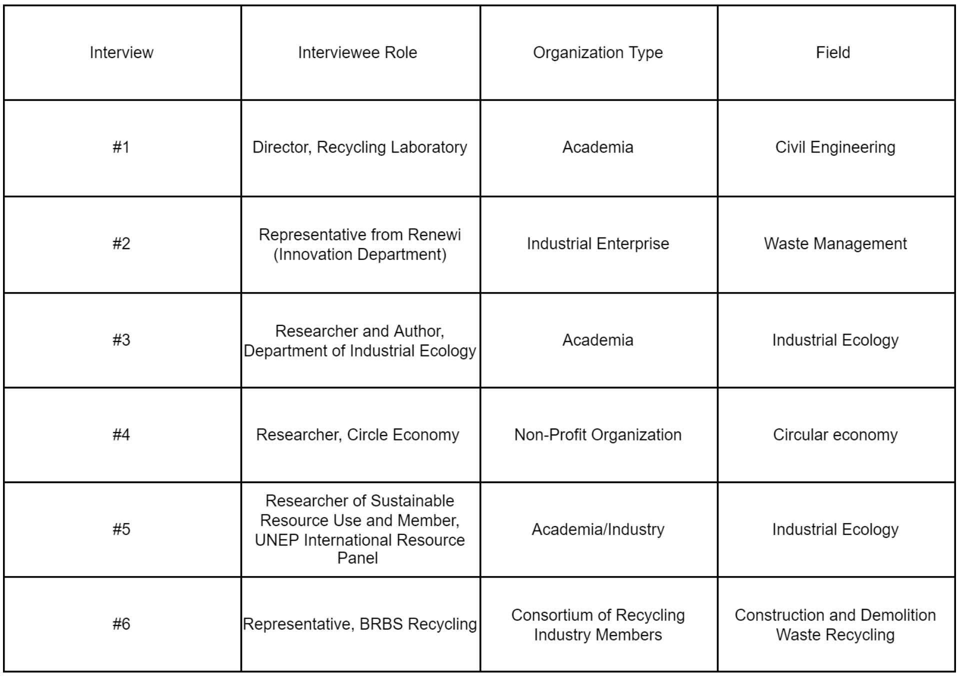
2.2.1. Desk Research

The desk research was used in multiple aspects of the research - to describe the problem, to get insights into the actor perceptions, to identify underlying mechanisms of the system and to gather data for model inputs. Circularity is a continuously evolving field and there is a need to capture the state-of-art literature and the real-world situation. These details and nuances are obtained from literature using a mix of scientific literature, grey literature and policy documents. Grey literature refers to materials and research produced by organizations outside of the traditional academic or scientific publishing and distribution channels. Common grey literature publication types include working papers, reports, government documents, white papers and evaluations. Such resources are a significant part of the information industry as they are not only a vehicle for other industries in the circular economy, but they themselves are part of an industry, which drives the circular economy (Farace, 2019). EU and Dutch Government policy updates and documents are also considered to ensure circular economy best practices that are aligned with the policymakers agenda. The scientific literature are obtained from search engines like Scopus, Google Scholar and ScienceDirect. The following keywords were used in different permutations and combinations to search for the relevant literature. *Keywords: "Circular Economy", "Construction and Demolition Waste", "Material Flow", "Systems Analysis", "Policy Analysis", "Impacts Assessment" etc.*

2.2.2. Semi-structured Interviewing

The desk research will be complemented with interviews with experts to corroborate the research and fill in the gaps. During this phase, interviews were conducted with experts in the CDWM sector. This involves both specialists in processing construction and industrial waste (industry perspective) and researchers from academia who have worked on this topic (academic perspective). An informal semi-structured interview is planned of one hour each with open ended questions. The interviewees were given the choice whether they would like to meet in person or have it online. A semi-structured interviewing format is used as it allows to explicitly gain access to the knowledge, experience and perspectives of research subjects (Baumbusch, 2010).

The aim of the interviews is to back the literature, and get information which is not easily available from the desk research. Common themes are identified and finally the data from the interviews and desk research will feed into the design for a conceptual framework. The interviews also give the opportunity to discuss and learn and can provide new ideas. The semi-structured format gives the freedom to adapt some questions when needed depending on the knowledge of the interviewee. The interviews were held with both primary stakeholders i.e. actors who are directly involved and active in the construction sector and researchers in the academic community. 6 interviews are planned and conducted as specified in Figure 5.1 following an interview guideline which can be found in Appendix A.1.



Interview	Interviewee Role	Organization Type	Field
#1	Director, Recycling Laboratory	Academia	Civil Engineering
#2	Representative from Renewi (Innovation Department)	Industrial Enterprise	Waste Management
#3	Researcher and Author, Department of Industrial Ecology	Academia	Industrial Ecology
#4	Researcher, Circle Economy	Non-Profit Organization	Circular economy
#5	Researcher of Sustainable Resource Use and Member, UNEP International Resource Panel	Academia/Industry	Industrial Ecology
#6	Representative, BRBS Recycling	Consortium of Recycling Industry Members	Construction and Demolition Waste Recycling

Figure 2.2: List of interview participants and their role

2.2.3. Quantitative Data Collection

For developing the model to calculate impacts, a quantitative data collection from different sources will be conducted. Main sources of data will include datasets like CBS and Eurostat, and figures from existing reports. Since studies may differ in scope (geographical or impacts), efforts will be taken to ensure the data are coherent and adapted to this case study. Life-cycle inventory data could alternatively have been taken from the Ecoinvent database but this was not done due to mandates placed by the scope of the study. Utilizing existing studies, this research also makes its own database for calculating carbon emissions from different CDW management and recovery processes.

A graphical summary of the research methodology is sketched in Figure 2.1. The next three chapters cover each of the research phases - problem formulation, system diagram and model building.

3

Problem Formulation

In this chapter, the system under study is demarcated and a rich picture of the perceived problem is formed. The problem is first analysed through the lens of a single actor, that of the Ministry of Environment and Water Management, and then looked at through a multi-actor perspective. This chapter helps answer the first sub-question - **"What are the gaps, barriers and opportunities in transitioning to a circular economy in the construction waste sector?"**

3.1. System Identification and Demarcation

The system boundary encompasses a portion of the entire system that includes all the important and relevant variables to address the problem and the purpose of policy analysis and design. This step also helps set the scope of the study. To help demarcate the system, a means-ends analysis was first conducted in which a relevant problem scope was chosen. After that, the current state of the system was identified based on available information from reports, studies and expert interviews.

3.1.1. Means-Ends Analysis

The solutions available to the problem of how to achieve a circular economy in the construction sector can be different depending on where the focus is. Problems are formulated at different levels for different needs or differently formulated for each actor involved, and thus choosing the right level and formulation can be an iterative process. A tool used to help represent problem levels is a Means-ends analysis (Enserink et al., 2022).

The means-end analysis as sketched in Figure 3.1 starts by formulating the client's discontent with the actual situation as an objective to reach the desired situation (Enserink et al., 2010), which in this case is supposed to be achieving a circular economy in the Dutch construction sector. Here, the client is assumed to be the Ministry of Infrastructure and Water Management [1], as it's their main objective is to achieve a circular economy in the construction sector as outlined in their 2015 report

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[1] When the report for circular economy in construction (Rijkswaterstaat, 2015) was released, it was commissioned by the then Ministry of Infrastructure and Environment. But in 2017 the ministry was renamed to Ministry of Infrastructure and Water Management. From here on, they will be referred to as this or shortened to Ministry of IWM

(Rijkswaterstaat, 2015). But another question that comes up is why do we want to achieve CE in the first place.

A series of 'why should this be achieved' questions are then asked to go up a level of the means-ends diagram. This is based on reasoning and helps identify the client's fundamental objective which points to their ultimate objective. Achieving a circular economy would help keep within planetary boundaries and eventually help achieve sustainable development goals which is identified here as the client's fundamental goal. After finding the fundamental goal, a series of 'How can we achieve this?' questions are asked to go a level down and find a variety of means possible to achieve that objective. Literature and reports on circular economy for the construction sector were synthesized to formulate the potentials solutions.

Circularity in the construction sector could be achieved by implementing circular construction and design, changing production and consumption behaviors and managing construction and demolition waste at their end of life. For each of these means, a more granular level of possible actions are explored. For instance, circular construction and design can be achieved by implementing material passport [2], building modular buildings using prefabrication [3] or using bio-based materials instead of concrete based materials (Metabolic, n.d.). Changing production and consumption behaviors may involve renovating existing buildings instead of demolishing (Rijkswaterstaat, 2015), or changing building ownership models (Circulairebouweconomie, 2021). Finally, managing CDW at it's end-of-life involves rethinking possibilities by the means of industrial symbiosis and urban mining, imposing circular demolition, developing a market for recycled materials and improving CDW management by having mono-streams instead of mixed streams (European Commission, 2018).

After sketching the means-end analysis, a suitable problem level is chosen as a starting point for further analysis, also termed as a focal objective. In this case, the focal objective and the starting point for systems analysis was selected to be 'Manage construction and demolition waste at end-of-life'. Thus, the identified system under study is construction and demolition waste management at end-of-life.

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[2] Material passport in the context of buildings as material banks (BAMB) refer to sets of data describing defined characteristics of materials in products that give them value for recovery and reuse (BAMB, 2022)

[3] A recent study on using prefabricated components found it had the potential to reduce a buildings' embodied emissions by 40%, end-of-life impacts by 90%, carbon emissions by 6% and costs by 10% (Tavares et al., 2021)

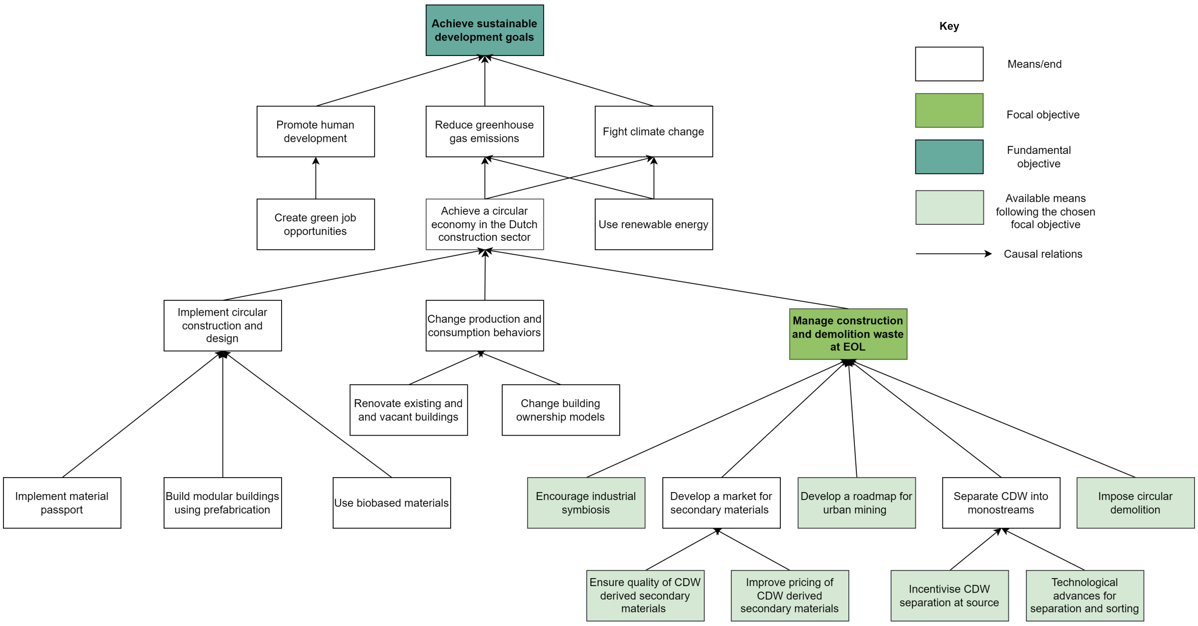


Figure 3.1: Means-Ends Diagram identifying 'Managing construction and demolition waste at EOL' as a focal objective. The highlighted green boxes at the bottom represent the different means possible to achieve this goal.

The means-ends analysis is not exhaustive, but rather gives a guideline of what solutions are possible to achieve the goal in the short run and long run. The means-ends diagram thus summarizes a variety of possibilities available to implement circularity in the construction sector. But not all of them would be effective, or even possible to be implemented by the Government alone. In the next sections, each of these means will be looked at through different perspectives to delineate the best ones which not only achieve the focal goal, but are also likely to be accepted in the multi-actor realm.

3.1.2. Overview of the current CDW management system

After identifying the system, the next step is demarcating it and defining the boundaries. This is done by studying the current process of CDW management in the Netherlands, where it starts and where it ends. The point of departure was the report 'Screening template for Construction and Demolition Waste management in The Netherlands' (Deloitte, 2015). The report outlines the process of CDW management, obstacles, and the main drivers to sustainable CDW management. However, the report was very high-level and identifying the influence of the drivers on the CDW material flow was missing. The report also came out in 2015, and a more recent snapshot of the practices was gained with the help of interviews.

The interview with Renewi (Interview 2) provided insights into current practices in CDW management. It starts when a structure is demolished. Waste management companies are hired by a client (usually big corporations or municipalities as they don't deal with household bulky waste) to manage the CDW after construction or demolition activities. Containers are put up on the demolition site where the waste is discarded without any segregation at source. The price is based on the number of containers used and not on the type of waste. Next, depending on the quality of the waste, they're either pre-sorted by the company itself before further processing or handed over to the recycling companies as it is. There are multiple methods of sorting - sorting lines, optical sorters, magnets, eddy current separators etc. Then the waste is transported to recycling centres for further processing - which could be either changing to recyclates and forming new products, downcycling for infrastructure purposes or disposal through incineration or landfilling.

The interview with BRBS Recycling (Interview 6) and the director of the concrete recycling lab (Interview 1) provided insights into current CDW recycling practices. Both agreed that the representation of recycled concrete in new construction is very low but their reasons for why that is the case differed. According to BRBS Recycling, the recycling companies can manufacture any size required by concrete producers and ensure a very high quality; but the main barrier is the lack of trust by concrete producers and their existing relationships with primary aggregate producers which prevent them from using a high percentage of recycled aggregates (Interview 6). According to the director of the recycling lab, the main barrier is in the nature of the material itself which prevents further high quality reuse (Interview 3). For instance, after demolishing, cement and silica (stones, pebbles) are often stuck together and are difficult to separate even with mechanical recycling. The new shape of the resulting concrete aggregate prevents good bonding in new construction. Two ways to get around this challenge would be to either continue using recycled concrete as road foundations as they don't have strict quality specifications (downcycling), or to implement selective demolition and ensure cleanliness of the waste stream. Interview 3 revealed that a big barrier to good selective demolition is the window of time given to demolish a building (Interview 3). Usually the time set for demolishing by the client is on average one or two week, which is too less to ensure proper removal.

Interview 3 also revealed insights into the problem with retaining the value of materials at the end of their life. A barrier to this is costs associated and the efforts required to keep the waste streams clean (Interview 3). Another barrier identified was the efficiency of the recycling process itself (Interview 3). When considering materials (concrete, glass, wood etc.) for recovery processes, not just physical value but the environmental impact of these materials should be taken into account (Interview 3). For example, concrete on account of its abundance in CDW may have the biggest impact compared to other materials, but that's not always the case; it may not be the material itself or the biggest flows, but could be the CO2 emissions equivalent in order to process it (Interview 3). This raises a question of where the biggest impacts are and what are the amounts of CO2 emissions that can be saved by reusing or recycling them.

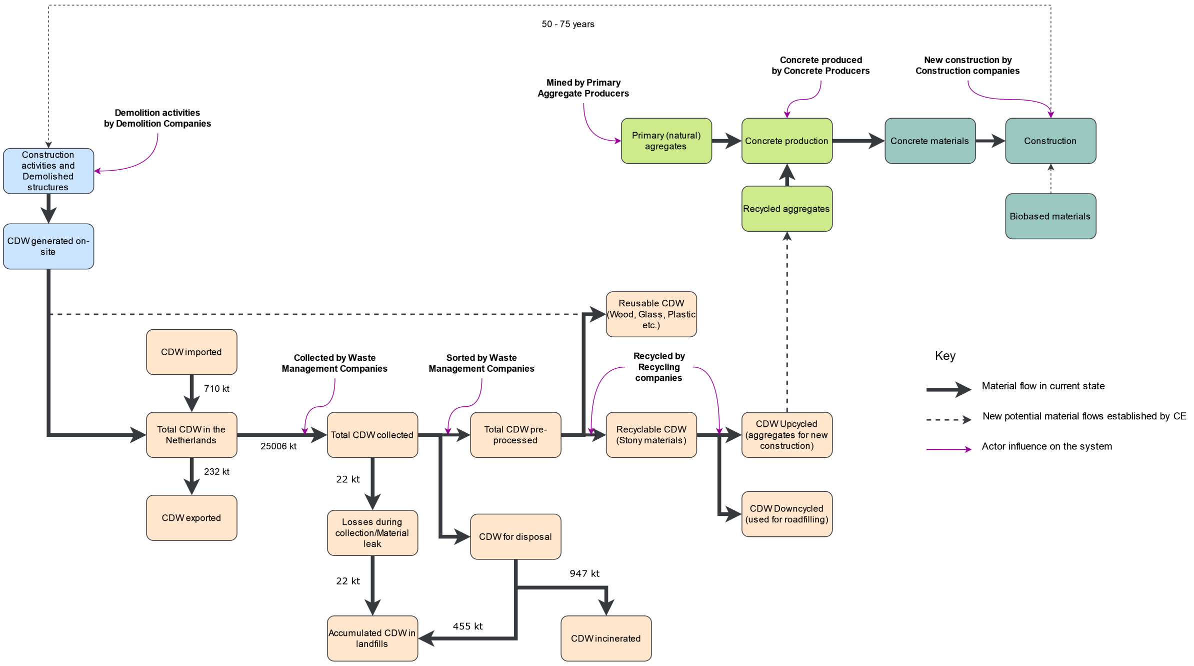


Figure 3.2: Current CDW Material Flow and the processes involved for the Netherlands

Based on the interview insights, Figure 3.2 sketches the updated version of CDW management system in the Netherlands. The system boundary starts when CDW is generated following demolishing and ends at the different processing routes taken for CDW management. The processes of CDW collection, pre-processing and losses during collection is added. The actor roles are also included i.e. demolishing companies, waste management companies, recycling companies, concrete producers and construction companies, along with the extended destination of upcycling i.e. new concrete production and its use in construction. Available material flow data is mentioned, but flows like how much CDW is collected or pre-processed are unknown, which also affect flows which are further down the line like CDW upcycled or reused which are dependent on collection rate.

In the next section, the actors identified in playing a part in the system are elaborated along with their interests, objectives and perceptions. This will form the basis of who is responsible to change the situation and how.

3.2. Actor Analysis

The Government cannot realize the goal of transitioning into a circular economy on their own, since all the means available to them require intensive cooperation among the construction value chain actors. Without societal initiative and the willingness to change, the government alone cannot achieve much. But knowing which actors are critical and likely to influence the situation, and who might only have a high level of interest in the matter will go a long way to design inclusive policies that takes actor needs into consideration.

According to Schraven et al. (2019), the CE literature on the construction sector has produced little empirical data on responsibility till now. Few studies recognize the government as an impactful player in CE, because they can share large amounts of resources and infrastructure, apply oversight to the industry for controlling disruptive effects of some changes and finally the governance structure helps to align supply chains to system changes (Cai and Wu (2014), Gaustad et al. (2018), and

Maaß and Grundmann (2018)). However, in circular supply chain structures, responsibility may also directly come from actors that drive these supply chains (Geissdoerfer et al., 2018). This is applicable to the supply chain of recycled aggregates market in the Netherlands. This could be business or competition related, as implementing CE can have radical implications for business models and may expose businesses to more risks impeding the change altogether (Masi et al., 2017). In the next section, an actor scan is undertaken to find who besides the government has the power and interest to change the situation.

3.2.1. Actor Scan

An actor network scan involves listing out all the actors involved in CDW management and their roles. It provides a basis for understanding their dependencies on each other. In the Netherlands, the construction and CDW sector constitute a lot of actors who organize and manage both the material and the waste flow.

The material flow is determined by the trade and movement of materials through two market places - the waste market and the recycled aggregates market (Schraven et al., 2019). The process of waste management starts as soon as a structure (buildings or infrastructure) is demolished, or when a construction or renovation is done and there's leftover material. The key actors in these two markets are Demolition companies, Waste management companies, Recycling companies, Concrete Producers and Construction companies. Outside the immediate supply chain, part of the system also include the primary aggregates producers who supply sand and gravel to the concrete producers and construction companies. Recycling companies and primary aggregates producers are competing for market share. The Dutch Government or in this case the client, the Ministry of Infrastructure and Water Management has an important role in overseeing everything, removing barriers, and implementing policies. Investors and banks also have a stake as they have green investments they are either willing to invest in or not. On the periphery of the system are also designers/architects and consumers who may have a role to play in how the future of sustainable buildings play out as well. This actor categorization and the dependencies is envisioned in Figure 3.3.

The actor scan reveals the multi-actor nature of the CDWM system, and how actors are dependent on each other for either resources or knowledge. Policies will need to be designed keeping in mind the interests of actors involved. In the next section, interests, objectives and possible actions of these actors are mapped out to study where there are synergies and where there might be disagreements.

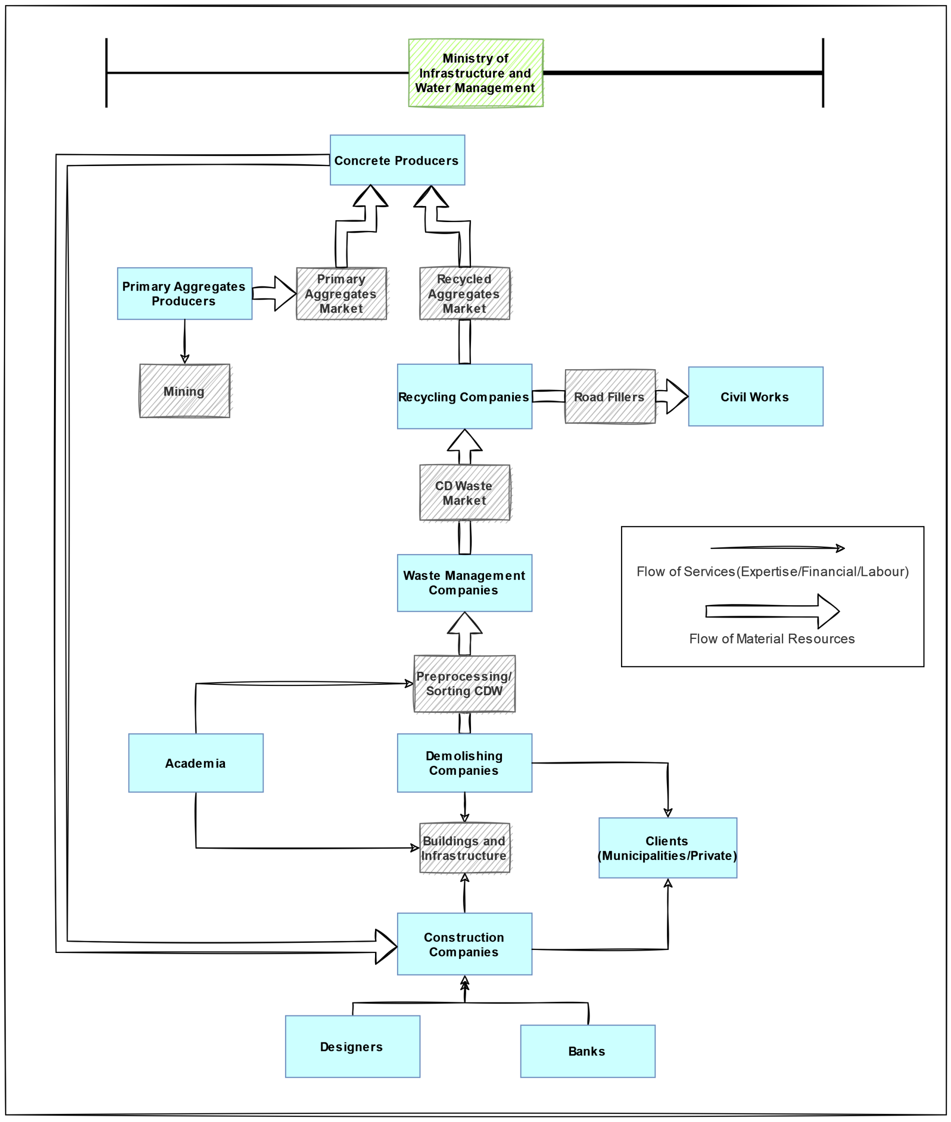
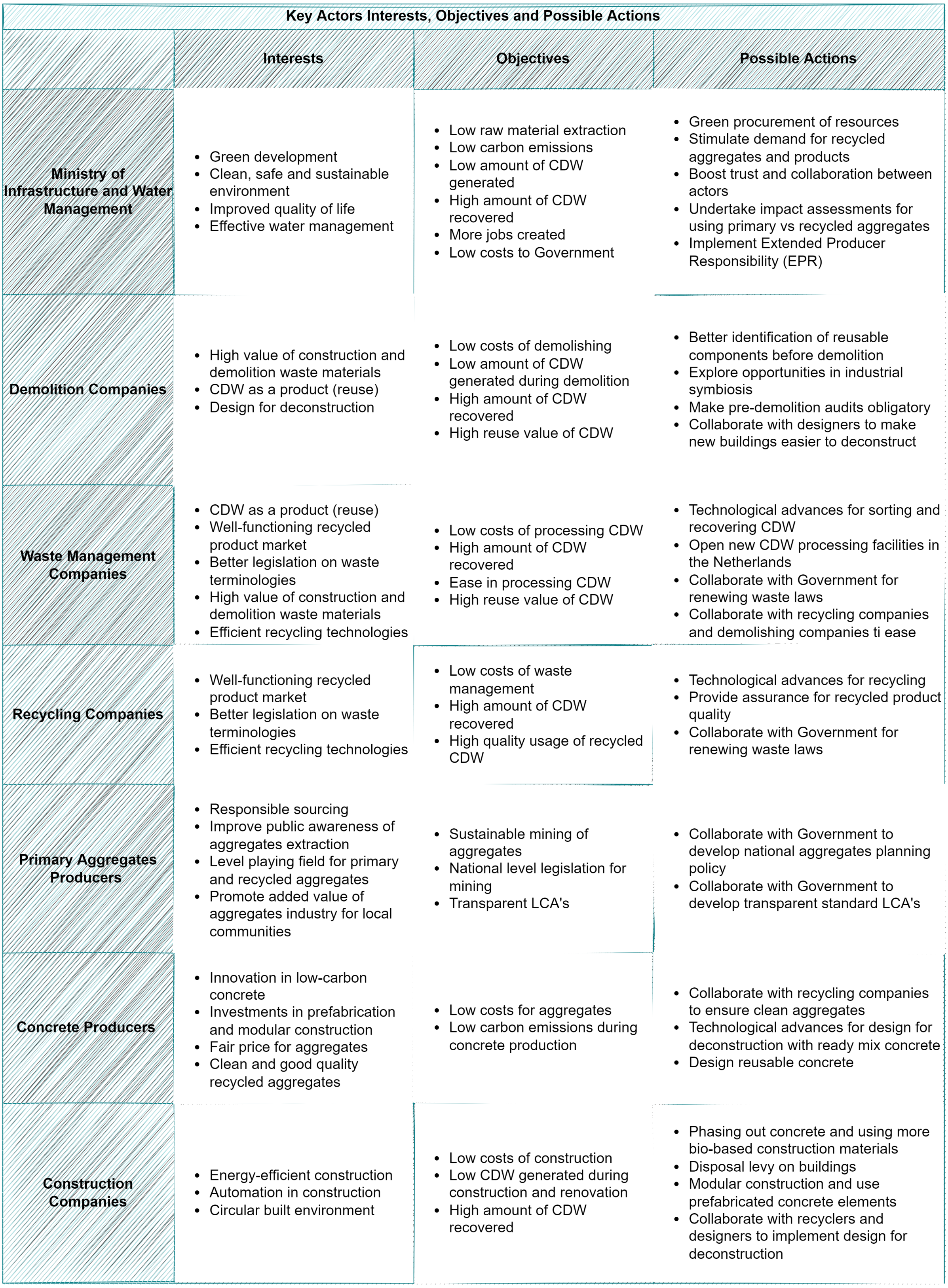


Figure 3.3: Actors in the CDW management and supply chain - in blue are the actors, the grey represents the different markets/products and the Government in green oversee everything

3.2.2. Interests, Objectives and Possible Actions

Based on the desk research and interviews, the interests, objectives and possible actions of all the different actors identified in the actor scan is first mapped. Insights for recycling companies, waste management companies and demolishing companies come from the interviews while for the other actors, it was synthesized from existing literature which includes scientific studies who have conducted first hand stakeholder mapping. The below section summarizes interests, objectives and possible actions for each actor. For the considered key actors, the information is visually summarized in visualized in Figure 3.4.



Key Actors Interests, Objectives and Possible Actions

	Interests	Objectives	Possible Actions
Ministry of Infrastructure and Water Management	• Green development • Clean, safe and sustainable environment • Improved quality of life • Effective water management	• Low raw material extraction • Low carbon emissions • Low amount of CDW generated • High amount of CDW recovered • More jobs created • Low costs to Government	• Green procurement of resources • Stimulate demand for recycled aggregates and products • Boost trust and collaboration between actors • Undertake impact assessments for using primary vs recycled aggregates • Implement Extended Producer Responsibility (EPR)
Demolition Companies	• High value of construction and demolition waste materials • CDW as a product (reuse) • Design for deconstruction	• Low costs of demolishing • Low amount of CDW generated during demolition • High amount of CDW recovered • High reuse value of CDW	• Better identification of reusable components before demolition • Explore opportunities in industrial symbiosis • Make pre-demolition audits obligatory • Collaborate with designers to make new buildings easier to deconstruct
Waste Management Companies	• CDW as a product (reuse) • Well-functioning recycled product market • Better legislation on waste terminologies • High value of construction and demolition waste materials • Efficient recycling technologies	• Low costs of processing CDW • High amount of CDW recovered • Ease in processing CDW • High reuse value of CDW	• Technological advances for sorting and recovering CDW • Open new CDW processing facilities in the Netherlands • Collaborate with Government for renewing waste laws • Collaborate with recycling companies and demolishing companies ti ease
Recycling Companies	• Well-functioning recycled product market • Better legislation on waste terminologies • Efficient recycling technologies	• Low costs of waste management • High amount of CDW recovered • High quality usage of recycled CDW	• Technological advances for recycling • Provide assurance for recycled product quality • Collaborate with Government for renewing waste laws
Primary Aggregates Producers	• Responsible sourcing • Improve public awareness of aggregates extraction • Level playing field for primary and recycled aggregates • Promote added value of aggregates industry for local communities	• Sustainable mining of aggregates • National level legislation for mining • Transparent LCA's	• Collaborate with Government to develop national aggregates planning policy • Collaborate with Government to develop transparent standard LCA's
Concrete Producers	• Innovation in low-carbon concrete • Investments in prefabrication and modular construction • Fair price for aggregates • Clean and good quality recycled aggregates	• Low costs for aggregates • Low carbon emissions during concrete production	• Collaborate with recycling companies to ensure clean aggregates • Technological advances for design for deconstruction with ready mix concrete • Design reusable concrete
Construction Companies	• Energy-efficient construction • Automation in construction • Circular built environment	• Low costs of construction • Low CDW generated during construction and renovation • High amount of CDW recovered	• Phasing out concrete and using more bio-based construction materials • Disposal levy on buildings • Modular construction and use prefabricated concrete elements • Collaborate with recyclers and designers to implement design for deconstruction

Figure 3.4: Interests, objectives and possible actions of actors in the CDW management and supply chain

Ministry of IWM

A study undertaken on the legislative policies empowering initiatives and companies working with secondary products by EME (2019) found that there's a lack of cohesion between the laws, markets, technologies and business models to implement circularity and are still in the process of being refined. The Ministry of IWM can work to remove these legislative barriers. This action is also echoed in the report 'Circular economy in the Dutch construction sector' (Rijkswaterstaat, 2015). In the current financial model of construction, the costs of demolition and recycling are not included; they are now often a societal cost, with the cost item often ending up as an 'unforeseen' item (Rijkswaterstaat, 2015). The Extended Producer Responsibility (EPR) coming out in 2025 might change this in the coming years, but information on how it will do is limited. Meanwhile, this can be overcome to some extent by having a disposal fee as part of pre-demolition audits, which the client will have to pay. The government can also play a big part in ensuring that there's trust between the actors and that recycled products are used back in construction by the means of certifications for high-standards.

Demolishing Companies
Demolition companies would prefer to deconstruct a building rather than demolish it, focusing on the optimum reuse of materials and products, but are not commissioned to do so by the client (Interview 3, Bukvic (2018)). The biggest barrier identified in doing so is the window of time given to demolish a structure (Interview 3). If time constraints are enforced, this would ensure better reusability. Apart from time, when it comes to selective demolition, demolishing companies also need space and their costs covered to recover difficult materials like insulation (Bukvic, 2018). In the long run, demolishing companies could also collaborate with designers to integrate a design for deconstruction in the design phase (Interview 1).

Waste Management Companies
Waste management companies' main business case is logistics but lately they are very active in the processing sector i.e. recycling and reusing as well and would like to improve on this. For instance, Renewi is currently testing if entire beams from demolished buildings can be reused for furniture while coming up with a wood waste strategy (Interview 2). They often have to transport CDW over distances, sometimes to Belgium, which leads to more transport emissions and to prevent this, they would like to have more space to process waste in the Netherlands (Interview 2).

Recycling Companies
Recycling companies rely on the government for changes to develop the recycling market (Interview 6). For recycling companies, a viable business case in recycling is dependent on regulations, it's their license to operate and on the efficiency of recycling technologies they use (Interview 6). On closing the material loop, they feel they're already doing a lot for the circular economy, but they would like to collaborate with other stakeholders in the supply chain to improve the process of recycling (Interview 6).

Primary Aggregates Producers
Primary aggregates producers need permits to mine in the Netherlands and due to the changing legislation, getting permits has become tough (Bukvic, 2018). There is currently no national level primary aggregates plan in place and no uniform LCA's on mining sand and aggregates (Bukvic, 2018). They want a level-playing-field through consistent implementation of EU law, if necessary through law enforcement of existing EU/national legislation (Bukvic, 2018).

Concrete Producers and Construction Companies
Concrete producers have the option to use either recycled aggregates or primary aggregates in different percentages to produce new cement and concrete (Interview 6). Their requirement is to have

good quality and clean aggregates for this. For forming a good market for upcycled aggregates, concrete producers have an important role in facilitation. Construction companies also have a part to play as they're at the receiving end of concrete. They might choose to use either concrete or biobased alternative building materials. They can also choose to undertake more efficient construction using prefabricated elements.

Banks, Designers and Academia
The banking sector have funds which they can invest in sustainable new construction projects but is conditional on Government support and risk assessments studies (Rijkswaterstaat, 2015). Designers can collaborate demolishing companies and recycling companies to design the next generation of infrastructure which can be deconstructed easily and be reused (Interview 1). The academia are involved in finding and assisting recycling companies to find the latest technology to increasing efficiency of recycling processes (C2CA, 2011).

Based on the knowledge gained about the actors interests, objectives and possible actions, in the next section, they're plotted on a power-interest matrix to identify the key players i.e. actors who have both a high interest as well as high power to change the situation.

3.2.3. Power-Interest Matrix

In the previous section, it was established that actors have varying degrees of both interest and power to influence the situation. To make this apparent, a power-interest matrix was created to identify the key players. This is visualized in Figure 3.5.

At the top right of the matrix with the most power and most interest is the Ministry of Infrastructure and Water Management as they're responsible to implementing a circular economy in the construction sector. Next would be the recycling companies. They have a strong presence in the Netherlands and play an important part for the country's top position in CDW recycling . The demolishing companies are also an important actor, but they are sometimes restricted by the client. If those barriers are removed for instance, through empowering them to enforce a pre-demolition audit, they are a significant actor. This places these three actors in the top right quadrant of key players with high power and high interest.

Both concrete producers and construction companies have the power to choose more recycled aggregates and products and change the recycled product market. But they often lack the incentive to do so due to hesitation about quality and cost factors. This puts them in context setters with a high power but low interest. If they have incentives, they can shift to key players.

Primary aggregates producers and waste management companies are placed in subjects i.e. with a high interest but low power. This is because of their role as primary producers and logistics management respectively, they play a supporting role and do not have the power to influence the system by themselves. However, waste management companies have the possibility to become a key player if they merge supply chains with either recycling companies or demolishing companies. For instance, some waste management and logistics companies also have divisions that do recycling as well like Renewi ATM (Interview 2). And some recycling companies for instance, Beelen have also started doing the demolishing themselves and have the power to decide what can be reused and how (Interview 2).

Banks, academia and designers are placed as crowds i.e. having low power and low interest. This is because they lack the incentive and the resources to change the situation by themselves.

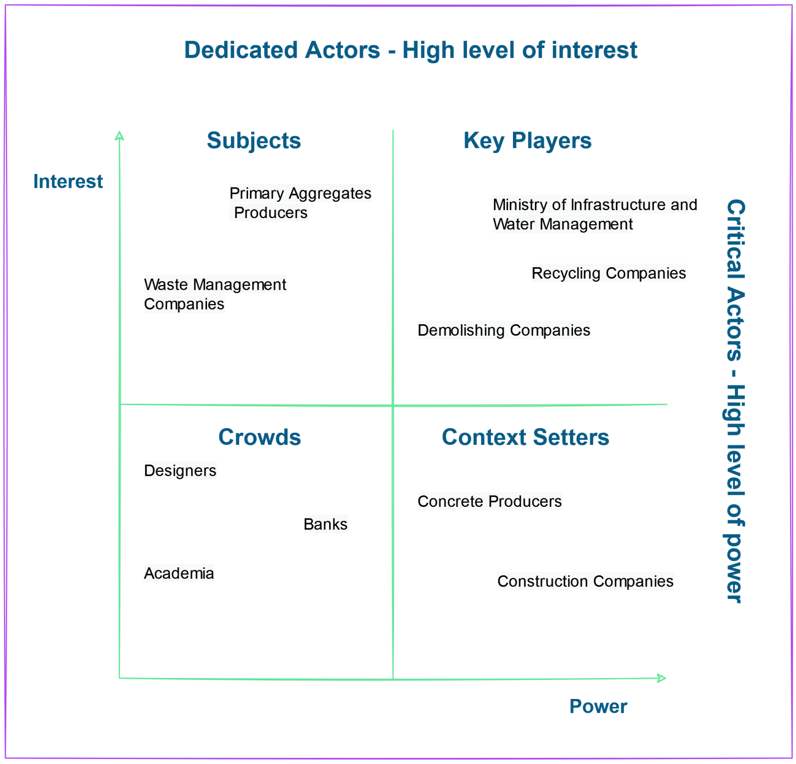
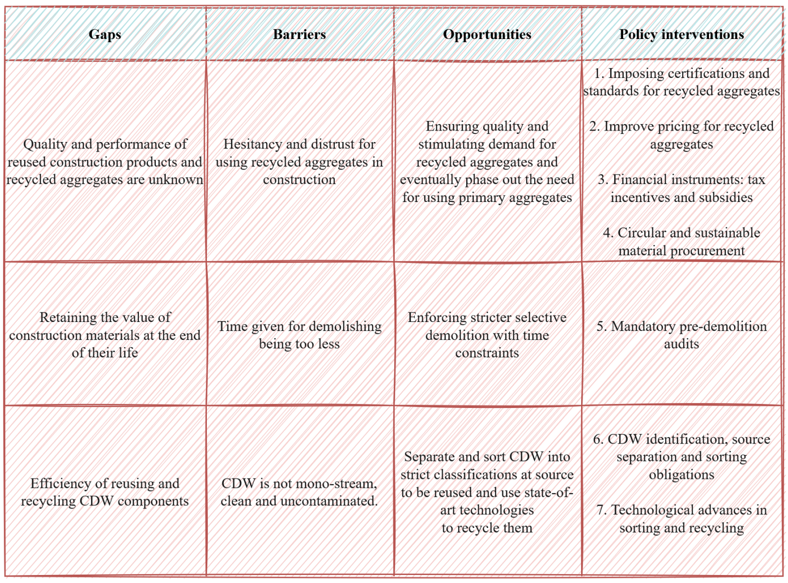


Figure 3.5: Power Interest Matrix

3.3. Gaps, barriers and opportunities

This section combines the means-end analysis and the actor analysis to identify the gaps, barriers and opportunities to move towards a circular economy in the construction and CDW management sector. The gaps and barriers were found through the interviews (Section 3.1.2) were corroborated with EU's last document on EU Construction and Demolition Waste Management Protocol (European Commission, 2018) which specifies the best practices for the development of CD waste management and recycling infrastructures in the EU. The opportunities were derived from the possible actions (Figure 3.4) of the key players (Figure 3.5). This analysis is visualized in Figure 3.6.



Gaps	Barriers	Opportunities	Policy interventions
Quality and performance of reused construction products and recycled aggregates are unknown	Hesitancy and distrust for using recycled aggregates in construction	Ensuring quality and stimulating demand for recycled aggregates and eventually phase out the need for using primary aggregates	1. Imposing certifications and standards for recycled aggregates 2. Improve pricing for recycled aggregates 3. Financial instruments: tax incentives and subsidies 4. Circular and sustainable material procurement
Retaining the value of construction materials at the end of their life	Time given for demolishing being too less	Enforcing stricter selective demolition with time constraints	5. Mandatory pre-demolition audits
Efficiency of reusing and recycling CDW components	CDW is not mono-stream, clean and uncontaminated.	Separate and sort CDW into strict classifications at source to be reused and use state-of-art technologies to recycle them	6. CDW identification, source separation and sorting obligations 7. Technological advances in sorting and recycling

Figure 3.6: Identified gaps, barriers and opportunities

The first main gap found was related to uncertainty regarding the quality and performance of recycled products. According to recyclers (Interview 6), they can get the aggregates to any size specification and of top-notch quality, but there is still a hesitancy and lack of trust to use it. Most of the recycled aggregates go for road fillers, which is a good application, but it's considered as downcycling. Thus, an opportunity here would be to ensure quality and stimulate demand for recycled aggregates and eventually phase out the need for using primary aggregates entirely. Specific policy interventions that the Government can take to help this could be to **improve pricing of recycled aggregates, imposing certifications and standards and providing tax incentives and subsidies.**

The second gap found was retaining the value of construction materials at the end of their life. This is to be expected to some extent due to the nature of CDW. It could also be overcome to an extent by designing new building and infrastructure to be deconstructed and reused easily without having to undergo mechanical recycling. However the effects of this concept might take the next 50 years to be visible. As for the shorter term, a barrier which severely restricts efficient selective demolition is the time given to demolition. This can be rectified through **enforcing a strict pre-demolition audits** with time constraints to allow demolishing companies to remove construction materials in a systematic manner. This also allows for better reuse and even reduce CDW processed that needs to undergo processing.

Finally, the third gap is that the efficiency of recycling CDW components is not known. A barrier to this is keeping the CDW mono-stream, clean and uncontaminated. This could be overcome by policy measures requiring **sorting obligations for several fractions and better CDW identification, separation and collection at source**. This not only reduces the pre-processing and sorting that is needed to get CDW into a mono-stream, but it also makes it easier for it to be recycled. Finally, **technological advances for sorting and recycling** could also help keep CDW largely mono-stream and clean and also make the whole process more energy and process efficient.

In the next chapter, each of these policies will be explored in detail using causal maps and system diagram.

4

System Diagram

This chapter uncovers and examines each policy measure as identified in the previous section - how it works to achieve the objectives, and what might be its positive or negative impacts. For this, causal maps are used. Towards the end of this chapter, a system diagram combines all the causal maps into one diagram that captures the working and effects of the policies. After that, a multi-criteria analysis is done to compare and rate the different policies. A system diagram is a good precursor to a computer model, since it helps to map out the structure of the system to be modeled and shows the factors and relationships that are important, and helps to start quantifying the linkages between factors (MindTools, 2022).

In line with the systems thinking approach, this chapter helps find out the underlying factors or 'leverage-points' affecting the system. First the objectives are identified, then for each policy measure, a causal map is sketched, which when combined all together forms the system diagram.

4.1. Objectives

A Multi-Criteria Analysis (MCA) is used to identify and compare different policy options by assessing their performance (Arjan, 2017). It helps provide a systematic approach for supporting complex decisions according to pre-determined criteria and objectives. The multi-criteria analysis provides a framework to explore trade-offs between different options. Criteria are derived from actor objectives. In the context of this problem as seen in the actor analysis, since different actors have different objectives, it becomes difficult to align conflicting policies. In this section, the main objectives are explored in more detail. This section, thus, helps answer the question **"What are the key criteria that should be taken into account to design effective circular economy policies for CDW management?"**

From the actor analysis in section interests, objectives and possible actions, the middle column represented the objectives of the actors (Figure 3.4). Common themes that were repeated more than once were identified which came out to be low costs, low amount of CDW generated, low carbon emissions and high amount of CDW recovered. Apart from that the objectives of the Government which included new jobs created and low raw materials extraction was also considered. These criteria are segregated broadly into environmental, financial and social and explored in more detail below.

4.1.1. Environmental criteria

Towards a zero waste future means not creating waste in the first place. But closing the loop means recovering all parts of waste that was generated in a meaningful way. This presents an interesting conundrum - whether waste prevention should be focused on, or waste recovery. So far, the statistics in the Netherlands is about how much CDW is recovered (Statistics Netherlands CBS, 2016). Figures on how much CDW is prevented through for instance source reduction measures is not available. This becomes significant as waste processing and recycling methods also involve carbon emissions (Blengini, 2009). Only having amount of CDW recovered as an objective is not enough, there is also a need to reduce the amount of CDW generated in the first place, which is a staggering 2.5 million kilotonnes a year in the Netherlands (Deloitte, 2015). The first two criteria are **Amount of CDW Generated**, and **Amount of CDW Recovered**. These will be expressed through kilotonnes/year.

The Global Resources Outlook report (IRP, 2019) has found that 90 per cent of biodiversity loss and water stress are caused by resource extraction and processing of materials, fuels and food, which incidentally also contribute to about half of global greenhouse gas emissions. Closing loops and recycling secondary materials to replace primary resources should reduce raw material consumption. In the case of this study, it refers to mining of natural aggregates (soil, stones, gravel, clay etc.). Thus, the third criterion is **Raw materials extraction**, expressed through kilotonnes/year.

Carbon footprint is one of the most widely used tools for assessing the environmental impacts of construction materials (Jiménez et al., 2018). It is represented by the amount of carbon dioxide and other greenhouse gases associated with its production and is expressed as CO2 equivalents (Jiménez et al., 2018). Efforts to reduce carbon can focus on different areas of the supply chain, such as using lower carbon materials, using prefabricated elements to reduce waste, maximizing reuse opportunities at end-of-life or to design buildings and elements that are more durable and easy to repair (Donatello et al., 2022). The Dutch government also has a national goal to reduce the Netherlands' greenhouse gas emissions by 49% by 2030 (Ministerie van Economische Zaken, 2019). So, the last environmental criterion will be **Carbon emissions**. In this research, carbon footprint is defined as the total emissions of GHGs and is expressed as CO2-equivalent per year related to recovery activities, that is, pre-processing, recycling, land-filling, road-filling and incineration of one tonne CDW.

4.1.2. Financial criteria

Implementing new policies requires some kind of investments or pre-financing from the Government. Some may require more financial help but aren't as effective, while some don't require too much pre-financing but are more effective, and finally policies may even yield a return on investment. To give direction to the Government on which policies might be worth investing in, the first financial criterion is **Costs to Government** expressed in Euros/year.

Till now, most of the objectives were related to the problem owner i.e. the Government of IWM to achieve. However, for the other actors in the supply chain, one of the most important objective is to keep the costs of CDW management as low as possible. Each actor might have a different processing cost which could be interdependent on each other. For instance, for making it easier for recyclers and to keep their costs low, additional costs may need to be taken on the demolishing companies or waste management companies' side to keep the CDW mono-stream and clean. Instead of externalising each actor's costs, a shared criterion for the supply chain actors would be **CDW processing costs**, expressed by Euros/year. Business prospects, expansions and profit are also of importance but are not considered here due to it being a private sector and being subject to market dynamics.

4.1.3. Social criteria

A comprehensive review of the academic literature on the circular economy by (Merli et al., 2018) has pointed out an important research gap: current academic discourses focus primarily on business models, cleaner production approaches and optimising performance and efficiency, but only marginally consider social implications. After synthesising multiple definitions of CE over the years, (Kirchherr et al., 2017) concludes that the main aim of CE is considered to be ”economic prosperity, followed by environmental quality while its impact on social equity and future generations is barely mentioned”. However, (Schroder, 2020) considers social equity and justice just as important for the CE as they are in the contexts of low-carbon transitions or digitization of the economy. Even the UN World Social Report points out what we need is ”a just, equality-enhancing transition that calls for the integration of climate action with macroeconomic, labour and social policies aimed at job creation, skills development and adequate support for those who will be harmed” (United Nations, 2020).

In the Dutch setting, this could be translated to the acknowledgement of labour concerns such as fair wages, career prospects, job security, and fair working conditions to anyone regardless of their gender, race, ethnicity, religion, sexual orientation, disability status, and nationality ((ILO, 2018); (Sharma-Mascarenhas, 2021)). To simplify this, and to focus on a criterion that can be easily measured, this study will look at **Jobs** as representative of the social pillar, measured by number of new jobs created.

The objectives and their criteria are summarized and sketched in Figure 4.1.

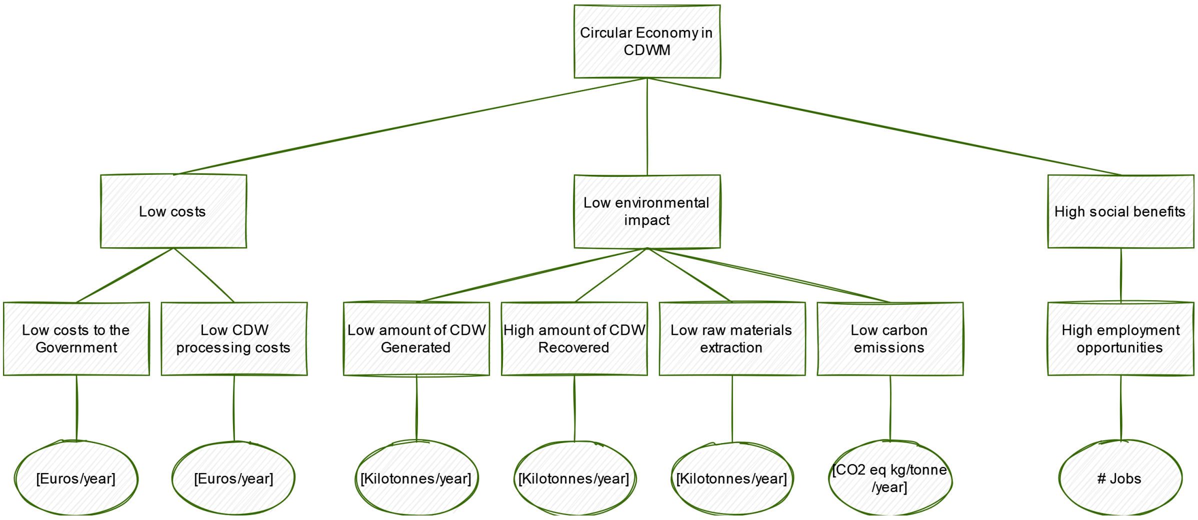


Figure 4.1: Multi-criteria objectives tree

4.2. Exploring policy levers through causal maps

From the previous section 3.3 on gaps, barriers and opportunities, 7 policy options that emerged were enforcing strict pre-demolition audits, better CDW identification, separation and collection at source with sorting obligations, technological advances for sorting and recycling, improving pricing of recycled aggregates, imposing certifications and standards and providing tax incentives and subsidies. In this section, these means are explored in more detail to help develop the causal relations in the system diagram. This helps find leverage points throughout a system which can be influenced by the policies.

Diagramming tools, such as causal loop diagrams (CLDs) and stock–flow diagrams (SFDs), are used to capture the structure of a complex system. CLDs are able to map the feedback structures of a complex system; they can show how the system is dynamically influenced by the interactions of all of the variables. A CLD consists of variables connected by arrows; the arrows denote the causal influences among the variables. Each causal link is assigned a polarity—either positive (+) or negative (–)—to indicate how the dependent variables are influenced by the independent variables. The important loops are highlighted by a loop identifier, showing whether the loops are positive (reinforcing) or negative (balancing).

The causal maps are made on the basis of desk research and input from the interviews. The reports and interviews used to synthesize the causal maps is given in Figure 4.1.

Policy	**Sources**
Policy 1: Imposing certifications and standards for recycled aggregates	1. Interview #1 2. Interview #6 2. EU Construction and Demolition Waste Protocol and Guidelines (European Commission, 2018)
Policy 2: Improve pricing for recycled aggregates	1. Investigation of the optimal price for recycled aggregate concrete - an experimental approach (Katerusha, 2022)
Policy 3: Financial instruments: investments, tax incentives and subsidies	1. Circular economy in the Dutch construction sector: A perspective for the market and government (Rijkswaterstaat, 2015) 2. Interview #6
Policy 4: Circular and sustainable material procurement	1. Change towards a Circular Economy: Eliminating inertia in supply chains: A concrete case of stony materials supply chain in the Netherlands (Bukvic, 2018)
Policy 5: Mandatory pre-demolition audits	1. Interview #3 2. EU Construction and Demolition Waste Protocol and Guidelines (European Commission, 2018)
Policy 6: CDW Identification, separation and collection at source with sorting obligations	1. Interview #2 2. Sorting efficiency in mechanical sorting of construction and demolition waste (Hyvärinen et al., 2020)
Policy 7: Technological advances in recycling	1. Interview #1 2. Upgrading construction and demolition waste management from downcycling to recycling in the Netherlands (Zhang et al., 2020) 3. Closing the loop of EOL concrete (Maio et al., 2017)

Table 4.1: Sources synthesized to make the causal maps

Reading the causal maps

Causal maps are based on cause-effects and help understand how a system and it's sub components work; they're especially useful for visualizing how a change in one factor may impact elsewhere - whether it's a positive change or negative; they also help to indicate the long-term impacts of a change. Finally, causal maps will show how changing a factor may feed back to affect itself (MindTools, 2022).

Before diving into this section, a few points should be clarified for reading the causal maps. On the left are the policy measures, color coded to each actor who can implement the measure. On the rightmost side are the criteria. In between are the causal factors and connections showing the relationship and direction of influence between the factors. If it's positive, this means that as one factor goes up so too does the next factor. The box represents the system diagram, and factors outside the box represent external factors which affect the system but are outside the scope of the actors. The causal maps should be treated in a qualitative way since it's a concept map. The key on how to read the maps is given in Figure 4.2.

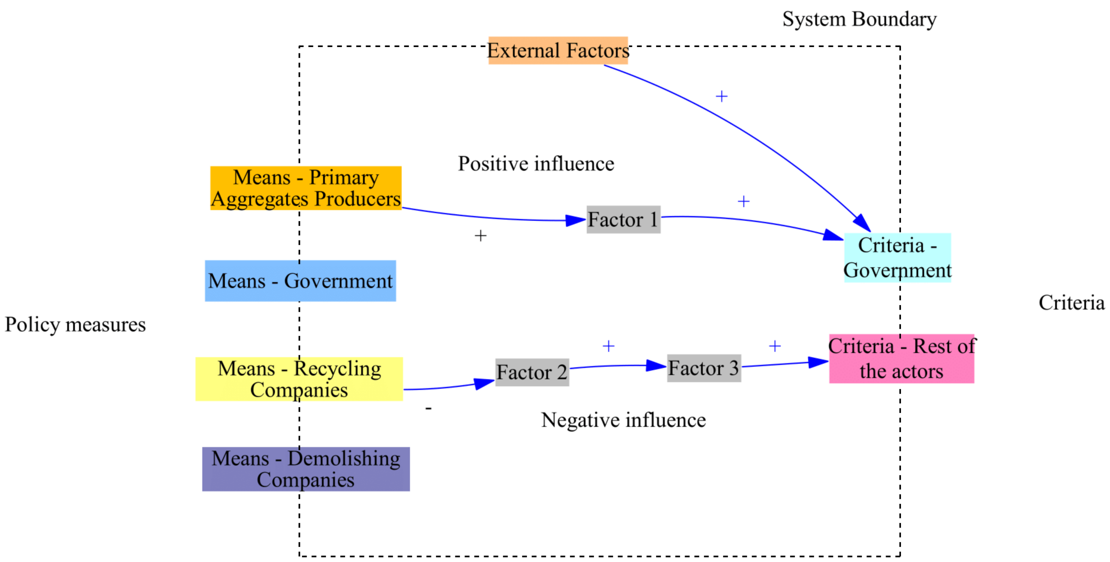


Figure 4.2: Reading the causal map/system diagram key

Policy 1: Imposing certifications and standards for recycled aggregates
The causal map for this policy is sketched in Figure 4.3. In the Netherlands currently, innovative opportunities are being increasingly explored to recover end-of-life concrete from CDW and use it to produce new concrete. For instance, the Rutte Group and New Horizon have set up a processing plant together where cement under the name Freement, is produced with recycled aggregates (Freement, 2022). However, the catch is that recycled aggregates for concrete have to fulfil strict requirements for size and purity. One of the common hurdles to recycling and re-using CDW in the EU is the lack of confidence in the quality of CDW recycled materials. There is also uncertainty about the potential health risk for workers using recycled CDW materials. This lack of confidence reduces and restricts the demand for CDW recycled materials. Imposing certifications and standards for the recycled products will increase the amount of recycled aggregates used in construction through two routes - increasing confidence of builders and ensure safe usage. The positive objectives this policy will have an effect on, is reducing raw material extraction through reduced primary materials, reducing carbon emissions by reducing the amount of embedded carbon and increasing CDW recovery from an increased usage of recycled aggregates.

However, there will be an added cost to the Government to carry out these quality assurance studies which lead to a pre-implementation investment. Furthermore, increased strictness of aggregate size and purity specifications will lead to an increased CDW processing costs. Thus this policy is effective in achieving three of the required objectives. The driving factor this policy measure has a major effect on is the demand for recycled aggregates. An external factor that also affects the sub-system is the future of bio-based construction. Bio-based construction involves the application of bio-based materials which are biodegradable, such as wood, hemp, elephant grass, etc (Schuttelaar and Partners, 2018b). It may mean the emergence of a new market where concrete is not used as much as before, thus restricting the need for both primary and recycled aggregates.

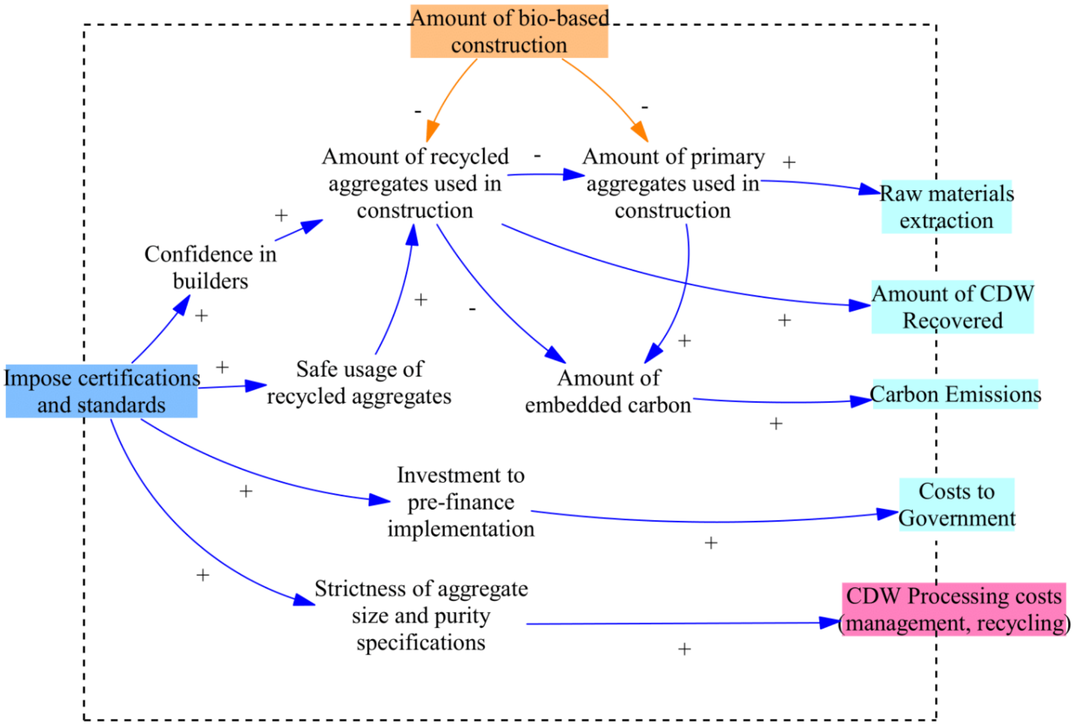


Figure 4.3: Policy 1: Causal map for policy intervention by the Government through imposing certifications and standards for recycled aggregates

Policy 2: Improve pricing for recycled aggregates

This policy measure involves making the price of recycled aggregates competitive enough to be bought by concrete producers and construction companies as an alternative to primary aggregates. One of the barriers identified for the uptake of recycled aggregates was that there were long-standing business relations between concrete producers and primary aggregates producers, which is difficult to influence or break (Interview 6). Similar to the previous policy, this policy also affects raw materials extraction, amount of CDW recovered and carbon emissions in a positive way through increasing the demand for recycled aggregates.

However, reducing the price may affect profit and might not be very beneficial for the recyclers in the short-term, which may require the Government to take up some of the implementation costs leading to increased costs to the Government. Similar to the first policy, an external factor that affects this policy is also the amount of bio-based construction. Another external factor that affects this system is the price of primary aggregates. Primary aggregates have continual price fluctuation (Maio et al., 2017). The causal map for this policy is sketched in Figure 4.4.

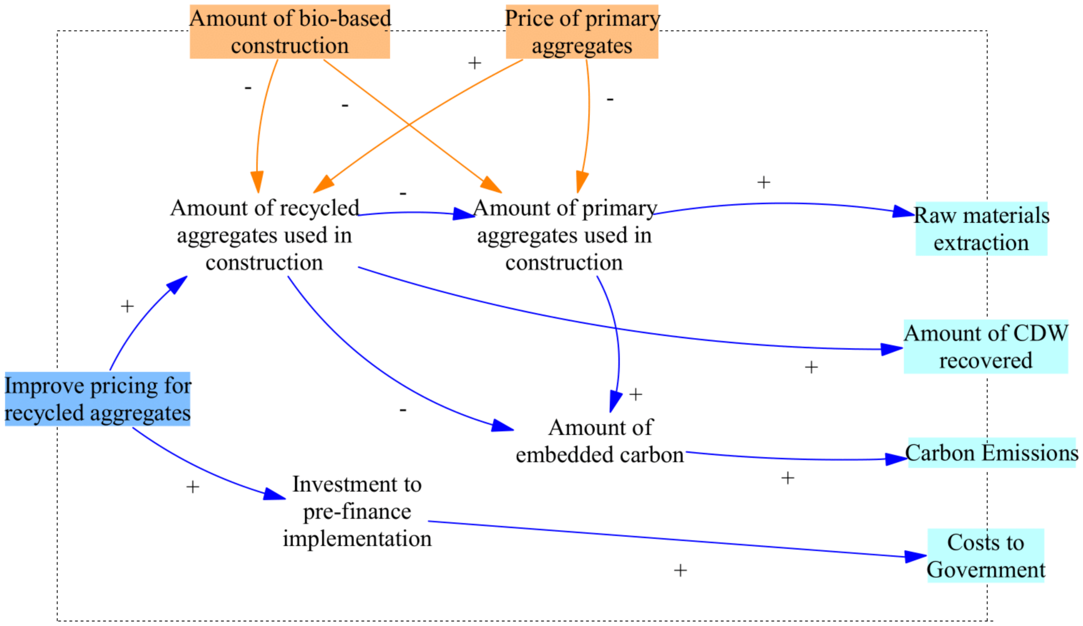


Figure 4.4: Policy intervention through improving pricing for recycled aggregates by the Government

Policy 3: Financial instruments: investments, tax incentives and subsidies

Financial instruments directed at achieving changes in waste generation and waste management offer significant flexibility to producers and consumers compared to direct "command and control" regulation (OECD, 2014). Subsidies and taxes can be used to discourage the sale of virgin materials and to encourage clients to renovate existing (or vacant) buildings instead of constructing new ones (OECD, 2014). However, a risk in this according to Bukvic (2018) is that if subsidies are enforced on the condition of a certain % of recycled materials, companies may procure cheaper materials from abroad, thus leading to more transportation and more carbon emissions. Thus there is a positive as well as a negative route to carbon emissions.

The banking sector have sufficient funds in the form of 'fiscally advantageous green investments portfolio' to invest in sustainable new construction projects (Rijkswaterstaat, 2015) which can give a boost to the construction sector and increase its turnover. This would lead to lower costs to the Government. Another advantage comes from a boost to the construction sector leading to new ventures in waste management and recycling and an increase in GDP and jobs. Figure 4.5 sketches a simplified causal map on the effect of financial instruments on the objectives.

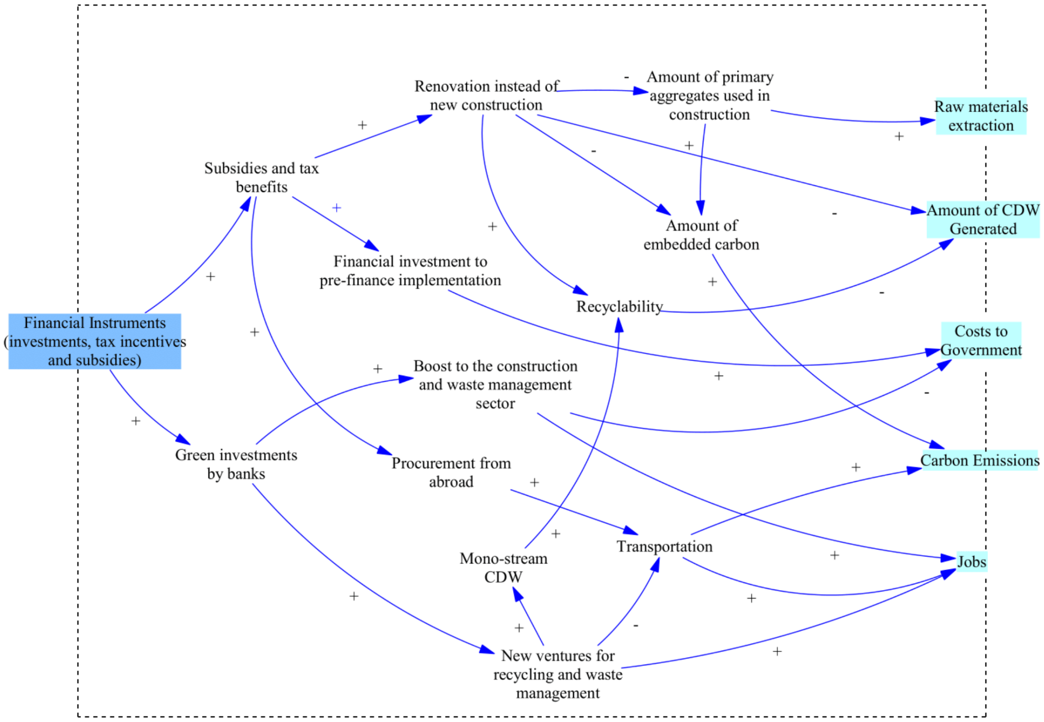


Figure 4.5: Policy intervention through financial instruments such as tax incentives and subsidies by the Government

Policy 4: Circular and sustainable material procurement

The aggregates sector is the largest amongst the non-energy extractive industries in Europe (UEPG, 2020). They can be produced from either natural sources through extraction from quarries, or dredged from sea or rivers. They can be secondary aggregates which are reprocessed materials manufactured from CDW or sourced from industrial processes such as blast or electric furnace slags or china clay residues (UEPG, 2020). The primary aggregates industry is also an important contributor to GDP; it was found that aggregation production in tonnes per capita increases almost linearly as the GDP per capita increases (UEPG, 2020). The European aggregates industry is also predominated by SMEs which provide important, long-term, secure, mostly rural employment (UEPG, 2020).

In the specific case of the Netherlands, the role of primary aggregates producers is more than just mining since they take aggregates from river banks, mainly in the provinces of Gelderland, Limburg and Overijssel (Bukvic, 2018). This also has a dual purpose - that of river widening, which in the Netherlands is a measure for flood protection (Bukvic, 2018). Moreover, primary aggregate producers in the country claim to also build natural and recreational areas around the river where they dredge the soil, which is paid for by the industry itself and not with the tax payers money (Bukvic, 2018). This could reduce costs to the Government while providing flood protection. But on the other hand, it mandates land use conversion and using natural resources that have no possibility to be replaced. Unsustainable sand mining could result in riverbank collapse, deepening of river beds, sinking deltas and coastal erosion as well as biodiversity loss, especially when coupled with the impacts of dams and climate change. This can be seen in the example of Mekong delta in Vietnam, where unsustainable mining over the last decade has resulted in river bank instability (Walton, 2019). For the Netherlands, which is already below sea level, this can be a cause for concern.

If the Government pushes for a better circular and sustainable aggregates procurement, it may lead to additional benefits such as bettering the area around where aggregates are mined, for instance, through urban regeneration and carbon offsetting. The causal map for this policy is sketched in Figure 4.6.

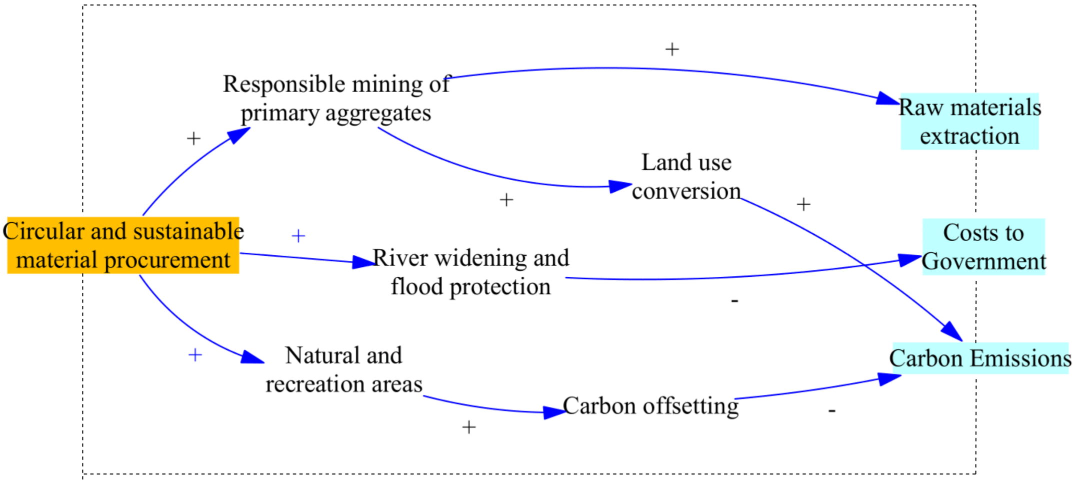


Figure 4.6: Policy intervention through circular and sustainable material procurement by primary aggregates producers

Policy 5: Mandatory pre-demolition audits

Processing good quality recycled materials starts way before the process of demolition itself (Federation Internationale du Recyclage, 2020). The trend in the recent past for the Netherlands has been slowly shifting to selective demolition where an inventory of building materials is made before demolition and materials are separately collected at demolition sites (Interview 2). During the interviews, the biggest factor which hinders deconstruction was found out to be time. A pre-demolition audit may enforce time restriction which may give enough time to reclaim reusable elements. However, to store reusable elements there also needs to be enough space which may increase costs to the government. A lack of storage spaces to keep reusable elements was identified during the interview. For some materials, such as wood, there are laws than mandate the storage due to risk of a fire (Interview 2). Pre-demolition audits may also include a disposal levy on buildings to be paid by the client (similar to Extended Producer Responsibility), which may generate some revenue thereby decrease the costs of processing waste and potentially decreasing costs to Government. The causal map for this policy is sketched in Figure 4.7. A main factor the policy affects is amount of CDW generated through source reduction and increasing reusable components.

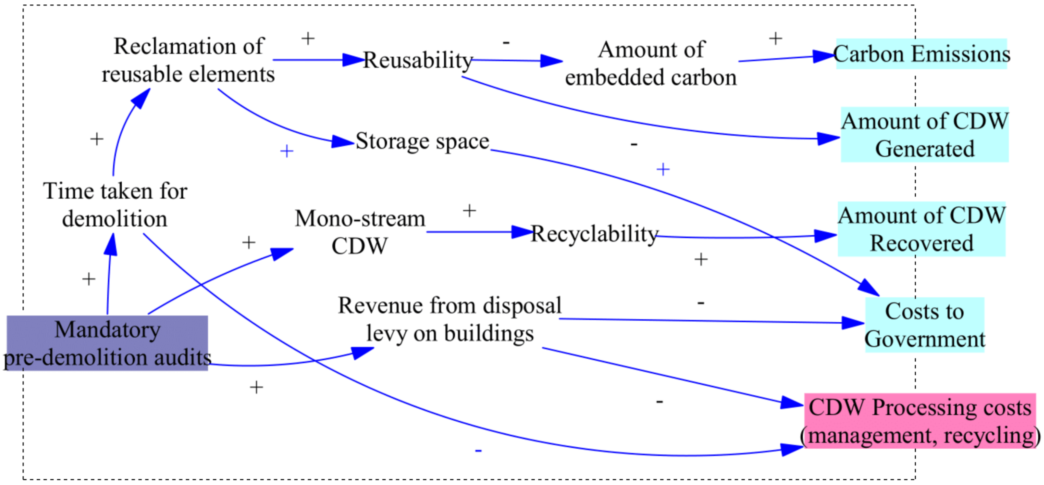


Figure 4.7: Policy intervention through imposing mandatory pre-demolition audits by demolishing companies

Policy 6: CDW Identification, separation and collection at source with sorting obligations

It is challenging to ensure good quality of waste provided by different sites under various production backgrounds. Implementing a clear and strict waste classification could be one of the most effective approaches to keep waste purity and reduce recycling costs (Yu et al., 2021). Taking the example of Renewi, currently, the conditions for CDW acceptance are as follows (Renewi, 2022):

- Mix of rubble/concrete waste (concrete, cement, masonry, bricks, pantiles, stoneware, tiles, natural stone etc.) and wood, building film and metal
- Max. 200 kg of a combination of residual waste, glass, roofing, carpets, lime products, gyproc sheets, insulation per tonne
- The container must contain 80% inert materials

Assuming, other CDW handling companies have a similar acceptance criteria, we see that CDW collected is majorly of mixed composition. This means that pre-sorting and pre-processing would be required to remove stony materials from other materials such as wood or glass before reuse or recycling. This also affects recycling efficiency due to the presence of contaminants. If source separation was enforced, it would not only reduce the pre-processing costs and emissions, but lead to more efficient recycling.

This may also lead to more jobs by appointing on-site CDW experts who may guide the identification and source separation. The main factors this policy affects are collection efficiency and sorting efficiency. The effects of this policy are sketched in Figure 4.8. An external factor that affects the policy however is hazardous waste fraction which may make it difficult to sort onsite.

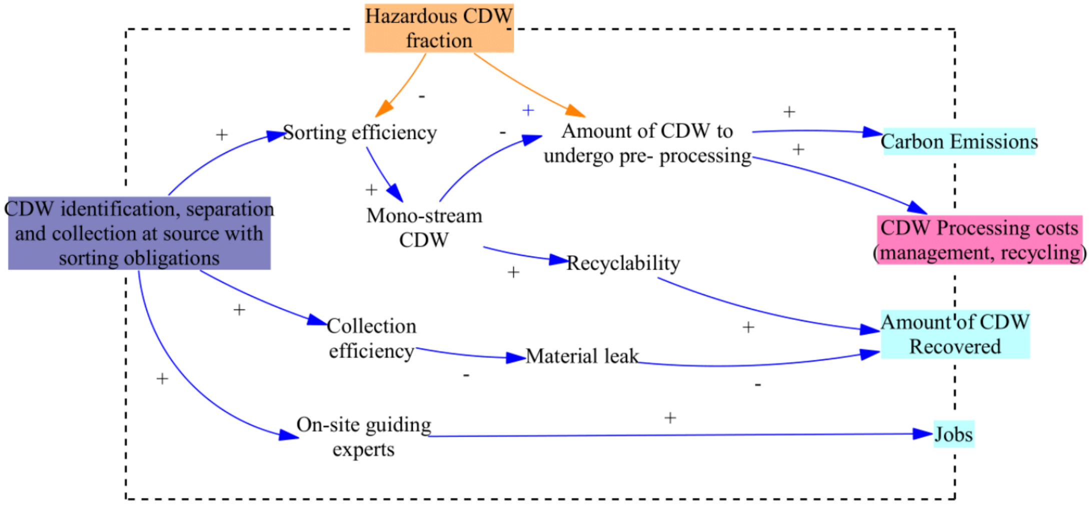


Figure 4.8: Policy intervention through CDW Identification, separation and collection at source with sorting obligations by demolishing companies

Policy 7: Technological advances in recycling

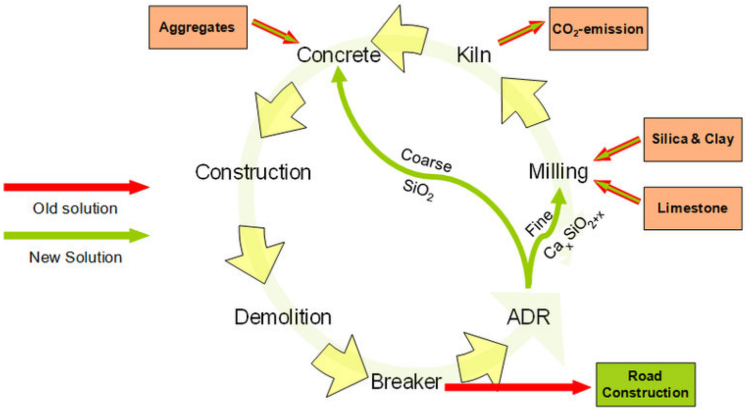


Figure 4.9: The process of C2CA for concrete upcycling Source:(Maio et al., 2017)

The upcycling efficiency of CDW not only depends highly on the innovation of recycling technologies but also strongly relates to the incoming waste quality (Brito & Saikia, 2013). According to (Deloitte, 2015), current state-of-the-art technologies such as C2CA [1] have an 80% efficiency. Efficiencies for other technologies are not known. It is also not known what processes are used by recycling companies in the Netherlands since the economy of concrete recycling is extremely dependent on the situation, local conditions and the recycling facility itself (Maio et al., 2017). Figure 4.9 shows the advancement in concrete recycling technology (C2CA) to be more effective in getting EOL concrete back to being used in construction instead of being used in civil engineering. The technology used here is a new low-cost classification technology called Advanced Dry Recovery (ADR) which is applied

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[1] C2CA stands for concrete into clean aggregates and cement which is a European funded project developed by Delft University of Technology (the Netherlands) in collaboration with 13 international partners. The project aims to develop an environmentally sound and cost-effective process technology that produces high-grade environmentally friendly concrete (C2CA, 2011)

to remove the finer contaminants. However, it also shows that some intermediate processes lead to more carbon emissions. The causal map for this policy is sketched in Figure 4.10.

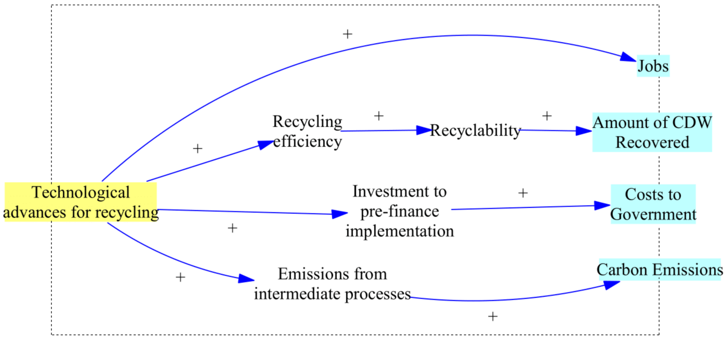


Figure 4.10: Policy intervention through technological advances in recycling by recycling companies

4.3. Building the system diagram

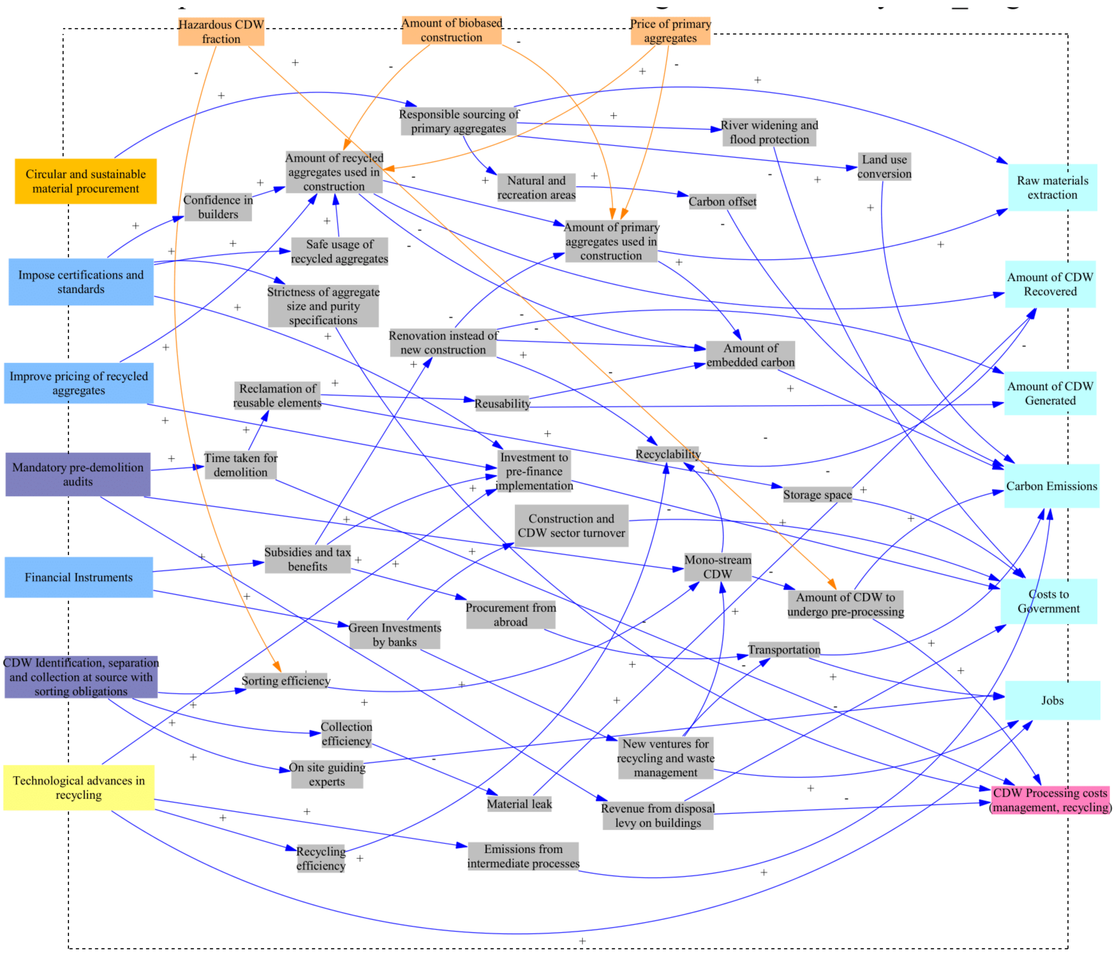


Figure 4.11: System Diagram: An overview of the system and its boundaries.

Figure 4.11 combines all the individual causal maps into one big map called the system diagram. It gives insight into how the material flows are affected by factors. For instance, factors such as recyclability or mono-stream CDW form the material flows, and factors such as collection or recycling efficiency affect these material flows. A system diagram can also be used to check if there are any additional possible measures that can influence in between variables and could alleviate the problem situation or could alleviate potential negative (side) effects. In the next section, an impact table is formed which sketches the paths from each policy to the criteria.

4.4. Results from System Diagram

4.4.1. Multi-criteria impact assessment

From the system diagram, a qualitative consequences table was made (Enserink et al., 2010) which is sketched in Figure 4.12. On the rows are the policies and on the columns are the criteria. The table is filled by following the pathway from each policy to the criteria - the signs of the causal map are multiplied to get a resultant sign. Multiple pathways means multiple signs separated by a slash. There is no one way to do the multi-criteria analysis. One can compare the policies based on how many overall criteria it affects positively, or which non-negotiable criteria it affects negatively.

The one criterion that all the policies have an effect on is carbon emissions. The next criterion being affected positively by 6 of the 7 policies is costs to Government. Amount of CDW recovered was affected by 5 policies.

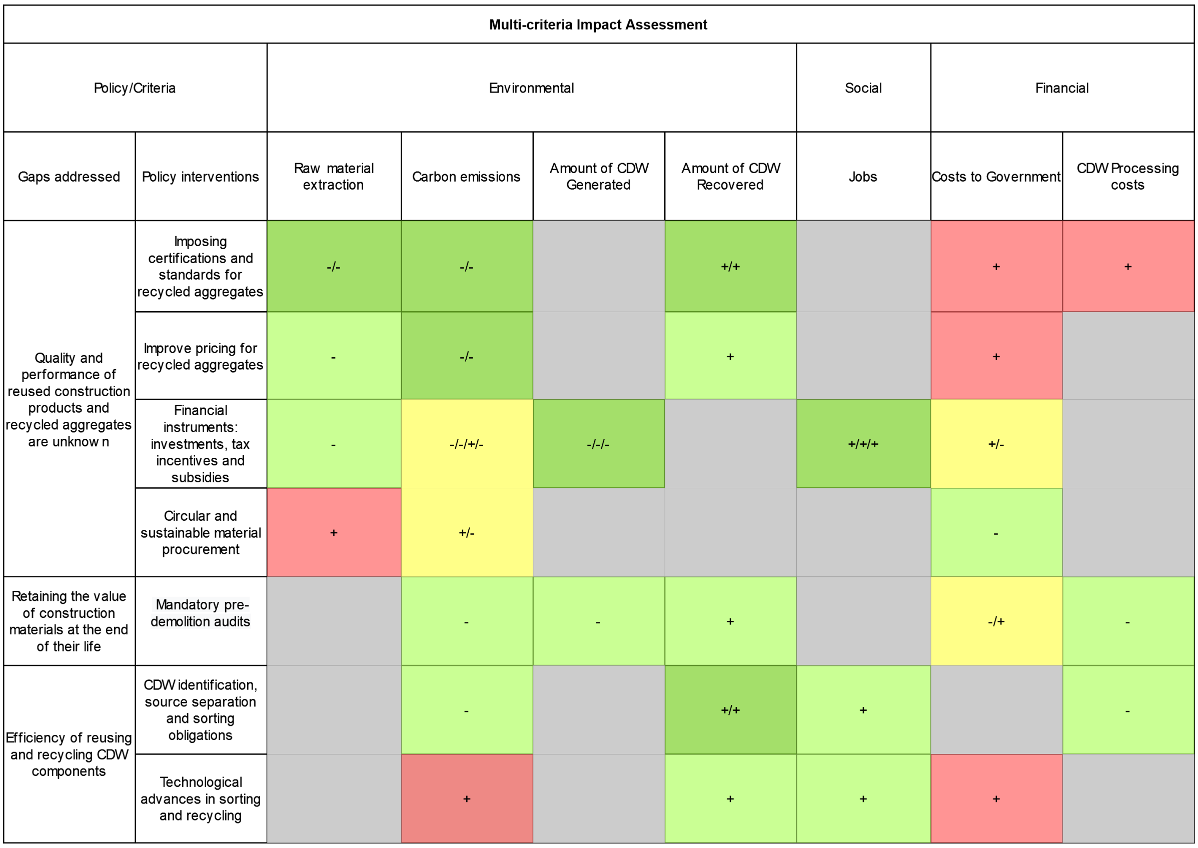
In the case of circular and sustainable procurement and financial instruments, the result on carbon emissions is ambiguous with one positive route and one negative. This is because they do offset carbon, but also lead to emissions through land use conversion. Technological advances in recycling increases emissions because of the intermediate processes that lead to cleaner recyclates also produce emissions.

Financial instruments and circular procurement do not have any effect on the amount of CDW recovered as they work on redirecting flows and reducing emissions respectively. But it should be noted that financial instruments does have a positive effect on reducing the amount of CDW generated in the first place. This is because through subsidies and tax incentives, they encourage renovation instead of new construction or demolition.

CDW identification, source separation and sorting obligations do not have any negative effect on any of the the criteria. The reason for this is because for this policy, the drawback is for the client as it would require them to pay more, or it would take more time. However, clients are not considered a key actor in this analysis.

There also seems to be a trade-off between costs to Government with carbon emissions and amount of CDW recovered which might suggest policies that reduce carbon emissions are expensive. This would helpful to know when implementing policies as it allows to compare not only costs between policies but also their impacts to make an informed decision rather than choosing the less expensive ones.

Finally, only three policies have an impact on jobs. They are financial instruments, CDW source separation and technological advances. The MCA table provides insights into benefits and risks and provides a basis for a decision model. However, a drawback of this is that different actors may consider different priorities fr criteria. This can be overcome by a stakeholder discussion and asking them to provide weights on the criteria. In the time scope of this study, this couldn't be done and it is recommended to be included in the future scope.



Multi-criteria Impact Assessment								
Policy/Criteria		Environmental				Social	Financial	
Gaps addressed	Policy interventions	Raw material extraction	Carbon emissions	Amount of CDW Generated	Amount of CDW Recovered	Jobs	Costs to Government	CDW Processing costs
Quality and performance of reused construction products and recycled aggregates are unknown	Imposing certifications and standards for recycled aggregates	-/-	-/-		+/+		+	+
	Improve pricing for recycled aggregates	-	-/-		+		+	
	Financial instruments: investments, tax incentives and subsidies	-	-/-/+/-	-/-/-		+/+/+	+/-	
	Circular and sustainable material procurement	+	+/-				-	
Retaining the value of construction materials at the end of their life	Mandatory pre-demolition audits		-	-	+		-/+	-
Efficiency of reusing and recycling CDW components	CDW identification, source separation and sorting obligations		-		+/+	+		-
	Technological advances in sorting and recycling		+		+	+	+	

Figure 4.12: Multi-criteria analysis. The + represents a positive path from policy to criteria and the - represents a negative path from policy to criteria. The table is color-coded with green representing a desirable outcome and red representing an undesirable outcome. Yellow is considered ambiguous due to the presence of both desirable and non-desirable outcomes.

4.4.2. System Diagram as a basis for the model

It should be noted that the system diagram is a highly abstracted representation of reality. Till now, the analysis provided a snapshot of the factors affecting the material flows and the potential impacts of each policy based on reasoning. However, this doesn't tell us anything about about which policy has the bigger overall impact. To calculate that numerically, it would be required to quantify all the flows from Figure 1.1, and study how the implementation of a policy might impact the flow. In this chapter, however, few factors became evident which affect the current CDWM system (collection efficiency, sorting efficiency, time for demolition and so on). In the next section, the material flow model is complemented with the factors identified in this chapter.

5

Model Building

In this section, a model is designed which builds on the system diagram and helps to quantitatively assess the environmental impacts of the 7 policies chosen. Due to the time scope of this research, only the impacts on 2 criteria out of the 7 is studied - carbon emissions, CDW recovered (which is further elaborated to upcycling and reuse rate as well). For calculating the impacts on costs and jobs, macroeconomic models such as E3ME or Input-Output models could also be integrated in this material flow model (Hawkins et al., 2007), but that is currently outside the scope and is part of further research.

5.1. Modelling phases

The model building follows four phases adapted through system dynamic modelling methods (Pruyt, 2013) - model conceptualization, model formulation, model validation and model implementation.

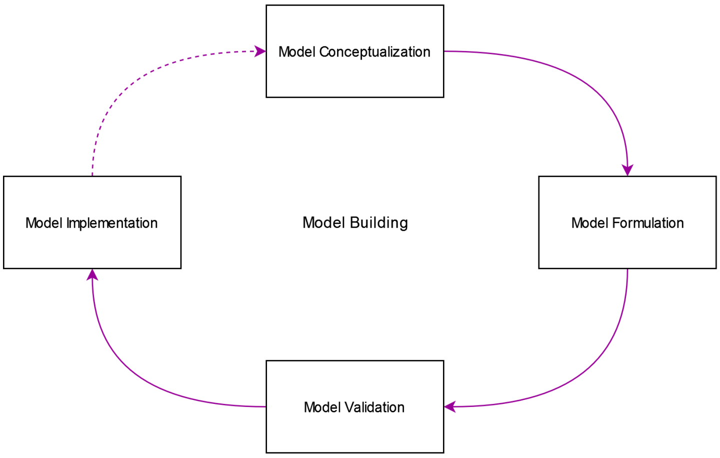


Figure 5.1: Modelling phases

In model conceptualization, the problem and the scope is defined. In this case, the results from problem formulation and system diagram form the basis for model conceptualization. In model formulation, the results from the model conceptualization is translated into equations and a computational model is built using a professional software package which allows for simulation. Model validation ensures that the model structure and simulation observations are aligned with real world data and principles and that they do not exhibit unrealistic behavior. Finally, model implementation is the application phase which allows to use the model to test the chosen policies and find their impacts. These steps are an iterative process and with with every step, active feedback may inform prior steps. The below sections describe each of the modelling phase in detail.

5.2. Model Conceptualization

The model conceptualisation is based on all the information gathered so far in the previous chapters. The system boundary started at the point when a structure is demolished at end-of-life and CDW is generated and ends at the different CDW destinations after processing. The main model is built on the material flow model identified in actor analysis (Figure 3.2). The material flow forms the basis for finding the criteria of CDW recovered. But to study the influence on amount of carbon emissions, emissions across the material flow is required. Thus, carbon emissions across different processes were also added to the conceptual model. Figure 5.2 sketches the updated figure of the material flows affected by identified factors and resulting carbon emissions from intermediate processes.

The figure follows the process of CDW management starting at CDW generation, which is then collected. The collection flow is affected by collection efficiency. Collection inefficiency results in material leak which is assumed to end up in landfills. Before the materials can be put up for sale in the recycled aggregates market, they need to be sorted and processed further according to the market needs. After collection, the materials undergo sorting which is affected by sorting efficiency. Some hard to sort materials may go for disposal instead. Disposal involves two methods - either incineration or accumulated in landfill. Sorted materials can take three routes - reuse, upcycling, or downcycling. To represent the amount that is upcycled, concrete production is also visualized. Concrete production involves both primary aggregates and recycled aggregates in different proportions. This depends on the demand for recycled aggregates and the requirement for total concrete. The demand for recycled aggregates also dictate the supply available from recycling companies. In the next section, the process explained here is converted into equations.

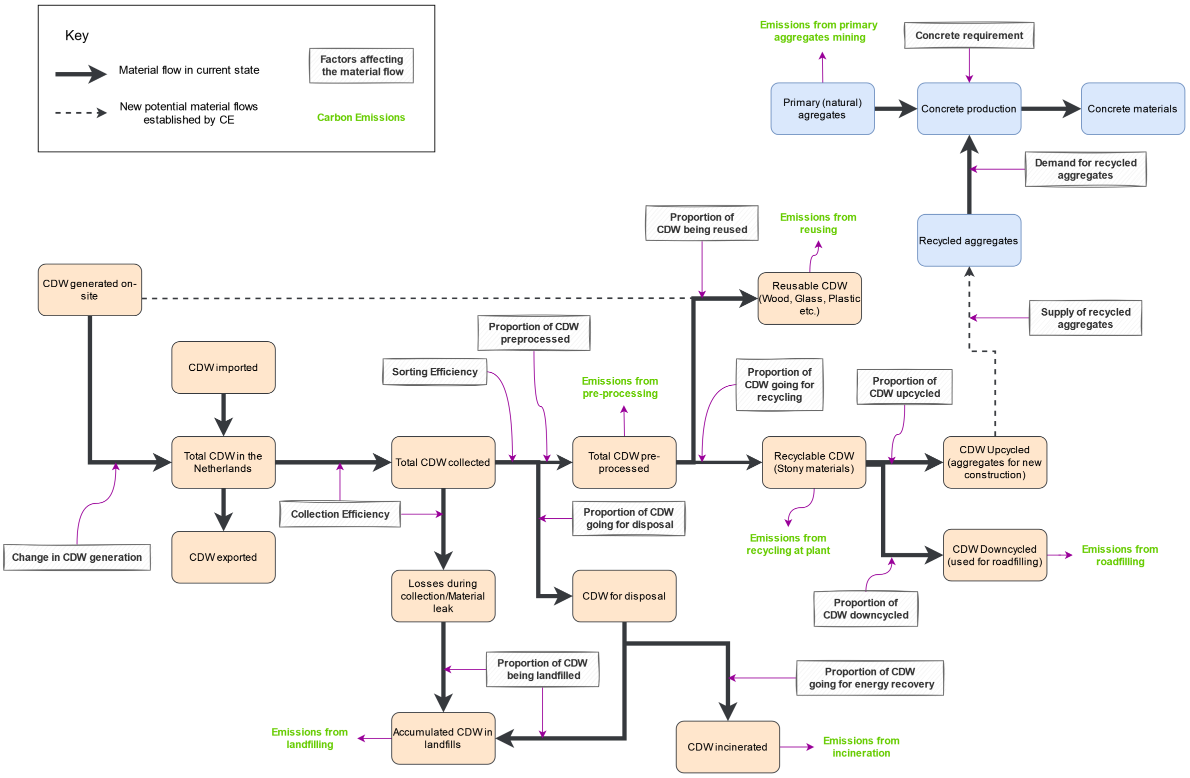


Figure 5.2: Model Conceptualization

5.3. Model Formulation

This section is divided into two main parts - quantifying material flows and quantifying carbon emissions.

5.3.1. Material Flows

The first step of formulating the model was deciding what variables become stocks and what variables become flows. Stocks describe the state of the system at a given point in time, whereas flow variables describe the changes in the system over a period of time (Hale, n.d.). Stocks are accumulated or depleted over time by flows, whereas flows represent the rate of movement of materials (in this case construction waste) in and out of stocks. Flows can be divided into inflows which that add to the stocks and outflows that deplete the stocks. This led to each CDW supply chain phase being modeled as a stock (for example - Generated, Collected, Sorted etc.), with raw CDW in-flowing and the processed CDW out-flowing after each stage. This also helps visualize inefficiencies in the processes and the resulting material losses throughout the management process. The conceptual model made in the previous section was first transferred to Vensim following the stock-flow structure and is represented in Figure 5.3.

An assumption was made to aggregate material compositions. The CDWM system is quite complex since waste streams are usually never mono-streams. For instance, depending on the building, it could be 70% concrete, 10% wood, 5% glass and so on. But this is to be expected by the nature of demolition waste. It highly depends on how the process of demolition took place - if it was selective, or if was controlled explosion, if they separated their waste at source or if the waste management companies did any pre-sorting. To account for this, assumptions were made regarding the aggregation of the flows - the system is divided into reusable CDW (which includes wood, glass, plastic etc.), recyclable CDW (which includes stony materials such as cement, concrete, sand, gravel etc.) and CDW to be disposed (which may include contaminated or difficult to recover waste types).

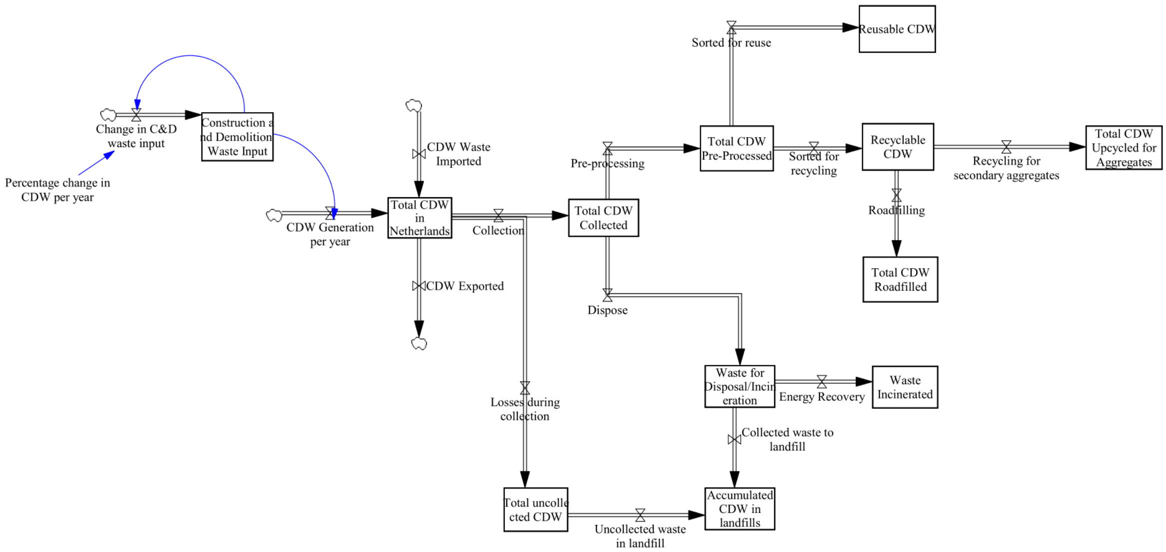
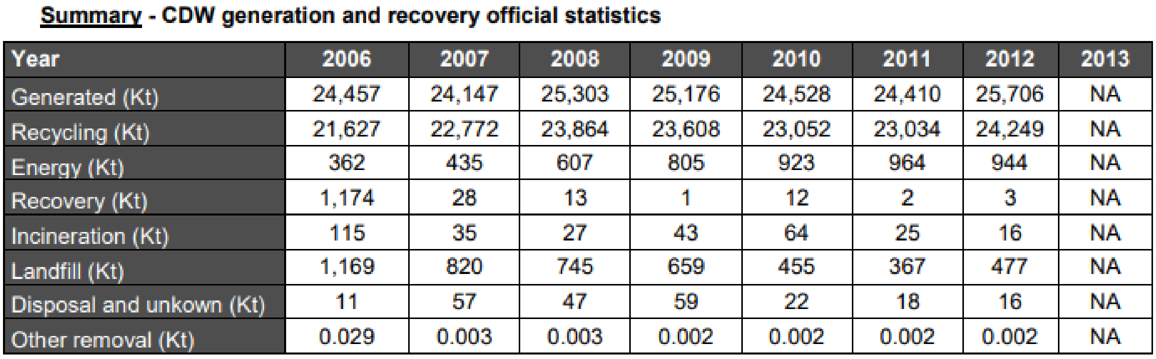


Figure 5.3: Material Flow conceptual model sketched in Vensim forms the backbone of the main model

The second step involved quantifying the stocks and the flows. There is limited reporting on CDW flows in the Netherlands and it varies amongst different reports. This is complicated by the fact that different compositions of waste streams are studied - stony materials, asphalt, concrete, wood, plastic etc. This model uses the figures from Zhang et al. (2020) and Deloitte (2015) to make estimations for initial stock values. The data for 2010 were used from Figure 5.4 because recent data was unavailable.


Summary - **CDW generation and recovery official statistics**

Year	2006	2007	2008	2009	2010	2011	2012	2013
Generated (Kt)	24,457	24,147	25,303	25,176	24,528	24,410	25,706	NA
Recycling (Kt)	21,627	22,772	23,864	23,608	23,052	23,034	24,249	NA
Energy (Kt)	362	435	607	805	923	964	944	NA
Recovery (Kt)	1,174	28	13	1	12	2	3	NA
Incineration (Kt)	115	35	27	43	64	25	16	NA
Landfill (Kt)	1,169	820	745	659	455	367	477	NA
Disposal and unkown (Kt)	11	57	47	59	22	18	16	NA
Other removal (Kt)	0.029	0.003	0.003	0.002	0.002	0.002	0.002	NA

Figure 5.4: Summary - CDW generation and recovery official statistics. Source: Deloitte (2015)

The starting point of the main model is the amount of CDW generated based on which the other flows are calculated. The amount generated may also change over the years. The value for this is estimated to be 24,528 kilotonnes which is how much construction and demolition waste was produced in 2010. But according to the figures collected by CBS from the last few years in Zhang et al. (2020), CDW generation has roughly remained around 2.385 2□5 million tonnes. Due to this reason, to represent the current scenario, change in CDW per year was assumed to be 0 which signifies that over time, the amount of CDW generated does not change. However, to signify an increase or a decrease in this amount, a provision is made in the model. The value of the variable 'Percentage change in CDW per year' can be changed and it accepts both a positive as well as a negative value.

After generation, the next step in the process is collection. The flow of collection of CDW is equated as the outflow from CDW generated multiplied by the collection efficiency, which was assumed to be 80%. The other outflow emerging from CDW generated is losses during collection which depends on the flow of collection. Thus, it is equated as the difference between CDW generation and CDW collected. This ensures that losses during collection is not a static value and is updated when collection is changed. The equations are given below as an example. The rest of the flows follow a similar approach. The data table representing values, equations and assumptions for all stocks and flows is given in Table 5.1.

Collection (Outflow) = Inflow (CDW Generation per year + CDW Imported - CDW Exported) * Collection efficiency
Losses during collection = Inflow (CDW Generation per year + CDW Waste Imported - CDW Exported) - Collection

The flow for recycling of secondary aggregates is the basis for upcycled materials which is used on new construction. The concrete producers can choose to use secondary or primary raw materials. Their choice is not straightforward and is essentially a business transaction. The concrete producers may order recycled aggregates of a specific magnitude and size and based on the business order, the CDW is recycled to meet the requirements (Interview 6). If there's no demand, the recycled CDW may all just go to the civil works to be used as road-filling. To represent this entire concept in the model, the variables 'Recycled aggregates requirement' was added which is influenced by 'Strength of demand for recycled aggregates' (which is estimated to be 13% currently [1] and can be influenced by policy measures). First this is calculated, and then roadfilling is equated as the difference between inflow of recyclable CDW and what goes for upcycling. This part of the model is represented in Figure 5.5.

Recycled aggregates requirement = Strength of demand for recycled aggregates*Total concrete requirement
Recycling for secondary aggregates (Upcycling) = Recycled aggregates requirement*Recycling efficiency
Roadfilling = Inflow (CDW sorted for recycling) - Recycling for secondary aggregates (Upcycling)
Recycled aggregates supply = Recycling for secondary aggregates

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[1] A study by Metabolic (2020) found that only 13% of all input materials consumed for buildings come from secondary and renewable sources. The study also found that in the Netherlands, an annual demand for 17 million tons of materials, most of which is concrete, followed by steel, bricks and wood is required. Thus, the annual concrete requirement is assumed to be 17 million tons in the model.

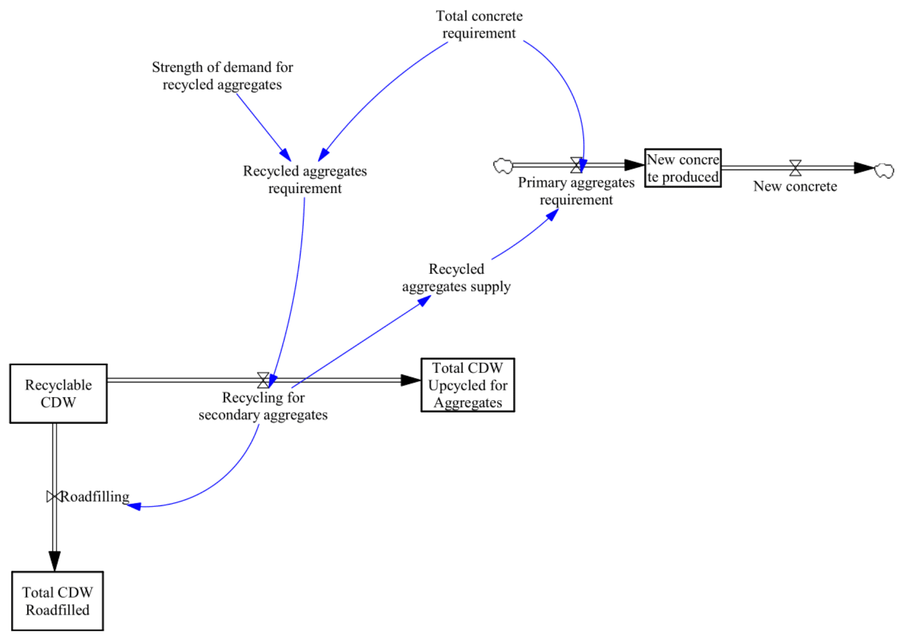


Figure 5.5: Snapshot of formulating the amount of CDW upcycled for new construction

Factor	**Type**	**Unit**	**Initial Value**	**Equation**	Reference
CDW Generation per year	Flow	Kilotonnes/Year	24528	x	(Deloitte, 2015)
Waste Imported	Flow	Kilotonnes/Year	710	x	(Deloitte, 2015)
Waste Exported	Flow	Kilotonnes/Year	232	x	(Deloitte, 2015)
Total CDW in Netherlands	Stock	Kilotonnes	25006	CDW Generation + Imported - Exported	x
Collection Rate	Factor	Dmnl	0.8	x	Assumption
Collection	Flow	Kilotonnes/Year	20004	Collection Rate*Total CDW	x
Losses during collection	Flow	Kilotonnes/Year	5000	Total CDW - Collection	x
Total CDW Collected	Stock	Kilotonnes	20004	Collection Rate*Total CDW	x
Proportion of CDW pre-processed	Factor	Dmnl	0.9	x	Assumption
Sorting efficiency	Factor	Dmnl	0.7	x	Assumption
Preprocessing	Flow	kilotonnes/Year	12602	Proportion of CDW pre-processed* Sorting efficiency*Collection	x
Disposal	Flow	kilotonnes/Year	7402	Collected - Preprocessed	x
Waste for Disposal/Incineration	Stock	kilotonnes	7402	Collected - Preprocessed	
Proportion of CDW going for energy recovery	Factor	Dmnl	0.67	x	Assumption
Energy Recovery	Flow	kilotonnes/Year	4959	Proportion of CDW going for energy recovery*Dispose	x
Collected waste to landfill	Flow	kilotonnes/Year	2443	Dispose-Energy Recovery	x
Accumulated CDW in landfills	Stock	kilotonnes	7443	Collected waste to landfill+Uncollected waste in landfill	x
Total CDW Pre-Processed	Stock	kilotonnes	12602	Proportion of CDW pre-processed* Sorting efficiency*Collection	x
Proportion of CDW going for recycling	Factor	Dmnl	0.97	x	(Statistics Netherlands CBS, 2016)
Sorted for recycling	Flow	kilotonnes/Year	12223	Proportion of CDW going for recycling *Pre-processing	x
Recyclable CDW	Stock	kilotonnes	12223	Proportion of CDW going for recycling *Pre-processing	x
Strength of demand for recycled aggregates	Factor	Dmnl	0.13	x	(Metabolic, 2020)
Total concrete requirement	Factor	kilotonnes/Year	17000	x	(Metabolic, 2020)
Recycled aggregates requirement	Factor	kilotonnes/Year	2210	Strength of demand for recycled aggregates *Total concrete requirement	x
Recycling Efficiency	Factor	Dmnl	0.7	x	Assumption based on (Deloitte, 2015) which places recycling efficiency of the C2CA technology to be 80%
Recycling for secondary aggregates	Flow	kilotonnes/Year	2210	Recycled aggregates requirement*Recycling efficiency	x
Roadfilling	Flow	kilotonnes/Year	10013	Sorted for recycling-Recycling for secondary aggregates	x
Sorted for Reuse	Flow	kilotonnes/Year	379	Pre-processing-Sorted for recycling	x

Table 5.1: Main data table showing the model variables and their numerical value

5.3.2. Carbon Emissions

In a circular economy, the impact is often calculated through avoided impacts of primary material consumption through replacing it with secondary materials consumption. In the case of the construction sector, significant emissions may be avoided by using recycled aggregates instead of primary aggregates. Calculating carbon emissions for the entire lifecycle of CDW often follows three levels - embedded, operational and transport to cover the full range of scenarios. But in this study, values for carbon emissions at each stage are taken from existing studies instead of following an entire lifecycle analysis from the ground-up. This was a limitation imposed by time constraints and the the research scale due to which licensing for lifecycle database (for instance, Ecoinvent) was not possible.

Although this can give a good estimation of the differences of emissions during each process, it is highly context specific to the area and the scope of the study. To account for the differences, sensitivity analysis will be done to validate these values in model validation. For normalizing the values, the unit taken was carbon emissions per tonne of processing CDW at each step in CO2 equivalent. When including transportation, per km was also taken which was then multiplied with an estimation of distance travelled based on the Netherlands, which came out to be 100km based roughly on the distance between Deventer or Gelderland where the mining takes place to major cities such as Amsterdam or Rotterdam. The data table for carbon emissions for each stage is given in Figure 5.2.

Table 5.2: Emissions value table

Factor	Description	Value (kg CO2 eq/tonne of CDW)	Source
Unit emissions from pre-processing (Sorting)	This is considering an average capacity of 18 m3 / h for the treatment of waste by the equipment and machinery Emissions from processing machines (could be cleaning, sorting or processing)	0.43	(Burciaga et al., 2019)
Unit emissions from pre-processing (Crushing)	This is considering an average capacity of 18 m3 / h for the treatment of waste by the equipment and machinery Emissions from processing machines (could be cleaning, sorting or processing)	0.43	(Burciaga et al., 2019)
Unit emissions from upcycling CDW	The process energy usage and resulting greenhouse gas emissions from recycling aggregates is around 4 kg CO2-e per tonne.	4	(Sustainable Aaggregates, 2022)
Unit emissions from using primary aggregates (Quarrying, Machinery, Pre-processing and Transport)	The InEnergy report published in 2010 estimates that the production of one of ton aggregate including extraction and processing, generates in average 8.1 kg of CO 2, with the assumption of transport distance of 50km. Assuming a transport distance of 100km for the Netherlands, it comes out to be around 10.9kg CO2.	10.9	(Meddah, 2017)
Unit emissions from roadfilling	Mostly stems from to transportation emissions to destination.	8.73	(Butera et al., 2015)
Unit emissions from landfilling	Decomposition methane emissions are generated from some non-inert CDW decomposition over the long landfill years. Decomposition emissions + transportation emissions	17.9	(Butera et al., 2015), (Xu et al., 2019)
Transportation emissions (simplified)	0.14 kg/tonne-km in UK per km. Assuming 100 km for NL, it comes to 14 kg/tonne.	14.25	(Yu et al., 2021), (Zhao et al., 2021)

A complete list of assumptions made to create the model can be found in the Appendix Section B.1. A screenshot of the final model is available in Appendix Figure B.1. The model is also made open source and can be found on Github

5.3.3. Key Performance Indicators

A key performance indicator (KPI) is a measurable value that demonstrates how effectively a policy achieves its desired objectives. Since the scope of the model involves only the environmental objectives, two key performance indicators are derived from the environmental criteria involves the **Total Amount of CDW Recovered** and **Total Carbon Emissions across the Value Chain**. According to the Waste Framework Directive (WFD), recycling is defined as "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes" (EU, 2018). However, this figure does not always reflect the correct picture, that is, if the waste generation is reduced, amount of CDW recovered goes down as well, which implies the policies aren't effective. Another instance is if there is more energy recovery, it will lead to more emissions, thus offsetting the reduction achieved through recycling. Thus, to account for these nuances, two other ratio KPI's are also studied. They are **Total Recovery Rate**, which is the ratio between CDW recovered (recycling, reuse and roadfilling) and the amount of waste generated; and **Upcycling and Reuse Rate** which is the ratio between CDW upcycled and reused and the amount of waste generated.

5.4. Model Validation

Validation here is defined as "the process of establishing confidence in the soundness and usefulness of a model" (Forrester, 1980). Moreover, validation allows to investigate whether the purpose of the study was met. Because of the assumptions taken when building the model, it was necessary to validate the model. Validation and verification was done by performing several tests that would check for change in behavior of the model under extreme and changing circumstances. Tests of model structure included validating data from literature and a dimension check. Tests of model behaviour included extreme conditions test and a uni-variate sensitivity analysis. Extreme conditions test tests the model behaviour under extreme conditions. Sensitivity analysis was done by changing each exogenous model parameter and checking the impact on the KPIs. Sensitivity analysis helped understand better the relationship between input variables and the output. The validation process for this model can be found in Appendix Section B.3.

Results from the model validation

Model data was derived from literature wherever possible and the rest assumed. The choice of ranges for CDW flow at each step was heavily influenced by Deloitte (2015). For data validation, input data for material flows was corroborated with the study by Zhang et al. (2020). However, the life cycle inventory data used for carbon emissions could not be validated. Thus, this data could be considered low quality since it doesn't come from a primary database and may lead to high uncertainty in the results. Due to this, a sensitivity analysis was done for the emissions based variables.

Extreme conditions test was done for the variables - *Percentage change in CDW per year* and *Total concrete requirement*. The variables was chosen because they're assumed to be a constant value in the model (0 and 17000 kilotonnes/Year respectively), but they're subject to change in the future. The results showed that all the KPI's changed as expected for percentage change in CDW per year both under high and low values. As for concrete requirement, only the KPI's for total carbon emissions and upcycling and reuse rate were affected. It does not affect total recovery rate and total amount recovered. This is because concrete requirement affects the requirement for recycled aggregates and subsequently the supply. This either increases or decreases the upcycling rate in the same direction. It also affects the primary aggregates requirement through which emissions are also reduced or increased based on how much concrete is required.

The results from sensitivity analysis for material flow factors (the values were changed by +-10%) showed that the different KPI's were sensitive to different factors. Upcycling and reuse rate were most sensitive to the proportion going for recycling. Both total recovery rate and amount of CDW recovered were most sensitive to sorting efficiencies. Finally, total carbon emissions showed no big changes to the material flow variables. This gives insights into where in the system interventions are needed to affect particular KPI's. Univariate sensitivity analysis was then done for emissions based variables (the values were changed by +-5 kg/tonne). The results from the sensitivity analysis on carbon emissions showed that it's most sensitive to emissions from mining primary aggregates and least sensitive to emissions from upcycling. The KPI was second most sensitive to preprocessing emissions. This analysis gives insights into the factor that affects carbon emissions the most, which in this case comes from mining aggregates.

Observed changes in behavior of the model could be explained and are within reason. The model can be considered fit for the purpose of studying impacts of policies affecting CDW management in the Netherlands.

5.5. Experimental Setup to Test Policy Interventions

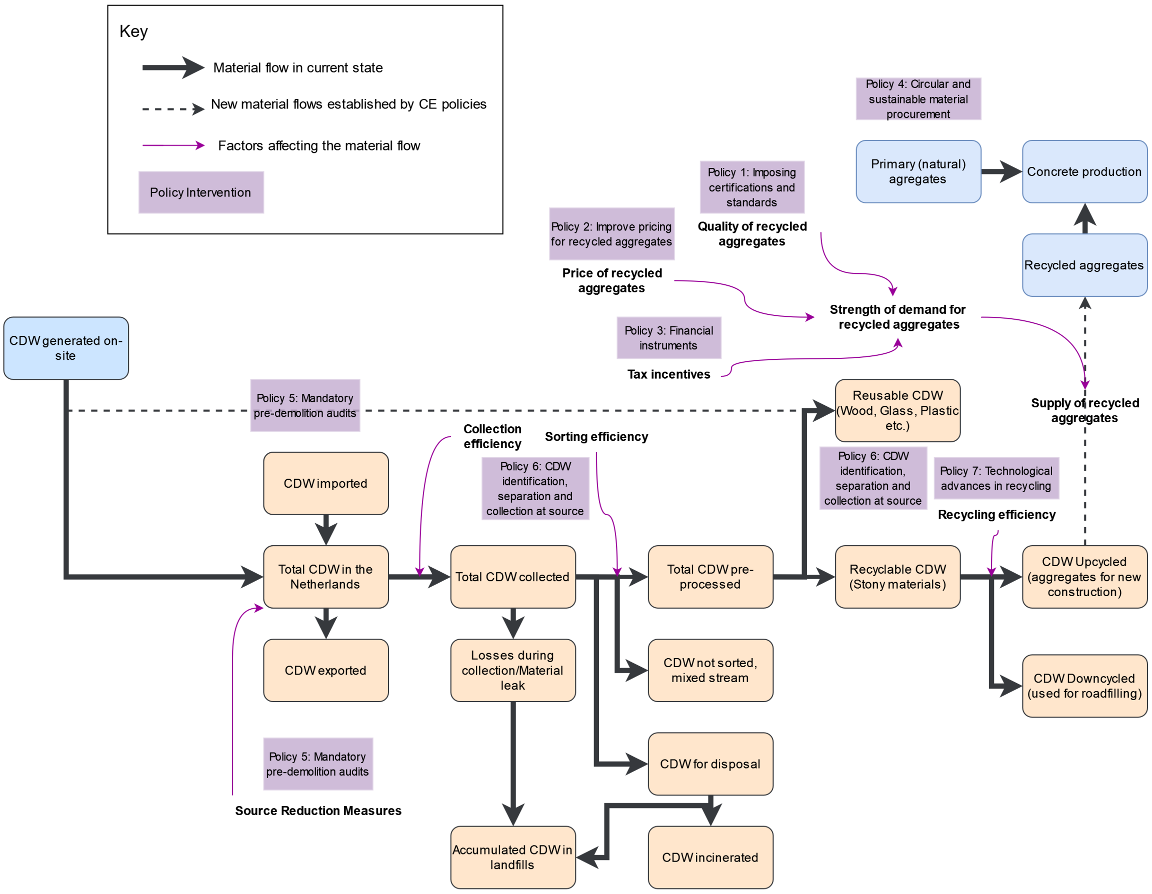
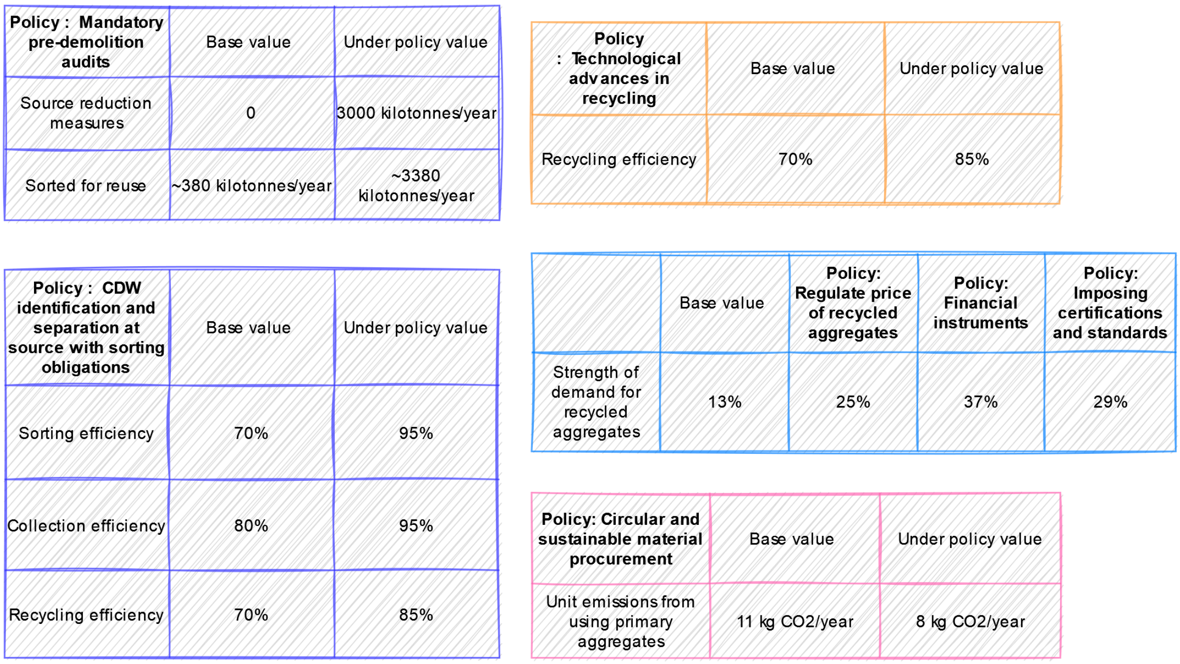


Figure 5.6: Placement of Policy Interventions in the system

After the model validation, effects of the policy interventions were ideated and implemented in the model. A first step towards this step is understanding where in the system do the interventions work. Based on the mechanisms as defined by the system diagram, the placement of policy interventions were designed which is represented in Figure 5.6. The baseline simulation of the model is done in the absence of any policy. The policy intervention setup is explained as below.

- Predemolition audits help reduce the waste at source and increase the chances of reusable waste being recovered. Due to this reason, predemolition audits reduce the CDW at source by a figure (assumed to be 3000 kilotonnes), and redirect it to reusable components.
- The policy of CDW identification and separation affects both collection efficiency and sorting efficiency. But this policy also affects technological advances in recycling as efficiency of recycling increases with better sorted monostream waste (increasing efficiency by 10%).
- Technological advances also affect the recycling efficiency by increasing it by 15% from 70% to 0.85% [2].
- Circular and sustainable procurement works by carbon offsetting emissions from mining primary resources. The effect of this policy is modelled as reducing the unit emissions from using primary aggregates from 11 kg CO2 to 8 kg CO2.
- Finally, improve pricing for recycled aggregates, financial instruments and imposing certification and standards affect the strength of demand for recycled aggregates through different percentages. The values for these could not be found from literature and were synthesized from the causal maps and the MCA table. Strength of demand for recycled aggregates was capped at 66% [3]. This was done because of the constraint placed on producing concrete currently that it cannot have all recycled content and needs to have some primary aggregates content (Interview 6). Given the current strength is 13%, this left 42% to be distributed among the policies. Based on the relative influence each policy had on the criteria (in Figure 4.12, the strength of demand increase on the base value was set as follows - improve pricing for recycled aggregates (12%), financial instruments (24%) and imposing certification and standards (16%).



Policy : Mandatory pre-demolition audits	Base value	Under policy value
Source reduction measures	0	3000 kilotonnes/year
Sorted for reuse	~380 kilotonnes/year	~3380 kilotonnes/year

Policy : Technological advances in recycling	Base value	Under policy value
Recycling efficiency	70%	85%

Policy : CDW identification and separation at source with sorting obligations	Base value	Under policy value
Sorting efficiency	70%	95%
Collection efficiency	80%	95%
Recycling efficiency	70%	85%

	Base value	**Policy: Regulate price of recycled aggregates**	**Policy: Financial instruments**	**Policy: Imposing certifications and standards**
Strength of demand for recycled aggregates	13%	25%	37%	29%

Policy: Circular and sustainable material procurement	Base value	Under policy value
Unit emissions from using primary aggregates	11 kg CO2/year	8 kg CO2/year

Figure 5.7: Model Policy Setup: This table highlights the factors who's values are changed to reflect the policy implications

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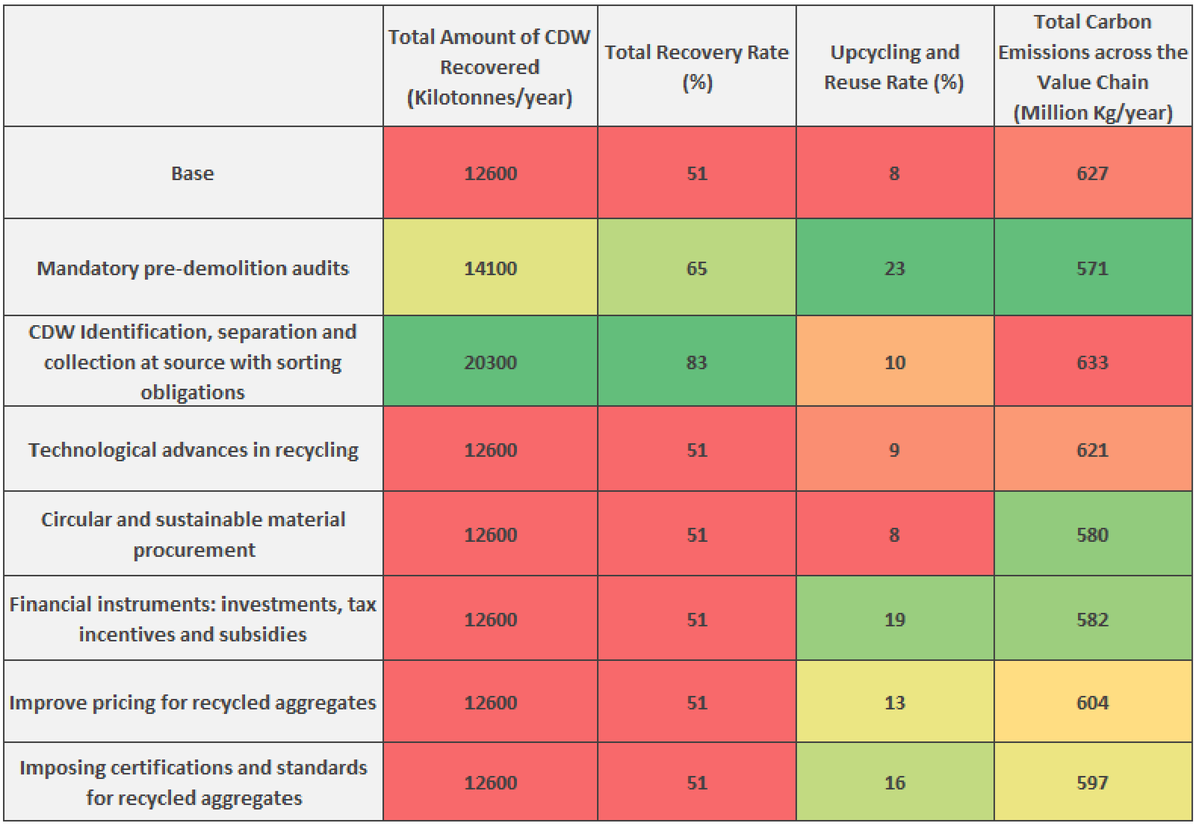
[2] Assumption based on the figures by (Deloitte, 2015) which places the efficiency of C2CA technology as 80%

[3] The study by (Verhagen et al., 2021) found that around 66% of the generated demolition waste can be recycled and implemented in the construction of new buildings at its EOL.

5.6. Model Results

5.6.1. Impacts from implementing one policy at a time

The first run of the model involved looking at the impacts of each policy at a time based on Figure 5.7 and capturing the results at a snapshot in time. The results on the KPI's were plotted into a heat-map and is given in Figure 5.8.



	Total Amount of CDW Recovered (Kilotonnes/year)	Total Recovery Rate (%)	Upcycling and Reuse Rate (%)	Total Carbon Emissions across the Value Chain (Million Kg/year)
Base	12600	51	8	627
Mandatory pre-demolition audits	14100	65	23	571
CDW Identification, separation and collection at source with sorting obligations	20300	83	10	633
Technological advances in recycling	12600	51	9	621
Circular and sustainable material procurement	12600	51	8	580
Financial instruments: investments, tax incentives and subsidies	12600	51	19	582
Improve pricing for recycled aggregates	12600	51	13	604
Imposing certifications and standards for recycled aggregates	12600	51	16	597

Figure 5.8: Model Run Results: Implementing one policy at a time. The table is in the form of a heat map where the values in each column are colour coded in relation to the base value. Red represents low desired change, while green represents high desired change.

The policy which performs the best for total amount of CDW recovered and total recovery rate is **CDW identification, separation and collection at source with sorting obligation**. However, it doesn't increase the upcycling and reuse rate and increases the total carbon emissions across the value chain. This is because although this policy increases the total amount of CDW recovered, it doesn't focus on high-quality recovery for upcycling. This means that most of the recovered waste goes into road-filling as in the current scenario instead of being a primary material substitute, so there's no saved emissions from not using primary aggregates. The increase in emissions is from processing an increased amount of waste.

The policy that results in the highest upcycling and reuse rate and the highest carbon emissions reduction is **Mandatory pre-demolition audits**. This is because it not only focuses on source reduction, but also increases reuse by ensuring there's enough time for components to be reused. It also has a positive effect on amount recovered and total recovery rate, second only to CDW identification and source separation.

Circular and sustainable procurement also reduces emissions compared to the other policies but it does not have any effect on the other criteria. **Technological advances to recycling** barely increases the upcycling and reuse rate or reduces emissions significantly.

Finally, **financial instruments** affects positively upcycling and reuse rate and the total carbon emissions across the value chain. It does not affect the amount recovered or the recovery rate, but works at redirecting flows which reduce emissions. Same goes for even **improving pricing** of recycled aggregates and **imposing certifications and standards** on them. Even they work on redirecting the flow from downcycling to upcycling and play a role in reducing overall emissions by offsetting emissions due to mining primary aggregates.

An observation that comes out of this result is that recovering more waste on its own will not be helpful in long run unless it's redirected towards low carbon usages. Knowing this, it would be good for the Government to have a strategic direction and combine policies for a net positive effect on the criteria. In the next section, strategies are based on how the policies work and they're combined logically to study the net effects of it on the criteria.

5.6.2. Impacts of combining and clustering policies

Combining several policies into clusters help provide a strategic focus and direction towards reducing consumption of primary materials and reducing carbon emissions. In this section, three strategies are formed - **Efficient supply chain, Prioritizing closed-loop recycling and implementing all 7 policies together**. The first strategy is modelled on the basis of the location of the supply chain where it affects, thereby increasing the efficiency of the process. The second strategy is all about increasing the share of recycled CDW that goes back in new construction, thereby prioritizing closed-loop recycling. However, for both scenarios, it is assumed that circular and sustainable procurement should be undertaken. The final strategy is one where all the policies work in harmony. Figure 5.9 summarizes the results from implementing policies strategically.

	Total Amount of CDW Recovered (Kilotonnes/year)	Total Recovery Rate (%)	Upcycling and Reuse Rate (%)	Total Carbon Emissions across the Value Chain (Million Kg/year)
Base	12600	51	6	626
Scenario: Efficient supply chain Mandatory pre-demolition audits + CDW Identification, separation and collection at source with sorting obligations + Technological advances in recycling + Circular and sustainable material procurement	21000	97	26	526
Scenario: Prioritizing closed-loop recycling Financial instruments: investments, tax incentives and subsidies + Improve pricing for recycled aggregates + Imposing certifications and standards for recycled aggregates + Circular and sustainable material procurement	12600	51	33	502
Scenario: All policies implemented together	21000	97	65	420

Figure 5.9: Model Run Results: Implementing multiple policies at a time under 3 strategies. The table is in the form of a heat map where the values in each column are colour coded in relation to the base value. Red represents low desired change, while green represents high desired change.

Efficient supply chain saw a significant increase in amount of CDW recovered, and it increased the total recovery rate to 97% [4]. Carbon emissions reduction for this scenario was 100 M kg CO2. It should be noted however, that without the implementing closed-loop recycling, majority of this recovered material may be downcycled and go to civil and infrastructure works. This explains why the upcycling and reuse rate increase to only 26%.

Prioritizing closed-loop recycling led to no change in material recovery or recovery rate, but led to significant carbon emissions reduction from 626 to 520 M CO2, which is a reduction of 106 M CO2. Upcycling and reuse rate increased to 33%. But compared to efficient supply chain scenario, the change in upcycling and reuse rate and carbon emissions is not a lot.

Finally all policies were implemented together, which led to positive effects on all criteria. Implementing all the policies together also led to a recovery rate of 97% and a carbon emissions reduction of 206 M C02. Furthermore, it increased the upcycling and reuse rate from a previous under 6% to above 48%. From the results comparing impacts of single policies and clustered policies, it is highly recommended to cluster policies to have a higher impact.

5.7. Comparison of results with literature

In this section, model results from this study was compared to other studies which provide insights into probable ranges. However, the studies available to compare were limited to 2. This was due to contextual differences across studies such as geographical location, system scope and type of intervention used (technological as opposed to policy).

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[4] This involves only reusing, upcycling and roadfilling and do not involve incineration or landfills

From the model run, without any policy intervention, the recovery rate (through roadfilling, upcycling and reusing) was found to be around 51%. This is comparable to the scientific literature on the average figure for CDW recycling rate which is 46% based on a TU Delft study (Lotfi et al., 2017). The difference between the studies however is the former focuses on the Netherlands, and the latter is for entire EU-27 countries.

Results from another Netherlands based study by Zhang et al. (2020) shows that the development of cost-effective technologies has the potential to improve the share of upcycling in the Netherlands from around 5% in 2015 up to 22%–32% in 2025. In this research, maximum upcycling and reuse rate observed was 23% which was achieved by mandatory pre-demolition audits. Thus the maximum upcycling and reuse rate is well within the boundaries set by Zhang et al. (2020).

6

Conclusion

This chapter compiles the main findings of this research to answer the research sub-questions and eventually the main research question. Thereafter, policy recommendations for implementing circularity in the construction and demolition waste sector are discussed. This is followed by highlighting the key limitations of the study. Lastly, the scientific and social contributions of this research are discussed.

6.1. Addressing the research questions

SQ1. What are the gaps, barriers and opportunities in transitioning to a circular economy in the construction waste sector?

To answer this sub-question, literature delving into existing CDW practices in the Netherlands and expert interviews were referred. Analytical tools used which helped structure the knowledge were means-ends analysis and actor analysis. Semi-structured interviews with experts included industry representatives from BRBS Recycling and Renewi; and academic experts who are active in this field (Section 2.2.2). Additionally, policy directives and EU waste management protocols were also consulted.

Three main gaps were found in the current CDWM system in the Netherlands -

- Quality and performance of recycled and reused products are unknown
- It is difficult to retain the value of construction materials at the end of their life
- Efficiency of reusing and recycling CDW components is unknown

For each of these gaps, barriers which prevented filling the gap were identified. Based on the gaps and to overcome the barriers, opportunities were identified. This method provides to The opportunities were corroborated to be line with EU's Construction and Demolition Waste Management Protocol (European Commission, 2018). The gaps, barriers and opportunities are summarized in Section 3.3.

The first main gap found was related to uncertainty regarding the quality and performance of recycled products. This is made difficult by a lack of trust and hesitancy to use recycled aggregates in construction. A circular opportunity here would be to ensure the quality and stimulate demand for recycled aggregates and eventually phase out the need for using primary aggregates entirely. Specific policy interventions that the Government could undertake to help this are 1. Improve pricing of recycled aggregates, 2. Imposing certifications and standards, 3. Providing financial help such as tax incentives and subsidies and 4. Ensuring only circular and sustainable procurement of primary aggregates.

The second gap found was difficulty in retaining the value of construction materials at the end of their life especially during demolition. A barrier which severely restricts value retention is the time given to demolition. This could be rectified by demolishing companies with the Government's help through enforcing a strict pre-demolition audit with time constraints. This would allow them to prioritize reuse and remove construction materials in a systematic manner.

Finally, the third gap identified is that the efficiency of recycling CDW components for high-quality usage is not known, which is why most waste ends up being downcycled. A barrier to this is keeping the CDW mono-stream, clean and uncontaminated. This could be overcome by policy measures such as 1. CDW identification, separation and collection at source with sorting obligations and 2. Technological advances for recycling could also help keep CDW largely mono-stream and clean and also make the whole process more energy and process efficient.

The answer to this sub-question helped provide a snapshot of the gap between the current system and a circular future system. It also highlighted what concrete actions could be taken to bridge the gap.

SQ2. What are the key criteria that should be taken into account to design effective circular economy policies for CDW management?

The answer to this sub-question forms a framework against which the policy alternatives can be compared and contrasted. Till now the EU has used the criterion of "Percent of CDW Recovered" to establish the degree of circularity in CDWM sector. Even though the Netherlands is leading in construction waste recovery, this can be misleading because it does not take into account the carbon emissions that goes into recovery processes or the loss in the value of material once it's downcycled. A multi-criteria framework based on environmental, financial and social consequences was synthesized for the context of this research

To identify criteria important to the client, the Ministry of IWM, and to the supply chain actors, their interests and objectives were mapped out (Section 3.2.2). Insights for recycling companies, waste management companies and demolishing companies come from the interviews while for the other actors, it was synthesized from existing literature. Common themes from their objectives that were repeated more than once were identified. They were low costs, low amount of CDW generated, low carbon emissions and high amount of CDW recovered. Apart from that the objectives of the client was also included - new jobs created and low raw materials extraction. These criteria were segregated broadly into environmental, financial and social objectives (Section 4.1).

Environmental criteria based on materials should not only include the amount of waste recovered but also the amount of waste generated and the amount of waste upcycled or reused. Recovery rates do not signify the amount of high-quality recycling or closed-loop recycling that is happening. Moreover, despite of how much of the waste is being recovered, it leads to carbon emissions during processing. Carbon emissions should thus be considered an important criteria to decide between policies. Raw material extraction is another factor that should also considered to prevent a potential resource scarcity in the future and to ensure that secondary materials are used as substitution wherever possible.

On the socioeconomic side, labour concerns such as fair wages, career prospects, job security, and fair working conditions should be acknowledged. In the Dutch context, it should be ensured that new policies in the recycling/waste management sector lead to new jobs that follow high labour standards.

Lastly, financial criteria like costs to the Government and costs to the actors should also be considered. Most policies require a pre-implementation investment. The criterion of costs to Government offers insights into which policies are worth investing in, and which ones may yield a return on investment. Considering costs to other actors should be considered because it offers insights into how willing the actors are to accept a policy change. In this research, costs to the other actors was expressed as CDW management costs, which should be kept as low as possible.

Based on this framework, a recommendation for designing effective waste management policies for circular economy in a multi-actor situation from this study would be to include not just recovery indicators as criteria, but also carbon emissions, raw material extraction, costs of policy implementation, and high-quality material recovery indicators (like upcycling and reuse rates).

SQ3. What are the effects of potential policies on the key criteria

To answer this sub-question, a system diagram was made which investigated the policy measures identified in the first sub-question and their effect on the key criteria identified in the second sub-question. The system diagram is discussed in detail in section 4.3.
The 7 policies that were studied are -

- Pre-demolition audits
- Technological advances for recycling
- Circular and sustainable procurement
- Financial instruments (tax incentives, subsidies)
- Price regulation of recycled aggregates
- Certifications and standards for recycled aggregates
- CDW identification and separation at source with sorting obligations

Causal maps were made for each policy. Causal mapping as a technique helped to capture information gathered that surrounded the complex situation. Causal maps for all the policies were combined into a system diagram. From the system diagram, a qualitative consequences table in the form of a multi-criteria table was synthesized. This can be found in detail in Section 4.4.1. It was found that not all the policies affect all the criteria. However, amount of carbon emissions stood out as one criteria that all the policies contributed to (with both desirable and undesirable impacts). The next criteria which was affected by 6 of the 7 policies was costs to Government, which also had both desirable and undesirable impacts. Amount of CDW recovered was affected by 5 policies, however, in this case, all of them were desirable impacts, that is, the policies were able to increase the amount of CDW recovered. Only three policies had a positive impact on jobs. They were financial instruments, CDW source separation and technological advances in recycling.

Finally, some impacts were ambiguous. For instance, for circular and sustainable procurement, there is a positive effect on emissions as it offsets C02 by introducing natural and recreational areas, as well as a negative effect due to more emissions from land use conversion. The net impact thus, is not known. This is a drawback of this multi-criteria analysis and in such cases, it is difficult to determine the effects of policies on the criteria. Nonetheless, the system diagram and the multi-criteria table presents the information in a format which makes it easy to explore causal pathways, study impacts of policy on the criteria at a glance and allows to check for trade-offs.

What policies can the Dutch Ministry of Infrastructure and Water Management use to stimulate a circular economy transition in the construction and demolition waste management sector

This sub-question is answered with the help of a material flow model based on construction and demolition waste management. The policy interventions identified were experimentally set up to study their individual and combined impacts. The setups are discussed in detail in Section 5.5 and the outcomes of the experiments are discussed in Section 5.6. The impact of the policies are observed through changing the factors which affect the material flow. This section answers the question based on simulation runs from the model. Seven policies were evaluated against four criteria - total amount of CDW recovered, recovery rate, upcycling and reuse rate and total carbon emissions across the value chain.

First the impact of individual policies was studied. The results of this can be found in Section 5.6.1. The model results showed that there's no one policy that has the highest effect on all the criteria. However, implementing pre-demolition audits has a positive effect on all the criteria. It increases the recovery rate from 51% to 65% and the upcycling and reuse rate from 8% to 23% which was the highest among all policies tested. The reason for this is because predemolition audits works on source reduction and prioritizes reuse by redirecting material flows (as opposed to other policies which prioritize recycling). CDW identification, separation and collection at source performed the best in total amount recovered and total recovery rate. It increased the total amount of CDW recovered by 7700 kilotonnes/year and the recovery rate to 83%. However, it only increased the upcycling and reuse rate to 10%. And surprisingly, it was the only policy that increased the amount of carbon emissions (by 5 million kg/year).

If the priority is on upcycling and reuse and reducing carbon emissions. the Government can also alternatively use financial instruments, improving pricing for recycled aggregates or/and imposing certifications and standards for them. Although they do not affect the material recovery they do affect the other two criteria. A combined effect of policies were also studied using scenarios. Three scenarios were created - an efficient supply chain, prioritizing closed-loop recycling and one where all 7 policies were implemented together. The details for the scenarios are given in Section 5.6.2. The results from the scenario analysis showed that combining policies result in a much higher impact on the four criteria than implementing policies on their own. If budget allows, it is highly recommended to cluster and implement policies together at the same time as they complement each other.

Rather than a clear answer, a salient question that comes out of this research is what do we consider more important while making policy decisions; if it is reducing the amount of waste generated or making sure whatever waste is generated ends up being completely recovered. This research proves that no matter how efficiently we recover waste, even if 100% of all materials are recovered, the processes that they go through will undoubtedly result in emissions. In the future, maybe this recovery process itself can be more green by using clean and renewable energy. The Dutch Government and even the European Union uses the measure of CDW recovered to signify circular economy. A recommendation would be that they should also include carbon emissions as a measure.

6.2. Policy Recommendations

A policy recommendation from this analysis would be to implement mandatory pre-demolition audits as it came out to have the most positive effect on all the criteria (and highest in upcycling rate and reducing carbon emissions). Predemolition audits refer to a tool which enlists and assesses all materials (and their potential value) within a building prior to demolition. They enable all stakeholders to get information on the composition of waste and makes it easier to find markets for different waste types. Although pre-demolition audits need to be carried out by demolishing companies, the Government can help by enforcing this as mandatory to be undertaken before any demolition activity. Enforcing it is necessary because otherwise it will be tough to get ti accepted by clients.

CDW identification, separation and collection at source is also recommended to be implemented since it results in the highest recovery of materials. It refers to making sure that after demolition or any construction or renovation activities, the different categories of waste are identified and sorted into relevant composition at the source itself and then handed to different recyclers who can handle it better. A way to do this would be appointing waste experts and sorting machines on site. This works in multiple ways - it first reduces the possibility of contaminants (lead, mold, asbestos etc.), it reduces the efforts and transportation required to sort and process it further and finally it also creates new jobs of waste auditors. This is also a measure that can be implemented by demolishing companies. However, similar to predemolition audits, implementing this would require more time and space.

A final policy recommendation that came out from this study is that policies that focus on recovering more waste on its own will not be helpful in long run unless it's redirected towards low carbon usages. Thus, they could be clustered with policies that prioritize reuse and upcycling for these recovered waste.

6.3. Limitations and Recommendations for further research

The results and recommendations of this study should be interpreted keeping in mind the assumptions undertaken as mentioned in Section B.4. Following are the main limitations of this study.

- The scope of the system included only waste management activities. This reduced the chance of exploring other waste prevention and reduction strategies during construction and operational phase of buildings. Although this doesn't affect the validity of the results, this may only paint the partial picture and limit the possibilities of reducing more carbon emissions. For instance, pushing for renovation instead of demolition. As identified in the means-ends analysis (Section 3.1.1) as a potential solution, the future scope of the system under study could also include circular construction and design and changing consumption and production behaviours.

- The actor analysis assumed interests and objectives of actors based on literature and interviews. This could have been alternatively done in a workshop format where the actors would be asked to rate the objectives that are most important for them firsthand. This would ensure that there's no analyst bias. In this research, the multi-criteria analysis was done without weights. Stakeholder inputs would also help validate the multi-criteria analysis and provide more insights into differences in actor perceptions.

- The level of aggregation chosen for processing of CDW composition is an assumption based on the highly dominated composition of stony materials. In reality, there there are other materials such as insulation materials, paper, steel etc. which make processing of CDW difficult and not straightforward.
- The current model only studies the impacts on material recovery and carbon emissions. It would be useful to include the other identified criteria such as costs and jobs into the model. This would make the model into an integrated tool which can calculate multiple impacts at once.
- Another major limitation of the model is in the quality of waste data used. Latest figures on CDW traceability are lacking especially in the last decade. Therefore, the model is built on the basis of data from 2010.
- The actor-network scan performed in this study is quite generic. Business relationships between concrete producers and primary aggregate producers or between recyclers and civil works are built over decades. Social dynamics like this is quite difficult to pinpoint in a research like this.
- The socio-technical system adapted in the model is an abstraction of reality and may not necessarily reflect the complex system in its entirety. The model is conceptualized to calculate the impacts of policies and is thus in equilibrium. It follows a non-dynamic linear patterns instead of incorporating non-linear behaviors such as feedback loops and delays. The next iteration of this model could include non-linear behavior to better represent reality.
- The model results are based on a snapshot in time. It assumes that the effects of policies are instant. To see the effects of policies may take years and constant monitoring and feedback. This is currently non represented in the model. Future scope could include certain delays on policies and study how they evolve over time.

6.4. Research contribution

Exploring pathways of circular economy in waste management will help bring synergies in both fields. Adding to the scientific literature on CDWM, this research provides both a mix-method approach based on systems analysis and a material flow model to assess policy impacts. Materials flow analysis models have traditionally been used to track the production, use, and consumption of materials. From an academic perspective, this study integrates a partial life-cycle assessment into a material flow analysis by adding carbon emissions to the material flow model. The mix-methods approach used can also be adapted to other value chains with a similar supply chain background. It also contributes to future application of an integrated material flow based model for built environment and infrastructure based decision making and resource-efficient waste management planning.

On the social side, few recent studies in policy design have grappled with issues such as overcoming historical policy legacies or issues around policy formulation and the nature of ‘design’ in policymaking (Howlett, 2017). These studies have also begun to establish insights into what makes a policy design ‘effective’ or likely to succeed in being adopted and accepted. By synthesizing and using a multi-criteria framework to calculate potential impacts, this research adds to this growing literature in policy design.

The impact assessment as done in this study could be very useful to researchers and the Government alike. A similar study is currently being developed as a monitoring system to map both the transition to and the effects of a circular economy in the Netherlands by a consortium of researchers, directed by PBL (Potting et al., 2018). In addition, they are also developing calculation models that can be used to analyze possible paths to the circular economy goals and to analyze the effect of various policy choices.

This research was done in collaboration with Inclusive Wise Waste Cities (IWWC) initiative, a collaboration between universities in the Netherlands and China and will contribute to the theoretical framework being developed to map inclusive wise-waste systems (Erasmus University, 2022).

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A

Problem Formulation

A.1. Interview Guide for Semi-structured Interviews

1. **On CDW management system in the Netherlands**
    - What is the starting point? What are the sources of CDW waste?
    - What are the processes involved for collection or processing?
    - What are the high impact waste streams – usual level of aggregation found in literature is CDW. But what about specific waste streams in CDW – concrete, minerals, sand, gravel?
    - Waste Processing Differentiation – Reuse, Recycle, Recover. Deep dive into the processes
2. **On the Waste Trade and the global context**
    - Do we import construction materials? If so, which and from where? If not, how are they procured in the Netherlands?
    - Is any of the CDW waste exported either in or outside EU?
3. **On Construction**
    - Do you use a lot of secondary materials in existing construction projects in the Netherlands? Why not?
    - What are the differences when using recycled materials vs virgin materials for construction?
    - Of all the materials used for a construction project, what might be the rough ratio between primary and secondary material sourced? What are the factors it depends on? (Type of project, scale etc.)
    - Does it make sense to say that the construction sector may benefit from a circular economy? If so, how?
    - What are the innovations on the design side happening for construction material/building structure which might make it easier to disassemble/reuse or recycle?

4. **On Circular Economy**
   - In the current scenario, what does CE mean for the construction sector? Why is it considered important? What about the future scenario?
   - Identifying Leverage Points – what do you think will have the biggest impact?
   - What might be a good criteria/KPI to measure circularity in the construction context?
5. **On recycling and reuse**
   - What does the recycling/reuse CDW process look like?
   - What factors or constraints affect the process of recycling/reusing CDW?
   - What are the inflow and outflow for recycling?
6. **Social Impacts**
   - To the best of your knowledge, what might be the social impacts of CDW in the Dutch context?
7. **Miscellaneous**
   - Are there any specific papers/data sources/websites you would suggest for more information?

B

Model Documentation

B.1. Assumptions and limitations

This section outlines all the assumptions taken for building the model. Most of these assumptions are checked for in the model validation section.

Data availability

CDW traceability and the latest figures are lacking especially in the last decade. Therefore, the model is built on the basis of data from 2010. An assumption looking at past trends is made that CDW trends don't change dramatically due to the conventional nature of the construction sector. However, this may not be true since after the ruling for circular economy and the increased focus after 2015 (CEAP, concrete agreement etc.), there may be changes in the past trends. There is a need for latest figures on CDW management to be readily available. For the model, behaviours such as CDW generation (at 25 million kilotonnes/year) or concrete requirement (at 17 million kilotonnes/year) is represented as a static value, which in real life is not the case as these might be affected by different factors. But apart from minor differences, the trend for CDW management has been quite uniform in the last decade which is even more reason for a policy reform in the entire sector.

Material Flow Composition and data aggregation

The level of aggregation chosen for processing of CDW composition is an assumption based on the highly dominated composition of stony materials. The current aggregates involves 3 divisions -reusable CDW (which includes wood, glass, plastic etc.), recyclable CDW (which includes stony materials such as cement, concrete, sand, gravel etc.) and CDW to be disposed (which may include contaminated or difficult to recover waste types). Other materials such as gypsum, PVC or asphalt which have a much lesser presence is not considered. Furthermore, they may need different recycling methods than for concrete.

Environmental Impacts

The last section on system diagram saw all environmental, social and economic criteria being considered. However, in this model, only the environmental criteria are calculated. This is because getting values of costs and the market prices was difficult to get since CDWM is a private sector and is highly subject to market fluctuations. The interviewees were unable to provide an answer to the cost difference between primary and secondary aggregates. This is also complicated by the fact that business relationships between concrete producers and primary aggregate producers or between recyclers and civil works are built over decades, which also influence the prices. Thus the price is considered as an implicit factor in ”Strength of demand of recycled aggregates”, rather than externalising it. On the social side, to calculate correctly the effect on jobs, economic models such as Input/Output or E3ME would need to be integrated. This was done by a study by Hawkins et al. (2007). This is part of future research work where economic models can be integrated into material flow analysis.

Non-dynamic nature of the model

This model is conceptualized to calculate the impacts of policies and is thus in equilibrium. And because of this, it is rather simple and follows a non-dynamic linear pattern instead of incorporating non-linear behaviors such as feedback loops or delays. Another reason for this is because it looks at the numeric values rather than behaviors or patterns. The next iteration of this model could include non-linear behavior to better represent reality.

Preference for policies based on recycling rather than reuse

In this research, more policies are formed around recycling and upcycling, rather than prioritizing reuse. This was based on the assumption that was gathered during the interviews that due to the nature of construction materials, reuse is not always possible but recycling almost always works. An example given for this is that, in earlier time, specified door or window frame sizes were different than the measurements now, because of which, entire door/window structures cannot be reused currently (Interview 6). The process of reusing often begins during product design and development and this landscape is also slowly changing, and stakeholders are realizing the potential of keeping the value of materials intact through reusing. But it will take some time before reuse is prioritized in the construction sector. Furthermore, construction relies on localized styles, preferences, technologies, regulations, and traditions etc., which may vary greatly and influence reusing.

Single cycle recycling

Another assumption this research uses is that all materials here are considered only for single cycle recycling instead of multiple cycles. This is because often building materials can stay for 50-75 years before being demolished. Due to this time frame, multi-cycle recycling has not been studied.

B.2. Modelling in Vensim

The model which was made in Vensim is made open source and can be found on Github. The screenshot of the the final model is represented in Figure B.1

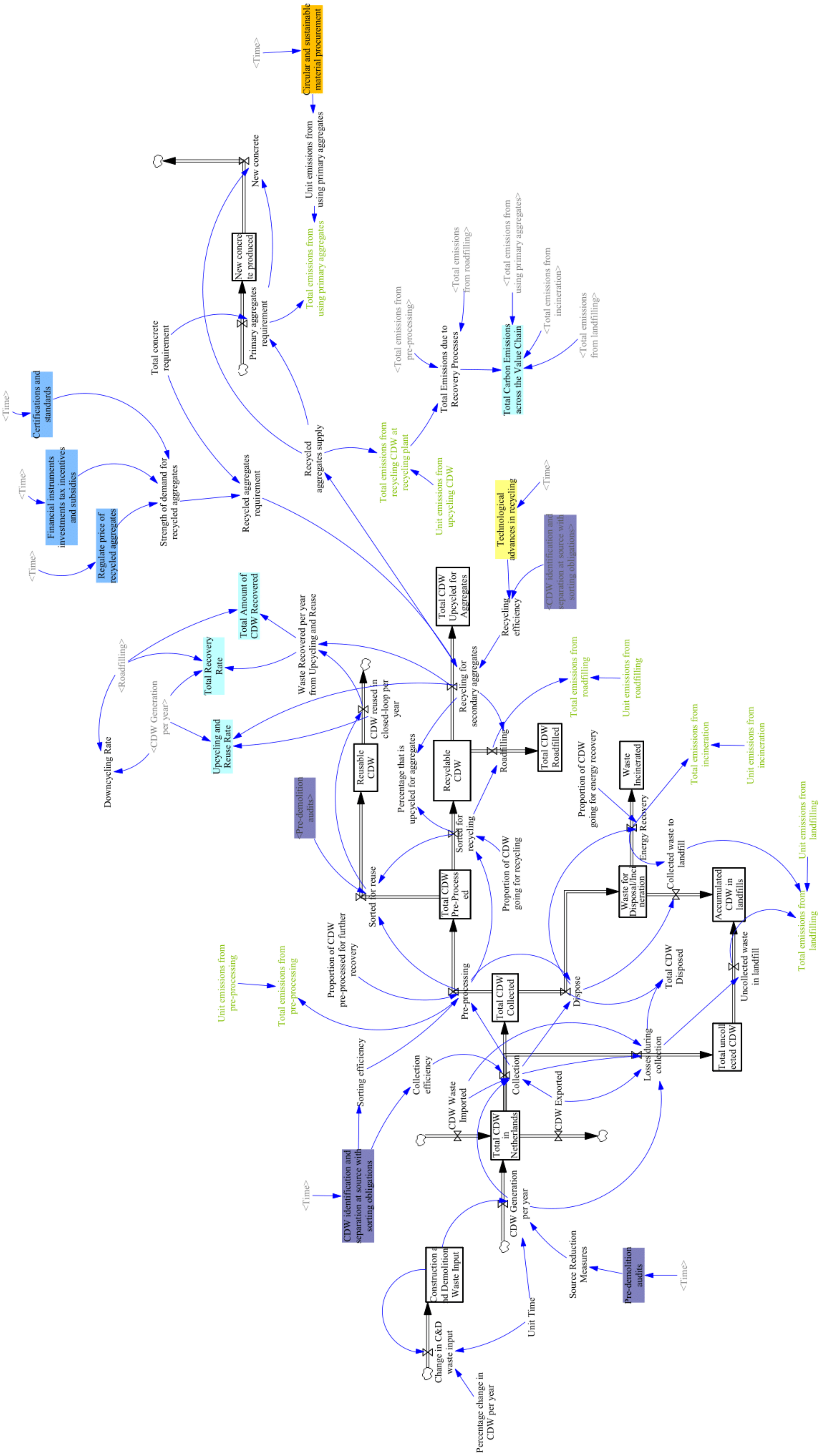

Figure B.1: Screenshot of the model in vensim

B.3. Model Validation

B.3.1. Model Data Validity

Model data was derived from literature wherever possible and the rest assumed. The choice of ranges for CDW flow at each step was heavily influenced by Deloitte (2015). But this data was corroborated with the study by Zhang et al. (2020) to get a general idea. Data from EU was disregarded due to it including dredging spoils which is not included in the scope of this study. The life cycle inventory data used could also be considered low quality since it doesn't come from a primary database and comes from other research, leading to a high uncertainty on the results.

Current data of CDW generation in the Netherlands for the last few years is missing, and hence looking at past trends the biggest assumption is that the amount of CDW has more or less remained constant at 2.5 million tonnes per year. CDW stream was projected to rise to 3.1 Mt in 2021 by a study done by Ministerie van Infrastructuur en Milieu in 2014, which is a 24% increase, but this couldn't be validated and thus was not used. It is difficult to consider the model data used to be from good reliable sources, and there are gaps and uncertainties. It is required to run a sensitivity analysis to check the effects of this.

B.3.2. Dimension Check

Unit or dimension checks are done to ensure that the model units are consistent with real-world units. The units were first compared with the real-world equivalent for instance, material flow (kilotonnes/year), stocks (kilotonnes), emissions (carbon equivalent in kg) to make sure they are the same. Then the model variables were also checked if the unit on the left hand side of the equations are equal to the unit on the right hand side. Vensim's® "dimensional/unit consistency check" was used to verify the model units. The dimensional check adheres to the guidelines of Forrester's test (Forrester, 1980).

B.3.3. Extreme Conditions Test

Variables have a practical or probable range. This creates a limitation in the model, where a variable may be outside its practical numerical range, but still inside the domain of all that is possible, although statistically improbable. This creates the need to test model behaviour at extreme conditions. This type of testing has been referred to colloquially as "black swan event" testing (Hume, 1739). Due to the scope of the model, it is not possible to do it for every variable. A variable of interest was "Percentage change in CDW per year" since it influences the initial flow of CDW generation on which the entire model is based on. This variable was chosen firstly, because it remaining constant is based on assumptions, hence an extreme value to the model - value increasing or decreasing by a 100% a year may well be an improbable but possible. Secondly, as the variables are input parameters, the model is most sensitive to these variables, therefore testing the most extreme fluctuations. Another variable which was tested for is the total concrete requirement. This was chosen because current value is fixed at 17000, but this can change in the future depending on the requirement for biobased materials.

Table B.1: Setup for extreme conditions test

Test	Variable	Base value	Low value	High value
Extreme Value Test	Percentage change in CDW per year	0	-1	1
Extreme Value Test	Total Concrete Requirement (kilotonnes/Year)	17000	10	260000

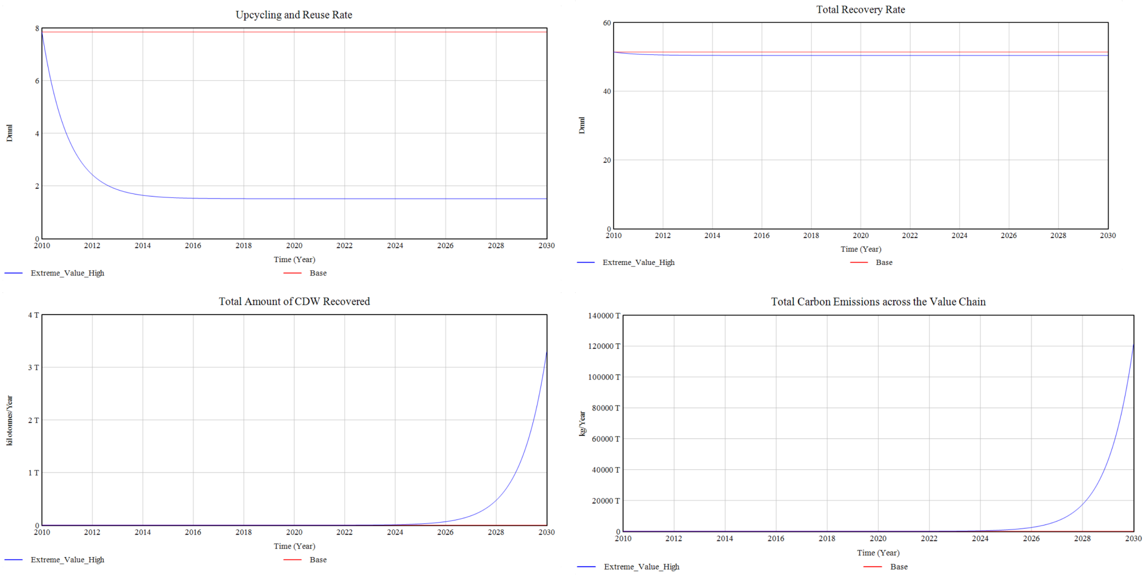

Figure B.2: Extreme condition test: High value for Percentage change in CDW per year at 1

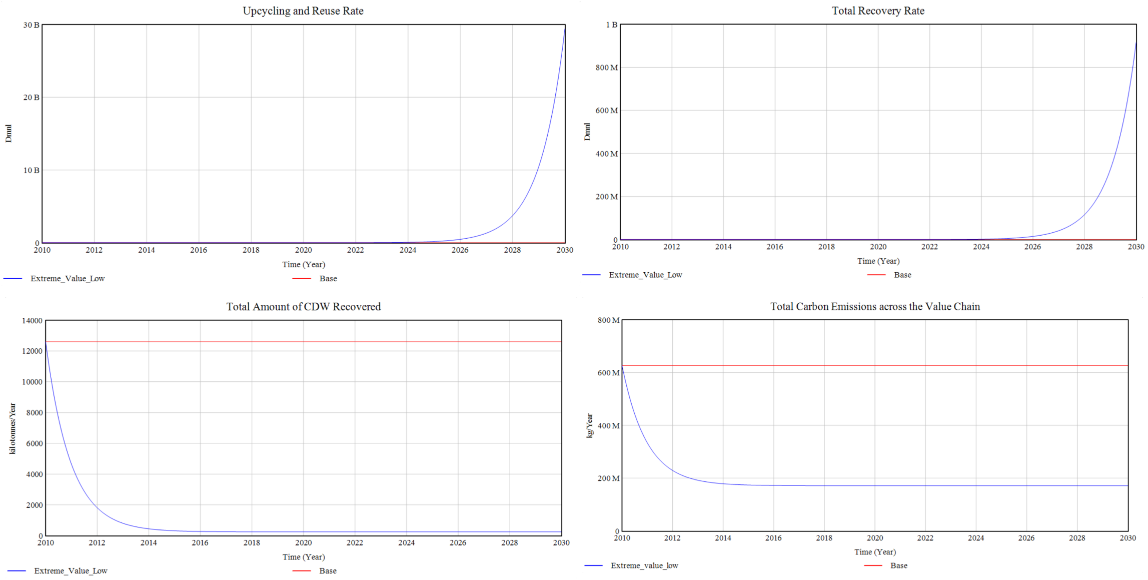

Figure B.3: Extreme condition test: Low value for Percentage change in CDW per year at -1

The results from the extreme high value for percentage change in CDW showed an exponential increase in amount recovered and emissions which is to be expected. Same goes for the results from extreme low value showing a steep decrease in the amount of CDW recovered and carbon emissions. However, for the KPI of total recovery rate remains the same for high value. This can be attributed to the fact that under the base case, recovered CDW increases linearly with CDW generated. This reinforces the fact that only having recovery rate is not helpful and doesn't tell us much.
The graph for upcycling and reuse rate for extreme high value shows a downward trend, because the value for upcycling and reuse (unlike total amount recovered) is not increasing linearly with the amount generated which is in the denominator. The graph for total recovery rate and upcycling rate

for extreme low value shows an upward trend. This is due to the fact that for both, the denominator (which is amount pf CDW generated) becomes extremely small.

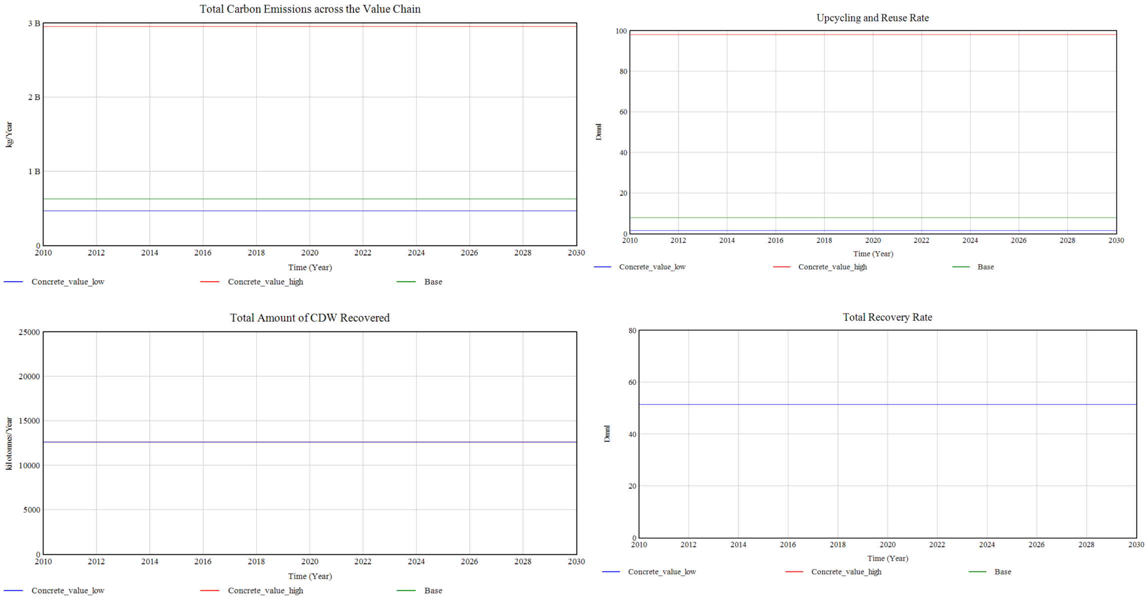

Figure B.4: Extreme condition test: Low and high values for Concrete requirement

Low and high values for concrete requirement is set as 10 and 260000 kilotonnes (this figure is based on the total material requirement in the Netherlands (CE Delft, 2015)). The results from the extreme high value for percentage change in CDW showed that change in concrete requirement only affected total carbon emissions and upcycling and reuse rate. It does not affect total recovery rate and total amount recovered. This is because it affects the requirement for recycled aggregates and subsequently the supply, which either increases or decreases the upcycling rate in the same direction. It also affects the primary aggregates requirement through which emissions are also reduced or increased based on how much concrete is required.

B.3.4. Sensitivity Analysis

As the model assumes a lot of relations, it is relevant to test how different values, which are used in different parameters or equations influence the outcome of the overall model and, hence, cover for the uncertainty inherent to these values. Sensitivity analysis is done here by changing each exogenous model parameter and checking the impact on the KPIs. Sensitivity analysis helps understand better the relationship between input variables and the output, tests the robustness of the system under uncertainty, and also helps find errors in the model due to unexpected behaviors or values.

Univariate Sensitivity Analysis for material flow factors

Table B.2: Setup for univariate sensitivity analysis

Test	Variable	Base value (%)	Low value (%)	High value (%)
Univariate Sensitivity Analysis	Collection efficiency	0.8	0.7	0.9
	Sorting efficiency	0.7	0.6	0.8
	Proportion of CDW pre-processed for further recovery	0.9	0.8	1
	Proportion of CDW going for energy recovery	0.67	0.57	0.77
	Proportion of CDW going for recycling	0.97	0.87	1
	CDW Imported	710	210	1210
	CDW Exported	232	0	732

First the univariate sensitivity analysis was done for material flow variables as defined in Table B.2. The values were changed by +-10% and the effects on the KPI was checked. The univariate sensitivity analysis helps investigate to which factor the model is most sensitive to. The results showed that different KPI's were sensitive to different factors. The results are displayed in Figure B.6.

For instance, upcycling and reuse rate were most sensitive to the proportion going for recycling. However, it was counter-intuitive. That is, upcycling and reuse rate increased the most when recycling proportion was low and vice versa. The reason for this is because the flow of reusable materials is assumed to be dependent on the flow of recyclable materials in the current state. When proportion of recyclable material flow decreases, the proportion of reusable materials increases. Furthermore, contrary to the waste hierarchy which prioritizes reuse rather than recycle, in the CDWM system however, recycling is currently prioritized. Mandatory pre-demolition audits is one tool that helps to prioritize reusability in the system.

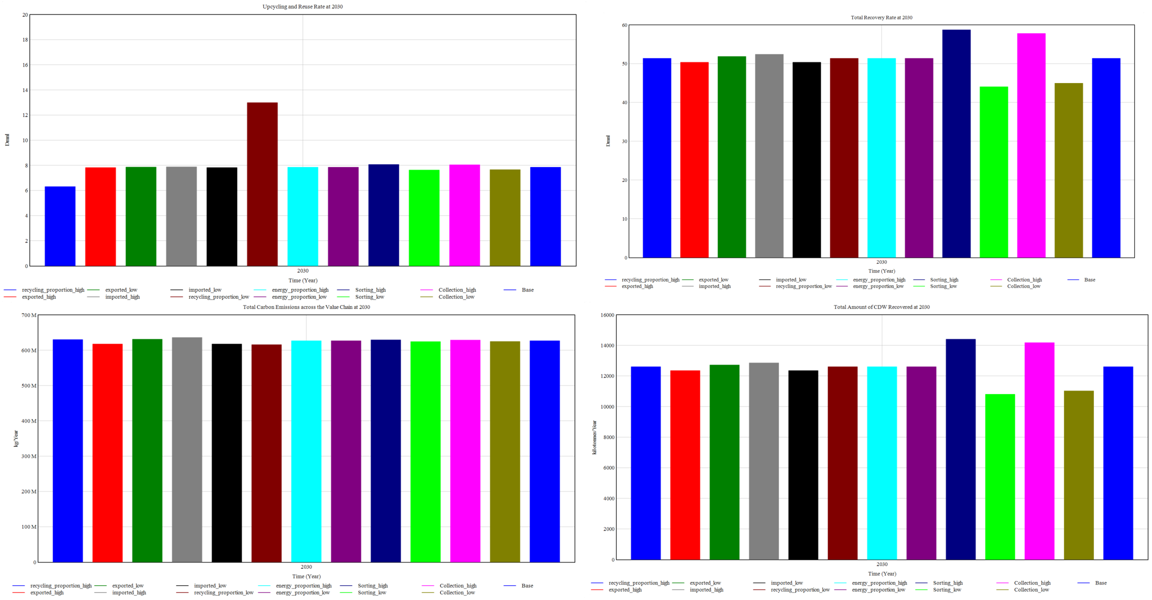

Figure B.5: Univariate sensitivity analysis for material flow based factors

Both total recovery rate and amount of CDW recovered were most sensitive to sorting efficiencies. They increased the most when sorting efficiency is high, and decreased the most when sorting efficiency was less. This might point to the fact that for policies aimed at increasing material flow, it would be useful to focus on the sorting. Finally, for the effects on total carbon emissions, it should be noted that there's no big change. This signifies that emissions is not that sensitive to material flows. In the next test, carbon emissions KPI is checked for different emissions based factors.

Univariate Sensitivity Analysis for emissions based factors

Univariate sensitivity analysis was done for emissions based variables as defined in Table B.3. The values were changed by +-5 kg/tonne and the effects on the KPI was checked.

Table B.3: Setup for univariate sensitivity analysis of emissions based factors

Test	Variable	Base value (kg/tonne)	Low value (kg/tonne)	High value (kg/tonne)
Univariate Sensitivity Analysis	Unit emissions from landfilling	17.9	22.9	12.9
	Unit emissions from incineration	17.9	22.9	12.9
	Unit emissions from roadfilling	8.73	13.73	3.73
	Unit emissions from pre-processing	10.74	15.74	5.74
	Unit emissions from upcycling CDW	4	9	-1
	Unit emissions from using primary aggregates	11	16	6

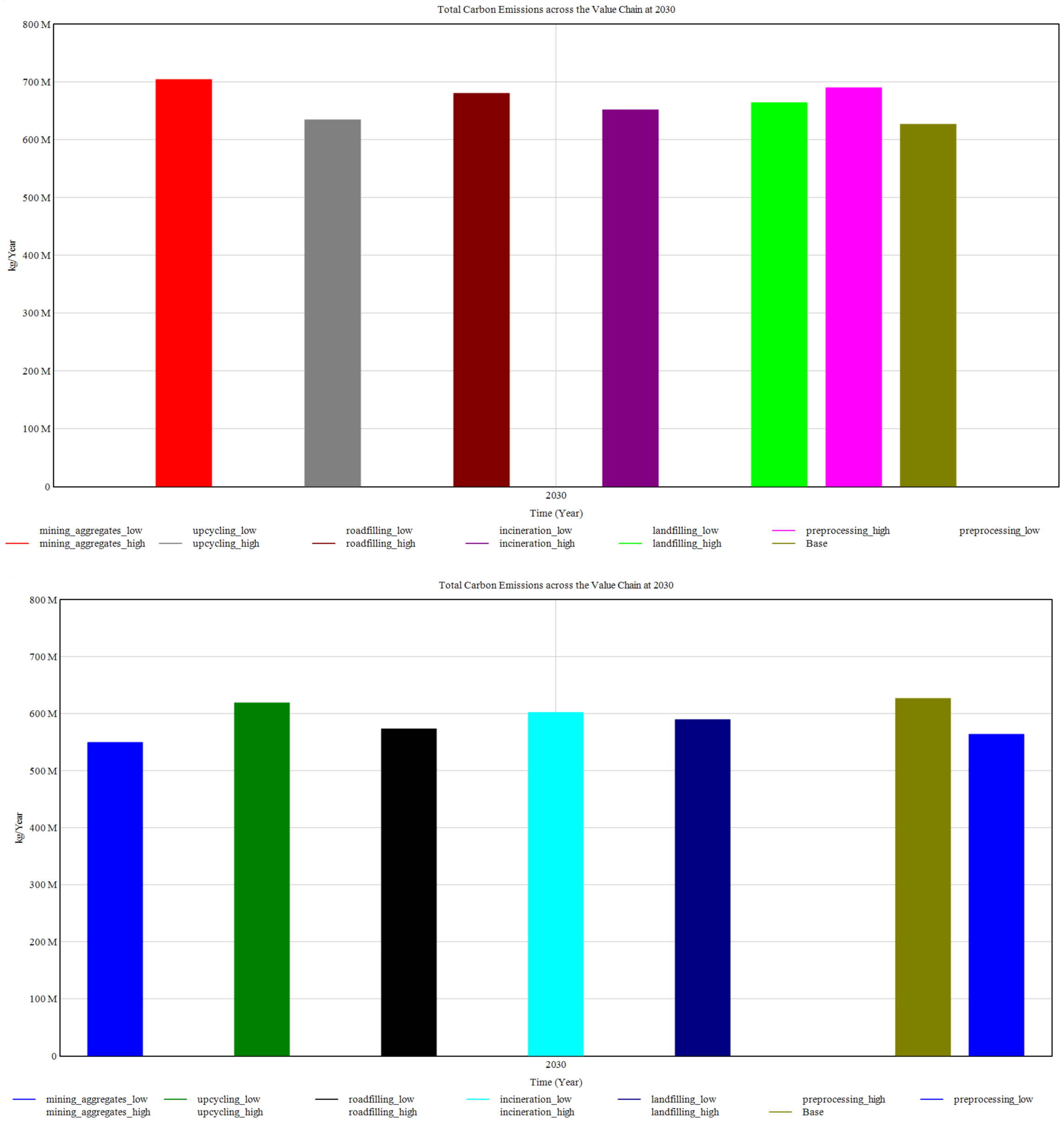

Figure B.6: Univariate sensitivity analysis for material flow based factors

The results from the sensitivity analysis on carbon emissions showed that it's most sensitive to emissions from mining primary aggregates and least sensitive to emissions from upcycling. The KPI is second most sensitive to preprocessing emissions. This analysis gives insights into the factor that affects carbon emissions the most, which in this case comes from mining aggregates.