Towards Circular Campus Management

Implementing Material Flow Management for Circular Campus Operations at Delft University of Technology

Thesis project Industrial Ecology

N.G. van Oppenraay

TU Delft

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by

N.G. van Oppenraay

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Student number:	4678095
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Thesis committee:	Dr.ir. G. Korevaar
	Prof.dr.ir. A.A.J.F. van den Dobbelsteen
	F.I. Terpstra, MSc

TUDelft

Preface

This thesis, titled ”Towards Circular Campus Management,” represents the culmination of my journey through the Master’s program in Industrial Ecology, a joint degree of Leiden University and Delft University of Technology.

Whilst studying for my bachelor’s degree at TU Delft, I developed a keen interest in sustainability. It was during this period that I was introduced to the concept of the Circular Economy, which resonated deeply with me and inspired me to explore its principles further. As a result, this thesis extends the application of the concept’s principles to the operations of TU Delft’s campus, which served as my academic home during my years as a student.

I would like to express my gratitude to those who have supported and guided me throughout this journey. Firstly, I would like to thank my main supervisor, Gijsbert Korevaar, whose guidance has been indispensable every step of the way. In moments of uncertainty, your support and constructive challenges have propelled my ideas forward, contributing significantly to the development of this thesis and the developed framework.

I also extend my gratitude to Andy van den Dobbelsteen for his important contributions and perspectives, which have greatly enriched my understanding and approach. It has been a pleasure to collaborate with you, and I am grateful for the guidance and expertise you have provided. Additionally, I would like to express my appreciation to Froukje Terpstra for your support and assistance in navigating the essential resources needed to conduct this study. Our conversations were enlightening, and your insights into the practical aspects of my research have been invaluable.

I am deeply grateful to all those who participated in the interviews for this research. Your generosity in sharing your time and expertise was integral to the success of this study, and I am thankful for your contributions.

Finally, I would like to express my gratitude to my family and friends for their unwavering support throughout this project. Specifically, I would like to thank my parents, Michiel and Caroline, for their support during my studies and for always standing by my decisions. I am also grateful to my friends and my partner, Thomas, for listening to my concerns and providing me with perspective. Your support enabled me to maintain my enthusiasm and keep my cool throughout the project!

Enjoy!

N.G. van Oppenraay
Delft, March 2024

Abstract

Higher Education Institutions are not just centres of learning. They are dynamic ecosystems with significant environmental footprints and societal responsibilities. Due to their expansive operations, these organisations typically have vast infrastructure and services, which require various products to support them. These products, in turn, generate substantial waste. However, despite the growing importance of Circular Economy principles, many continue to operate within linear systems. Moreover, challenges arise when implementing strategies aimed at enhancing circularity. This thesis proposes a novel approach that combines technical and organisational aspects into a single framework; Material Flow Management. It supports the transition towards circular campus operations. The application of this framework is demonstrated through the case study of Delft University of Technology.

The Material Flow Management framework is designed specifically for TU Delft's campus management structure and operations. The Material Flow Management Model is a key component of the framework, quantifying and visualising material flows within the campus ecosystem. This provides decision-makers with real-time data accessibility to identify areas for improvement and monitor progress. The framework supports the management of material flows and encourages critical evaluation of the current management structure in relation to implementing Circular Economy strategies. This evaluation is done by conducting interviews with important decision-makers within the organisations to ensure effectiveness.

It is committed to data-driven decision-making and continual improvement, ensuring TU Delft's leadership in sustainable material management practices. This framework can be used by stakeholders to promote broader transitions towards a Circular Economy, both within and beyond the campus. This will help to advance the collective journey towards sustainable practices.

Executive Summary

Leveraging the iterative nature of the Deming Cycle, the framework supports the implementation of CE initiatives at the TU Delft through a systematic process of managing material flows, exemplified in Figure 1. This methodology serves to demonstrate the practical application of the Material Flow Management (MFM) Model by decision-makers within the TU Delft.

The Plan phase sets the foundation for action, encompassing a thorough assessment of the current state, data gathering, and strategic planning using the MFM Model. Crucially, this stage involves establishing tangible targets and engaging diverse stakeholders to ensure the viability and inclusivity of proposed solutions.

Subsequently, the Do phase involves piloting the devised strategies and putting them into practice on a trial basis. Concurrently, the Check phase evaluates the efficacy of these initiatives, leveraging real-time data provided by the MFM model to assess progress towards set targets and uncover unforeseen challenges or opportunities.

Finally, the Act phase entails the implementation of refined strategies based on the insights gained from the previous stages. It underscores the iterative nature of the transition, emphasising the need for adaptability and continual improvement.

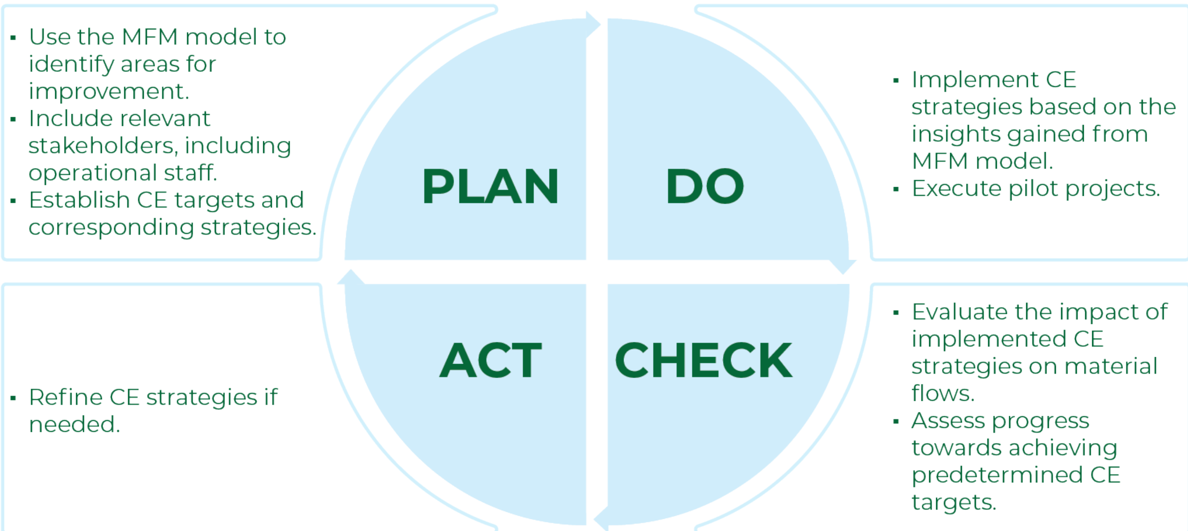

Figure 1: Plan, Do, Check, Act cycle. Adaptation from Deming (1982)

Recommendations for the Executive Board at the TU Delft

In the pursuit of a circular campus at TU Delft, the influence wielded by governmental bodies, particularly the Executive Board, is paramount. Through interviews conducted with staff members during the Evaluation Phase, it has become evident that while the Executive Board exerts significant power in various spheres, their impact on the specific topic of circularity remains relatively limited.

Staff members universally expressed a sense of ambiguity of useful guidelines provided by the Executive Board regarding the integration of CE principles into their work. This absence of clear direction has left individuals grappling with how to navigate the complexities of circularity and discern the appropriate course of action within their respective roles. As a consequence, the transition towards circularity within TU Delft is still nascent.

As revealed through interviews, it is evident that individuals across the university place significant reliance on the statements and directives issued by the Executive Board. This underscores the Board's pivotal role in shaping the trajectory of TU Delft's sustainability agenda. In light of these findings, the following recommendations are proposed:

Tangible CE Objectives: The Executive Board should spearhead the creation of more detailed and tangible CE objectives and targets for the university. The objectives should be specific and measurable, such as "*a reduction of plastic packaging use by 75% by 2030*" or "*a single-use packaging free campus by 2030*." Collaborating with key stakeholders at both strategic and operational levels to create these objectives ensures alignment and feasibility.

Strategies for CE Objective Dissemination: Transparent communication about the new CE objectives must be disseminated throughout the organisation via various channels such as social media, newsletters, and official announcements. It is essential for students and staff to easily access and understand TU Delft's commitment to becoming a circular campus. This will help to create a strong TU Delft community ready to contribute to these objectives. This includes the University Services and Faculties as well as all the students and staff members.

Accountability Measures: Tangible targets should be allocated to various organisations within TU Delft, ensuring accountability and motivation for change. Using the MFM Model, progress can be tracked and reported, facilitating discussions with buildings and Faculties to navigate towards set objectives. Additionally, exploring the implementation of nudge techniques for organisations failing to meet targets can provide extra motivation for engagement, especially for faculties that may require additional encouragement.

Faculty Alignment through Dedicated CE Teams: Recognising the complexity of transitioning towards circular practises, it is essential to ensure that every Faculty has a dedicated CE Team. These teams should consist of individuals with diverse expertise in CE implementation, with the inclusion of the Local Sustainability Coordinator being particularly crucial. These teams serve as key drivers in navigating the transition within their respective buildings, fostering a culture of sustainability and innovation. These teams need to have a comprehensive understanding of the broader initiatives taking place across TU Delft and to identify opportunities for their Faculty to contribute meaningfully to the faculty-specific transition. They are also responsible for monitoring progress and ensuring that the faculty is effectively working towards achieving the set targets.

Recommendations for Campus Real-Estate and Facility Management

Through an analysis of the management structure, it is evident that Campus Real-Estate and Facility Management (CREFM) wields significant influence over TU Delft's circularity and sustainability initiatives. As the primary interface with suppliers responsible for providing products and services essential for campus operations, CREFM plays a pivotal role in shaping the university's environmental footprint. Furthermore, CREFM's selection of waste management partners directly impacts the handling and disposal of waste generated by campus activities. This dual responsibility underscores the immense potential for CREFM to drive tangible change in promoting circularity and sustainability practices within TU Delft.

However, it is crucial to recognise that CREFM's influence extends far beyond the confines of the university. By fostering collaborative partnerships with suppliers and waste management companies, TU Delft can leverage its stature to inspire and incentivise sustainable practices throughout its supply chain. Therefore, the ripple effects of such partnerships extend beyond TU Delft's campus boundaries, permeating into broader industry practices. By championing circularity, TU Delft can serve as a catalyst for positive change within its sphere of influence and beyond. In light of these findings, the following recommendations are proposed:

Establish CE Teams for Flow Categories: Formulate dedicated CE teams for distinct product and material flow categories within TU Delft, including Canteen, Cleaning materials, Furniture, Lab equipment, Office supplies, and Vending. Ensure each team comprises individuals knowledgeable about circularity to strategise and implement targeted sustainability initiatives tailored to the unique characteristics of each category.

Set Flow-specific Targets: Define specific and achievable targets for each flow category, considering their individual complexities and challenges. For instance, while a single-use packaging-free campus may be feasible for the Furniture category, alternative strategies may be required for the Vending category, where packaging is essential. Tailor strategies accordingly to maximise effectiveness.

Involve Contract Partners: Foster closer collaboration with contract partners involved in supplying products and services to the campus. Clearly communicate set targets and expectations to contract partners from the outset, emphasising their role in contributing to TU Delft's circularity objectives. Integrate specific sustainability criteria into tender documents to incentivise and guide partners towards adopting more sustainable practices.

Monitor Developments: Implement robust monitoring mechanisms to track progress towards set targets and evaluate the effectiveness of implemented strategies. Regularly assess whether strategies are yielding desired outcomes and adjust approaches as necessary. Monitor compliance of contract partners with established sustainability criteria and provide guidance or intervention as needed to ensure alignment with TU Delft's objectives.

Improve Data Collection and Modelling: Enhance data collection processes to gather comprehensive and standardised data essential for informed decision-making. Implement tactics such as standardised data sheets, centralised data collection systems, and bin audits to improve data accessibility, availability, and accuracy. Streamline data collection efforts to facilitate the continuous refinement of the MFM Model.

Promote CE Experimentation: Encourage a culture of experimentation and innovation within TU Delft's facility management sectors. Utilise the MFM Model to monitor developments from pilot initiatives, providing insights into the effectiveness of different strategies. Embrace opportunities to explore new approaches and technologies to drive sustainable practices university-wide.

Contents

List of Abbreviations

Abbreviation	Definition
AE	Aerospace Engineering
AS	Applied Sciences
Arch	Architecture and the Built Environment
CE	Circular Economy
CEG	Civil Engineering and Geosciences
EB	Executive Board
EEMCS	Electrical Engineering, Mathematics & Computer Science
EMF	Ellen MacArthur Foundation
FM	Facility Management
HEI	Higher Education Institution
IDE	Industrial Design Engineering
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LSC	Local Sustainability Coordinator
ME	Mechanical Engineering
MFA	Material Flow Analysis
MFM	Material Flow Management
SPT	Sustainability Project Team
TPM	Technology, Policy and Management
TU Delft	Delft University of Technology
CREFM	Campus Real-Estate and Facility Management

1 Introduction

In the context of current environmental challenges, Higher Education Institutions (HEIs) are recognising the need to adopt circular practices in their operations. This chapter provides an introduction to the research, outlining its origin, purpose, and scope. This study was conducted in collaboration with Delft University of Technology's Campus Real Estate & Facility Management. The study aims to provide a framework for TU Delft to transform its predominantly linear campus operations into a system that embraces the principles of the Circular Economy (CE).

The need for this change is driven by the university's desire to align with global sustainability targets and demonstrate leadership in environmental stewardship. TU Delft has committed to achieving carbon neutrality, climate adaptability, and circularity by 2030. This commitment demonstrates the university's responsibility in mitigating climate change and dedication to fostering a sustainable future. Furthermore, TU Delft aims to improve the quality of life on its campus while also promoting biodiversity.

1.1. Background and context

The latest report by IPCC (2023) delivers a stark message: The Earth's surface temperature has risen by 1.1°C above pre-industrial levels, resulting in unprecedented changes to the climate system in every region of the world. From rising sea levels to extreme weather events and a rapid decrease in biodiversity, the ramification are severe. This warming trend is fuelled by ongoing increases in global greenhouse gas emissions, stemming from unsustainable practices in energy use, land-use change, as well as unsustainable consumption and production patterns.

In light of pressing global challenges the need for transformative solutions has never been more urgent. Our current linear economic model, which is characterised by a take-make-waste system, is proving unsustainable (Ellen MacArthur Foundation, 2021; European Commission, 2020). It is depleting resources, exacerbating environmental degradation, and perpetuating social inequities. However, in the face of these challenges, a promising framework emerges the concept of the CE (Blomsma & Brennan, 2017; Khan et al., 2022).

The CE proposes a new approach that aims to transform all aspects of our consumption and production systems. It envisages a world where resources are sustainably managed, products are designed for longevity and recyclability, and materials are continuously cycled back into the economy (McDonough & Braungart, 2002). The CE offers a pathway to address multiple interconnected challenges simultaneously. This transition promotes prosperity, job creation, and resilience, while also reducing greenhouse gas emissions, waste, and pollution (Ellen MacArthur Foundation, 2021; Geissdoerfer et al., 2016; Saliba et al., 2023).

However, achieving a CE demands a significant shift in mindset, policies, and practices across all sectors and society as a whole. In the context of resource management, product design, and waste reduction, innovative approaches are necessary (Blomsma & Brennan, 2017; Bocken et al., 2016; Ghisellini et al., 2016). Collaboration and commitment from businesses, governments, communities, and individuals are required (Kirchherr et al., 2017, 2023).

HEIs play a crucial role in promoting the CE agenda. As knowledge creation, innovation, and societal influence hubs, they have the potential to drive transformative change (Nunes et al., 2018; Serrano-Bedia & Perez-Perez, 2022). By incorporating circular principles into their operations, research, and educational curricula, HEIs can contribute to the transition towards a CE (Wanke, 2017). Additionally, they can inspire and empower future generations to advocate sustainability (Leal Filho et al., 2017).

1.2. Problem statement

Despite the notable strides made by certain academic institutions in researching CE, the collective body of knowledge remains in a stage of development (Nunes et al., 2018). While some universities have conducted assessments of their material flows, these evaluations often lack real-time or predictive data, hindering effective decision-making. HEIs face considerable challenges in effectively implementing CE strategies, due to the absence of appropriate analytical frameworks (Mendoza et al., 2019a). This is also the case for the TU Delft.

A method used within the context of HEIs to asses material flows within an organisation of the method of Material Flow Analysis (MFA). In theory, by tracking the flow of materials throughout a system, the evaluation of resource loops, waste generation, and opportunities for material reuse and recycling, essential components of CE initiatives aimed at minimising resource depletion and environmental impacts, MFA should be a useful tool.

In practice though, this is different. HEIs are often characterised by their large and intricate organisational structures and struggle with complex decision-making processes that are necessary to drive CE initiatives forward (Stephan et al., 2019). There is consensus that MFA is often not integrated well into the complex decision-making processes of these types of environments, coupled with its exclusion from the relevant assessment methods employed by decision-makers (Brunner, 2002; Lindqvist-Oestblom et al., 2001).

1.3. Research questions and objectives

Recognising the significant gap in current research, this thesis study aims to close the disparity between analytical frameworks and the intricate decision-making processes inherent in HEIs. Utilising a case-study methodology, the study aims to tackle the multifaceted challenges associated with implementing CE practices in HEIs. Introducing the Material Flow Management (MFM) framework, specifically tailored to the intricate management structures within HEIs like TU Delft, the study aims to develop a tool to support stakeholders within TU Delft with implementing CE strategies.

The primary objective of this thesis study is twofold: to develop a model utilising the MFM framework for analysing and integrating CE strategies within HEIs and to understand the specific management challenges within TU Delft and provide recommendations to address them. To achieve these objectives, the TU Delft serves as a case study, enabling the collection of relevant data and insights to construct and validate the MFM model.

Ultimately, the study aims to equip TU Delft stakeholders with actionable recommendations to enhance CE performance and overall sustainability on campus. In light of these objectives, the primary research question is formulated as follows:

How can Delft University of Technology effectively implement material flow management to improve circular campus operations?

Several sub-questions need to be addressed to answer the main research question:

1. *What does the concept of a Circular Economy entail?*
2. *How can Higher Education Institutions contribute to the advancement of a Circular Economy?*
3. *How can material flows be modelled to implement and assess Circular Economy strategies in the context of the TU Delft?*
4. *What noticeable results can be derived from modelling material flows in the context of Higher Education?*
5. *What challenges and opportunities are there for implementing Material Flow Management?*

1.4. Overview of the methodology

The methodology for implementing the CE principles within HEIs addresses identified complexities and limitations by proposing a novel MFM framework. This framework, depicted in Figure 1.1, comprises four phases: Analysis, Modelling, Evaluation and Decide.

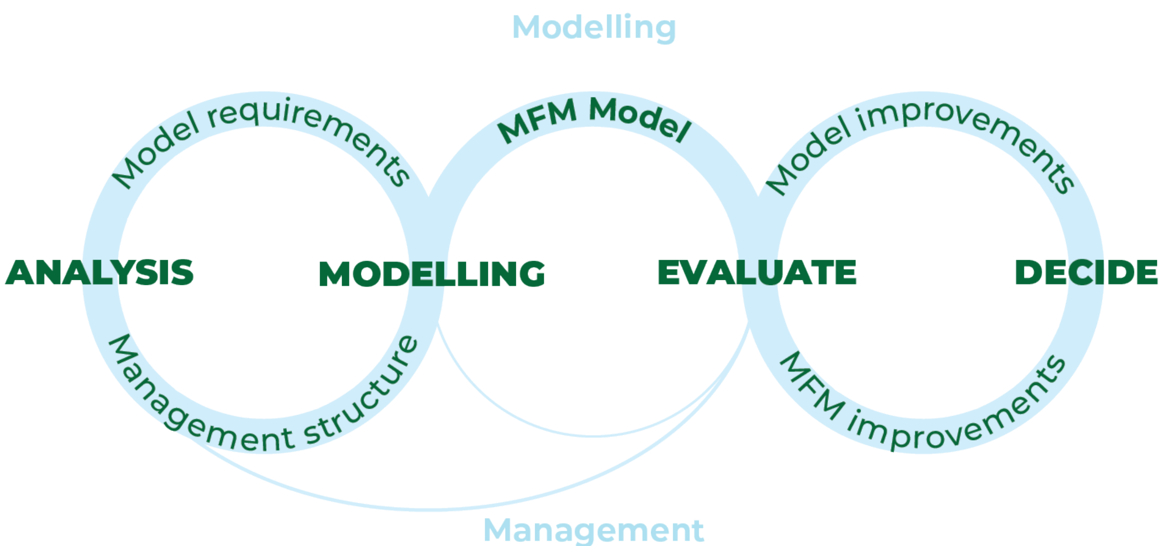

Figure 1.1: The Material Flow Management Framework

In the Analysis phase, the management structure governing material flows within the campus is examined. Stakeholders across various domains influence decisions on products and waste, acting as material flow managers. This phase identifies material flow categories and associated stakeholders, leading to the identification of model requirements.

The Modelling phase involves the modelling process, drawing upon MFA. Relevant data is acquired, waste flows are established, and the system's scope is visualised. Insights from the Analysis phase guide the inclusion of material flow categories and data necessary for modelling, tailored to stakeholder needs.

The Evaluation phase assesses CE strategy implementation, focusing on data availability, presentation, and utilisation by key decision-makers at TU Delft. Through interviews and analysis of data reliability, this phase identifies current obstacles to CE strategy implementation and explores the role of information and data in overcoming these challenges.

Finally, the Decision phase involves implementing the insights gained during the Evaluation phase. The focus is on identifying improvements to the MFM model to maximise its effectiveness in supporting decision-makers in implementing CE strategies. Additionally, organisational improvements can be made to ensure effective CE implementation across the entire university.

1.5. Deliverable

The deliverable of this thesis consists of three parts. First, as explained in Section 1.4, this thesis delivers a novel framework that can be applied in the context of the TU Delft and possibly other HEIs to manage material flows in the context of a CE.

Secondly, by applying the MFM framework in this study, it also delivers a first iteration of the MFM Model, as illustrated in Figure 1.2. This iteration incorporates two primary flow categories: the products sourced from vending machines and the various waste streams managed by the university's waste management service, each of which is quantified by weight. Ideally, a comprehensive MFM model would encompass all inflow categories to provide a holistic understanding of TU Delft's total material consumption and its trajectory over time. However, owing to constraints on time and resources, this study has prioritised vending products as its focal point.

Figure 1.2: Overview of the MFM Model in Use

Thirdly, the development of the MFM model allows the formulation of recommendations aimed at improving the collection and quantification of material flow data, which were developed during the Evaluation Phase. Similarly, the interviews conducted shed light on the drivers and barriers inherent in the current management structure that governs material flows in the context of CE. These findings provide TU Delft's stakeholders with the necessary guidance to take the first steps towards improving their campus operations by moving from their prevailing linear practices to a circular operating framework. Therefore, the third deliverable is a set of recommendations.

1.6. Structure of thesis

Chapter 2 introduced the subject of CE and delved into its meaning. Next, Chapter 3 further explores CE within the context of HEIs, aiming to discern the tools presently employed to effectively implement CE strategies and monitor progress. It also investigates why current analytical tools often fall short in guiding HEIs towards the transition to circular campus operations. Armed with this understanding, a novel framework, the Material Flow Management Framework, is developed and explained in Chapter 4. This framework is not only conceptualised but also applied in this thesis study to ensure efficacy, entailing an examination of the management structure concerning material flows in Chapter 4. Subsequently, Chapter 5 illustrates the modelling steps for crafting the MFM Model. Following this, Chapter 6 presents intriguing findings derived from the model. Chapter 7 encompasses the outcomes of the Evaluation Phase, wherein both the MFM Model and the management structure are assessed for potential improvements.

2
An Introduction to the Circular Economy

This chapter is dedicated to addressing the sub-question: *What does the concept of a Circular Economy entail?* Understanding the contribution of HEIs to a CE necessitates a foundational grasp of the principles underlying CE. Without this understanding, it is challenging to articulate how HEIs can actively contribute to the advancement of a CE.

In light of this, Section 2.1 provides an overview of the general evolution and origins of the CE, tracing its development over the years. Next, Section 2.2 delves into the key principles that form the foundation of the CE concept. To provide a cohesive link between the various sections, Section 2.3 offers a summary of the key findings of the literature reviewed in this chapter, setting the stage for subsequent chapters in the thesis.

2.1. The development of CE

The development of the CE concept is shaped by several factors, although its origin is uncertain (Murray et al., 2017). Initially, the shift in our understanding of Earth's carrying capacity gave rise to the first concepts that can be linked to CE (Wautelet, 2018; Winans et al., 2017). Although climate change is now a globally recognised issue, this was not always the case. Previously, the large majority of the population approached our world as a 'cowboy economy' in which resources are being extracted endlessly from the Earth without having consequences. This linear model is associated with adverse environmental consequences such as pollution.

Boulding (1966) was among the first to challenge this notion and contested the sustainability of this approach, asserting that it rests on a flawed understanding of long-term physical possibilities. In contrast to the cowboy economy, Boulding introduced the concept of the "spaceman economy," conceptualising Earth as a closed system with minimal exchanges of matter with the external environment. Within this economic paradigm, a circular relationship defines the interactions between the economy and the environment, where inputs and outputs are interconnected.

Another potential inspiration for the CE concept is the 1972 *'Limits to Growth'* report by the Club of Rome, which ignited a global debate about Earth's capacity to sustain continuous human and economic expansion. The study predicted that our current economic model is unsustainable and will eventually lead to an unmanageable decline in population and industrial capacity. To avert this future, a shift from economic growth to global resource equilibrium is imperative (Meadows et al., 1972). Noticeably, both theories emphasise the Earth's finite carrying capacity and the urgency of adopting sustainable resource management practices.

It became evident that conventional economics, with its focus on resource allocation, failed to consider the complex relationship between the economy and the environment. Environmental economics emerged to address this gap, recognising the environment's multi-faceted role in supporting economic activity. The work of Pearce and Turner (1990), *'Economics of Natural Resources and the Environment'*, proposed a shift from a linear to a circular economic system in which "*everything is an input to everything else*". This perspective has significantly influenced contemporary economic thought and is considered one of the building blocks of concepts such as the CE (Merli et al., 2018; Wautelet, 2018).

Over the years, various concepts have arisen, influenced by these key ideas and thereby interconnected with CE (Korhonen et al., 2018; Murray et al., 2017; Winans et al., 2017). It is intertwined with various other significant studies (Merli et al., 2018), such as industrial ecology (Ghisellini et al., 2016; Murray et al., 2017; Wautelet, 2018) industrial ecosystems (Jelinski et al., 1992), and industrial symbioses (Chertow & Ehrenfeld, 2012). Likewise, it builds on the concepts of eco-efficiency, eco-effectiveness or cradle-to-cradle (Nunes et al., 2018).

The CE approach is also convergent with the broader requirements of sustainable development listed by Hopwood et al. (2005), as it promotes better use of finite resources, increases the resilience of the economic system, increases job opportunities, and encourages developments in technology and business studies (Ellen MacArthur Foundation, 2013). It provides opportunities for new business models, such as product leasing, targeted reverse logistics, and re-marketing, which recognise the value of the resources embedded within products whilst at the same time offering a better service to the user (Bocken et al., 2016). More recent theories such as performance economy (Graedel, 2019), biomimicry (Benyus, 2002) and blue economy (Pauli, 2010) have contributed to further refining and developing the concept of CE.

The multitude of intertwined concepts that revolve around resource management is therefore extensive, substantiating the study of Blomsma and Brennan (2017) in which was stated that CE is an umbrella term, encompassing multiple concepts.

2.1.1. Recent shift in studies

Upon examining recent studies on the CE, a clear shift in focus becomes evident. Notably, more previous research tends to prioritise resource strategies as a pivotal element for the CE (Kirchherr et al., 2017, 2023). These strategies predominantly involve efforts to reduce, reuse, and recycle materials to enhance circularity, also referred to as a variation of the R-framework. Kirchherr et al. (2017) examined 114 definitions and concluded that recycling found to be the most common component in the definitions examined (79 % of definitions), followed by reuse (74%–75% of definitions) and reduce (54%–55% of definitions). These findings are seen in other work including the study of Schoeggl et al. (2020).

Despite the practical and clear guidelines provided by waste hierarchy strategies, it is argued in some studies that considering them as the exclusive components of CE may be an oversimplification. It can be argued that labelling a company as circular solely based on investments in recycling strategies could be an overstatement (Saidani et al., 2017). This questioning of the CE definition is echoed in additional studies.

One of the key organisations promoting a CE, the Ellen MacArthur Foundation (EMF), proposed a newer perception and mentioned CE as *"a system that is designed to be restorative and regenerative"*. Compared to the R-framework, this perception examines a more systems perspective way of thinking. From this moment on, a clear shift is perceived in studies, that shift away from the safely used R-principles, emphasising that CE should entail a systemic shift, incorporating multiple levels of society and corporation with multiple stakeholders (Serrano-Bedia & Perez-Perez, 2022).

Contemporary research underscores the importance of establishing a comprehensive coalition of participants, encompassing not just consumers and companies but also policymakers and academics, to promote the transition to a CE and, consequently, achieve sustainable development (Geissdoerfer et al., 2016; Kirchherr et al., 2023). In line with this perspective, the EMFs' latest report underscores the importance of viewing CE as a holistic transformation (Ellen MacArthur Foundation, 2021). It states that recognising the systemic nature of the CE transition can unlock a multitude of economic, environmental, and societal benefits, making it a promising avenue to address pressing global challenges such as the climate crisis. Multiple studies have followed this line of action and incorporated the multi-level perspective in their definition of CE (Elia et al., 2016; Ghisellini et al., 2016; Kirchherr et al., 2017, 2023; Merli et al., 2018), acknowledging that different actors in the CE landscape have different interpretations of the concepts.

2.2. Key principles of CE

By analysing the development of the CE concept, it becomes apparent that its core principles have given rise to various related ideas (Merli et al., 2018). Upon examining recent definitions, there is a noticeable lack of universal agreement on what exactly CE is (Elia et al., 2016; Ghisellini et al., 2016; Kirchherr et al., 2017). This lack of consensus is also reflected in how CE has evolved (as shown in Section 2.1), with more recent studies taking a broader, systemic perspective.

Given this lack of a universally agreed-upon definition among leading researchers, this thesis does not aim to provide one definitive explanation for the CE. Instead, it recognises it as an umbrella term encompassing multiple evolving concepts (Blomsma & Brennan, 2017; Milios, 2018; Murray et al., 2017). Although there is no single definition, there is general agreement on key foundational elements (Masi et al., 2017), as discussed in Section 2.1—specifically, resource strategies and a systemic perspective.

Recognising the challenges posed by a rigid definition, Broman and Robèrt (2017) advocate for the establishment of key principles instead. The authors argue that a detailed definition of sustainability can be restrictive and hinder the analysis of sustainable practices. According to the authors, opting for guiding principles provides a more versatile, intuitive, and practical approach to supporting sustainable development—a viewpoint that extends seamlessly to the realm of CE, as emphasised by Mendoza et al. (2019a). Consequently, this section delves into these core principles that collectively shape our understanding of CE.

2.2.1. Managing material loops

At the heart of the CE concept lies the fundamental idea of assigning value to materials within a closed-loop system, as highlighted by various studies (Bocken et al., 2016; Murray et al., 2017; Winans et al., 2017). This principle underscores the perspective that waste should be regarded as a valuable resource, advocating for the reusability of every raw material or substance without compromising its inherent value, a concept deeply rooted in works such as those by Pearce and Turner (1990) and the cradle-to-cradle philosophy by McDonough and Braungart (2002).

To carry out this principle, a comprehensive set of strategies, often referred to as slowing, closing, and narrowing material loops, can be implemented—equivalent to the familiar reduce, reuse, and recycle strategies (Blomsma & Brennan, 2017; Bocken et al., 2016; Kirchherr et al., 2017, 2023). Slowing material loops emphasises extending the use and reuse of goods over time, achieved through the design of durable products and the extension of product life. Similarly, closing material loops involves the recycling and recovery of materials to foster their reuse. Finally, narrowing loops aims at reducing resource consumption associated with both the product and the production process, as outlined by Bocken et al. (2016).

Introduced by McDonough and Braungart (2002), the concept determined two cycles for material circulation: the biosphere, accommodating biodegradable and compostable materials, and the technosphere, facilitating the perpetual reuse of materials for industrial applications. This conceptual framework has significantly influenced the work and research of the Ellen MacArthur Foundation (EMF), contributing to the development of various studies. Figure 2.1 depicts the widely utilised "Butterfly Diagram," crafted by the organisation. Therefore, the CE concept revolves around the central idea of 'slowing, closing and narrowing material loops' to transition from a linear to a circular system regarding resource management.

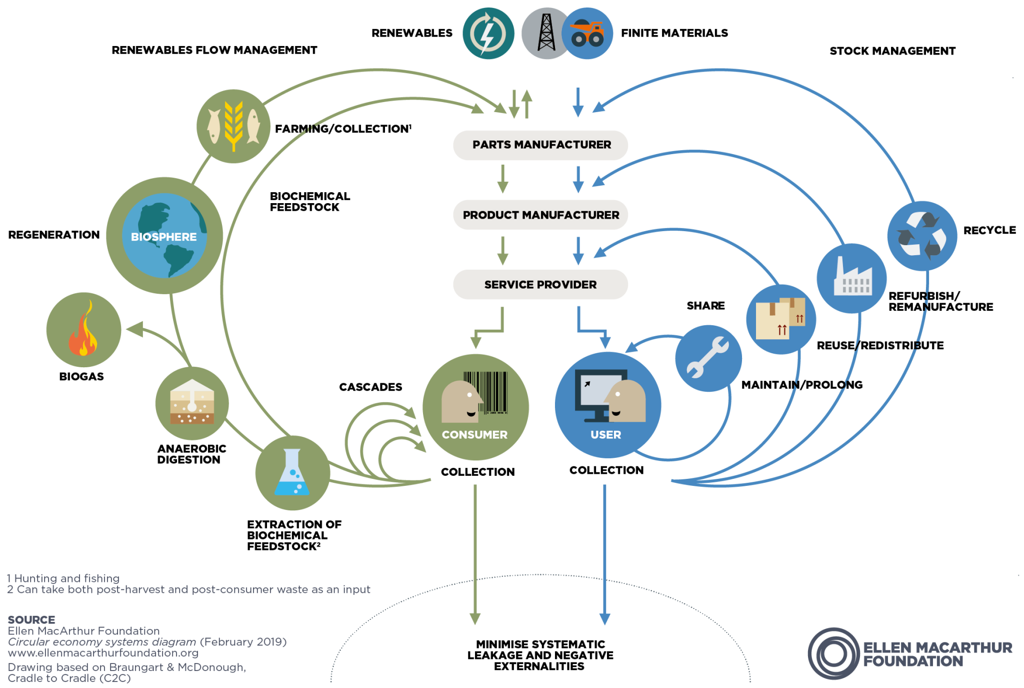

Figure 2.1: The Butterfly Diagram (Ellen MacArthur Foundation, 2019)

Waste hierarchy

Strategies for managing resources have become a crucial framework for the practical implementation of 'slowing, closing and narrowing material loops' (Corona et al., 2019; Winans et al., 2017). Over time, diverse variations have emerged, with Kirchherr et al. (2017) presenting it as the 4R framework (reduce, rescue, recycle, and recover) or waste hierarchies. Waste hierarchies involve categorising the various Rs in a specific order, reflecting the degree of circularity associated with each. A commonly utilised version, as presented by Potting et al. (2017), is illustrated in Figure 2.2.

It's important to note that the application of the R-framework should be approached with caution. It serves as a 'rule of thumb' because the order is not always consistent. This underscores the presence of exceptions and secondary or rebound effects, indicating that the R-order may

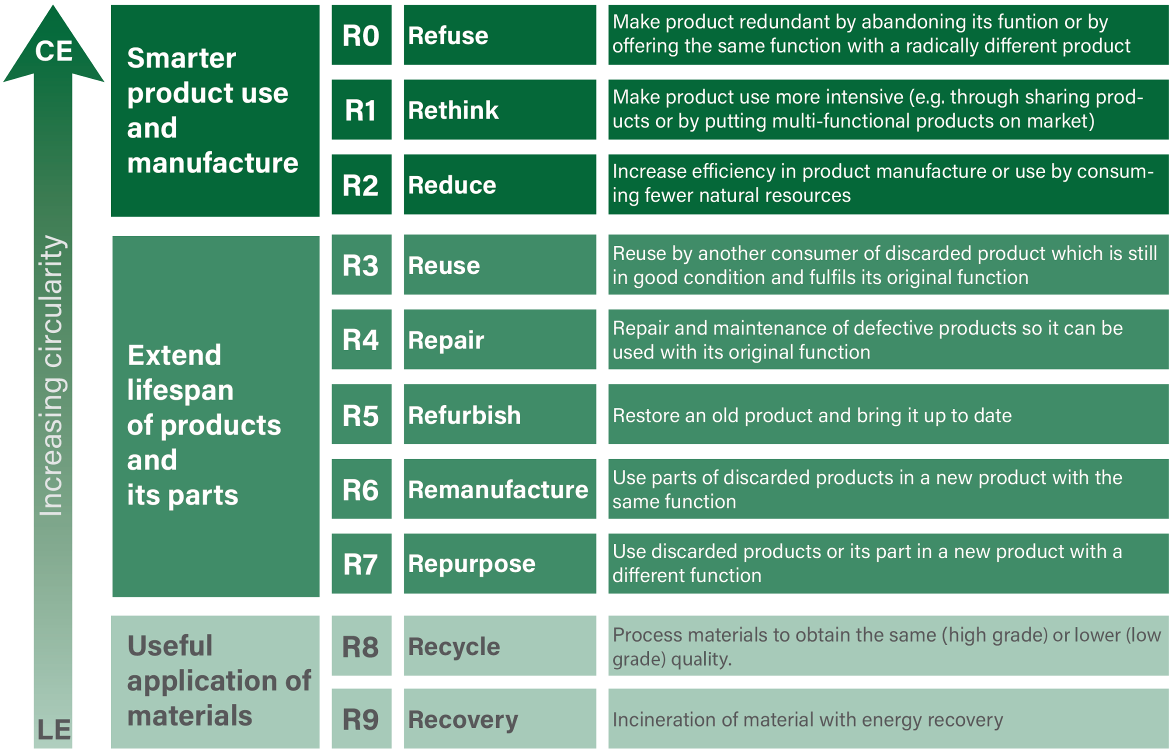

Figure 2.2: The 9R Framework for applying CE strategies. Adapted from Potting et al. (2017)

not be suitable for certain products and under specific conditions. Despite this, the hierarchy among strategies can offer a useful orientation when examining CE strategies (Morseletto, 2020).

2.2.2. Systems perspective

Another crucial aspect of the contemporary understanding of a CE is the systems perspective. Multiple authors argue that CE entails systemic change and can be perceived as a transition (Ghisellini et al., 2016; Kirchherr et al., 2017, 2023; Serrano-Bedia & Perez-Perez, 2022). This transition to a CE needs to occur at three levels (Murray et al., 2017), which can be interpreted as three layers of the CE system: the micro, the meso, and the macro-system (Ghisellini et al., 2016; Kirchherr et al., 2017; Merli et al., 2018). Each level represents a unique aspect of the overarching CE framework.

The approach to transitioning to a CE is therefore not uniform but varies based on the specific system under consideration. This diversity in systems prompts a corresponding variety in CE transition processes (Morseletto, 2020). These processes exhibit distinct roles of innovation, spanning technology, product design, and revenue models. Simultaneously, socio-institutional changes come into play, involving shifts in consumer behaviour and the actions of stakeholders (Morseletto, 2020). This diversity underscores the intricate and multifaceted nature of CE transitions, emphasising the need for adaptable strategies across different systems.

CE at micro level

The micro level mostly focuses on products, individuals and companies (Kirchherr et al., 2017). Ghisellini et al. (2016) categorised the micro level into three sub-categories:

- CE in the production sector

- CE in the consumption sector
- CE in waste management

In the production sector, the introduction of a CE program entails a company implementing diverse strategies to improve the circularity of its products. Concepts that are often applied, but not limited to in this area are eco-design, eco-efficiency or design for the environment (Blomsma & Brennan, 2017). Another important aspect of CE is the development of new business models (Bocken et al., 2016).

According to Blomsma and Brennan (2017) within the realm of circular business models the distinction is made between ’slowing resource loops” and ”closing loops”. Within the consumer sector, the emphasis is on inducing behavioural change and nudging consumers towards more sustainable behaviour. Tools employed for this purpose include ’Design for Sustainable Behaviour’ which explores how design can influence user behaviour to reduce environmental impact as well as unwanted social behaviour (Bhamra et al., 2011).

As for waste management, there is a growing perspective that recognises waste management as a mechanism for resource recovery and environmental impact prevention (Taelman et al., 2018).

CE at meso level

The current application of the CE concept can also clearly be seen at the meso level (Ghisellini et al., 2016; Kirchherr et al., 2017), which includes the industrial sector (Winans et al., 2017). The process industry, notorious for its pollution and high energy consumption, often faces public scrutiny, particularly when located near urban areas. To address circularity and sustainability concerns, industrial zones can be developed to foster synergies among production activities.

The primary objective is to enhance resource utilisation efficiency, achieved through the adoption of resource-efficient and clean production technologies, along with innovative collaboration models. These models, involving partnerships between companies and nearby urban centres, aim to maximise the re-use of waste streams and by-products while minimising overall waste generation (Gibbs & Deutz, 2005; Winans et al., 2017). This application of CE principles at the meso level is exemplified by industrial symbiosis, a concept crucial for decarbonising the production industry (Feiferytė-Skirienė & Stasiškienė, 2021).

In essence, industrial symbiosis entails capturing and redirecting surplus resources generated by one industrial process to serve as new input for other production processes, rather than discarding them (Chertow & Ehrenfeld, 2012). Successful implementation relies on collaborative efforts among companies, enabling a reduction in environmental impact, and operational costs, and increased job creation (Oughton et al., 2022). (Feiferytė-Skirienė & Stasiškienė, 2021) even identifies it as one of the key principles of CE.

CE at macro level

At the macro level, the emphasis lies on the profound influence of our industrial structure on the economy and production and consumption patterns (Kirchherr et al., 2017). The development of CE in cities, provinces, or regions requires the integration and redesign of four systems: the industrial system, the infrastructure system delivering services, the cultural framework, and the social system. The success of CE implementation relies on the effective involvement and collaboration of all actors across all tiers (Broman & Robèrt, 2017; Ghisellini et al., 2016). This is echoed in the work of Ellen MacArthur Foundation (2021) in which the authors call all businesses and policymakers at different levels of our economic system to collaborate and support goals for transitioning to a CE.

These goals, applicable across sectors and value chains, serve as a foundation for a systemic shift to guide policy development globally (Corona et al., 2019). Therefore, within the macro perspective, collaboratively created goals and targets play a pivotal role in governance, offering specific direction to achieve predetermined outcomes (Lester & Neuhoff, 2009; Morseletto, 2020). These goals not only motivate actors to strive for results but also facilitate monitoring advancements by guiding effective measurement (Milios, 2018).

Naturally, the right analytic framework has to be in place to effectively monitor progress, as mentioned by Mendoza et al. (2019a). Governance targets play a pivotal role in guiding actors to transition from their current state, offering a practical perspective on the objectives that need to be accomplished (Lester & Neuhoff, 2009). Consequently, various studies have been conducted to identify suitable circularity metrics for assessment, as demonstrated by Corona et al. (2019), Elia et al. (2016), Milios (2018), and Saidani et al. (2017).

2.2.3. Sustainable development

The link between CE and sustainability, with its three fundamental pillars—environmental, ecological, and social—has gained significant attention in the literature (Geissdoerfer et al., 2016; Murray et al., 2017). Elkington (1998) introduced these three dimensions, forming the basis for understanding the holistic nature of sustainability.

In a comprehensive analysis by Merli et al. (2018), who examined over 300 papers, a pervasive relation between CE and sustainability was observed. The majority of studies considered sustainability as a foundational element in their analyses, with a particular emphasis on the environmental aspect, aligning with the principles of the triple bottom line (Corona et al., 2019). Notably, recent research reflects a more explicit integration of all three dimensions of sustainability, marking a departure from previous works that may have been less focused on the social dimension (Geissdoerfer et al., 2016).

This evolution is developed by the expanding understanding of the link of economic activities with societal well-being. As underscored by Winans et al. (2017) and Murray et al. (2017), CE, through the practical application of its principles, such as the well-known ”reduce, reuse, recycle” strategies, provides tangible solutions to alleviate environmental pressures on ecosystems (Ellen MacArthur Foundation, 2021). Kopnina (2018), in their study defines CE for sustainable development as follows:

> ”*The environmental objective of CE is to reduce the production-consumption system virgin material and energy inputs and waste and emissions outputs (physical throughput) by application of material cycles and renewables-based energy cascades. The economic objective of CE is to reduce the economic production-consumption system’s raw material and energy costs, waste management and emissions control costs, risks from (environmental) legislation/taxation and public image as well as to innovate new product designs and market opportunities for businesses. The social objective is the sharing economy, increased employment, participative decision-making and more efficient use of the existing physical material capacity through a cooperative and community user (user groups using the value, service and function) as opposed to a consumer (individuals consuming physical products) culture.*”

2.3. Chapter conclusion

This chapter aims to answer the following sub-question: *What does the concept of a Circular Economy entail?*

In search of its meaning and definition, it became evident that there is no singular, dominant definition for CE. Three primary reasons account for this. Firstly, CE draws inspiration from various concepts, and conversely, it influences and contributes to other concepts, resulting in blurred boundaries around its definition. Consequently, CE functions as an umbrella term encompassing several related concepts (Blomsma & Brennan, 2017).

Despite this, there are discernible principles where authors find agreement. The main principle of CE is the *slowing, closing, and narrowing of material loops* for the sake of *sustainable development*. Furthermore, CE involves a *systemic transformation* in which the three system perspectives plays a crucial role in promoting the transition.

Secondly, researchers struggle with reaching a consensus on a definitive definition due to the rapid evolution of the concept's meaning. Only in recent years have authors agreed that CE involves systemic shifts, extending across multiple levels within a system. This realisation highlights the dynamic and evolving nature of the CE concept.

Thirdly, the interpretation of the concept varies depending on the involved actors and the system under consideration. The definition of CE may shift according to the specific context in which it is being analysed. This is also the case for HEIs. Thus, depending on the chosen system boundary, the "definition" of what CE entails and means, reflecting the contextual nature of the concept.

3

CE in the Context of Higher Education

This chapter is dedicated to addressing the sub-question: *How can Higher Education Institutions contribute towards the advancement of a Circular Economy?* Section 3.1 outlines the overarching importance of HEIs in the CE landscape, emphasising their unique position as catalysts for change. Subsequently, the significance of sustainable campus operations in instilling circular principles within HEIs is explained in Section 3.2. In addition, the challenges encountered by HEIs in implementing circularity strategies, including the limitations of conventional analytical frameworks are discussed in Section 3.3. At last, the conclusion of this chapter is provided in the final section, Section 3.4.

3.1. The pivotal role of Higher Education

As CE is increasingly being recognised as a systemic shift (Ghisellini et al., 2016), the role of HEIs in this transition is being redefined (Giannoccaro et al., 2021; Kirchherr et al., 2023). This shift underscores the growing acknowledgement of HEIs' importance within the CE landscape, transcending their traditional role in academia (Serrano-Bedia & Perez-Perez, 2022).

Traditionally, HEIs contribute by advancing novel CE frameworks for either businesses or governmental organisations and teaching courses on CE. But it is now understood that their influence extends beyond mere framework provision (Ellen MacArthur Foundation, 2021; Nunes et al., 2018). HEIs, by partnering with local municipalities and industries, can exert significant influence within their regional CE landscape (Ellen MacArthur Foundation, 2019; Mendoza et al., 2019a, 2019b; Serrano-Bedia & Perez-Perez, 2022).

This influence extends to their ability to mobilise policymakers, stakeholders, and business leaders, urging them to adopt new perspectives and actively participate in driving the transition (Merli et al., 2018). This is important, as the success of a transition, as most socio-technical transitions, hinges on collaboration between actors at various levels of society (Geissdoerfer et al., 2016; Kirchherr et al., 2017; Salvioni & Almici, 2020).

Within their institutions, HEIs shoulder the responsibility of educating the future policymakers, business leaders, and researchers who will shape our economy. It is imperative to cultivate an educational environment that not only motivates but also inspires them to embrace sustainability principles, both in the present and for the long term.

This task of fostering environmentally conscious leaders highlights again the crucial role that HEIs play in the larger CE systemic shift (Mendoza et al., 2019a; Pee & Vululleh, 2020;

Serrano-Bedia & Perez-Perez, 2022). A growing body of literature underscores the pivotal role played by HEIs in exemplifying sustainable practices and fostering a culture of environmental responsibility. This endeavour is rooted in the belief that to inspire their students, staff members and researchers to engage in sustainability initiatives actively, HEIs must first exhibit a commitment to transformative change within their own operations (Barth, 2013; Ferronato et al., 2020; Mendoza et al., 2019a).

Aligned with this way of thinking, Serrano-Bedia and Perez-Perez (2022) brought to light that there are five roles in which HEIs contribute to the transition to CE. These roles encompass not only the conventional roles of teaching principles of CE to students (1) and promoting CE-related research (2) but also relatively novel responsibilities such as students taking the lead in driving innovations (3), actively participating in the management of their campus (4) and influencing local transformative initiatives (5).

3.2. Circular campus management

Effective campus management plays a pivotal role in facilitating the transition to a CE across diverse fronts (Anacio, 2017; Barth, 2013). However, managing campus operations proves to be a significant challenge, given that the waste production of HEIs can be comparable to that of larger industries (Alshuwaikhat & Abubakar, 2008). The impact of this challenge is contingent on factors such as the number of students, staff members, and the extent of research personnel within the organisation. HE campuses often span extensive physical areas, housing multiple facilities that necessitate continuous maintenance. These infrastructures demand essential resources, including electricity, water, furnishings, cleaning supplies, and food.

The complexity associated with the CE concept poses a significant challenge for organisations attempting to systematically implement circularity principles (Hopff et al., 2019; Mendoza et al., 2019a, 2019b). As demonstrated in the study by Hopff et al. (2019), campuses function as intricate processes involving diverse stakeholders and actors, forming a complex network of relationships. Different types of actors have different types of goals and motivations, that influence the effective implementation of CE strategies. This makes HEIs complex organisations (McNamara, 2013). Similarly, decision-making is influenced by personal preferences, social norms, and cultural backgrounds, aspects challenging to capture in quantitative models (Danius, 2002).

Therefore, it is unsurprising that, according to Mendoza et al. (2019a) the primary obstacles hindering HEIs from implementing CE strategies include the absence of appropriate analytical frameworks for implementing and assessing CE solutions, along with challenges related to stakeholder engagement and diverse perceptions of what CE entails. Such an analytical framework should include effective data-gathering systems and appropriate KPIs to identify, evaluate, prioritise, implement, monitor and manage CE solutions.

3.2.1. Analytical frameworks in prior studies

In the pursuit of circular campus management, several universities have utilised analytical frameworks for the development of CE strategies. Notably, a shared emphasis among these endeavours is the focus on material flows. Recognising the importance of closing and slowing material loops as a key element of the CE, universities are aligning their practices with sustainability and resource efficiency principles. A key method being utilised is Material Flow Analysis (MFA). In essence, MFA involves systematically tracking the flow of materials throughout the entire life cycle and supply chain of, in this case, a university, from procurement to disposal. This analytical approach allows universities to identify opportunities for more sustainable practices, particularly in resource usage and waste management (Brunner & Rechberger, 2004).

One of the first studies has analysed material flows of a university campus to implement CE strategies is the study of Lopes Silva et al. (2015), conducted at the Universidad Autònoma de Barcelona. In this study, MFA was combined with a life cycle assessment (LCA) approach. This combination proves advantageous, particularly in studies involving complex systems such as countries, cities, regions, economic sectors, or industrial and service areas (Lopes Silva et al., 2015). The study primarily centred on the built environment, including energy and water flows alongside food, land use, and paper while excluding a broader spectrum of usual material flows necessary to support campus facilities. It's important to note that they were based on several assumptions, resulting in estimates rather than precise assessments of the situation. For example, average data on human food consumption was utilised as material input for food, instead of purchase data from the university. As a result, the accuracy and reliability of the study can be debated. Nevertheless, they paved the way for further exploration of CE in HEIs.

One research project applied a systems approach to understanding material flows on a university campus, using the case study of Furman University, a small university in the USA (Dripps et al., 2017). This study employs a metabolic framework, traditionally used in urban metabolism studies, to analyse the university's campus metabolism. The approach involves mapping inflows, transformations, and material outflows for water, energy, food, and materials, and identifying key stakeholders. MFA is employed to quantitatively evaluate these flows, breaking down inputs, outputs, and transformations. While the project concentrated on the systemic aspects of the campus and its methodology, it refrained from reporting specific results. Nevertheless, the endeavour was novel in its application of a systems perspective to analyse campus operations.

Another notable contribution in this direction is the work of Stephan et al. (2019), focused on the University of Melbourne in Australia. The study aimed to quantify material flows and associated embodied energy, water, and greenhouse gas emissions across the university campus. In this study, the material inflows were based on transaction data, which provides more exact information than assumptions, such as the study from Lopes Silva et al. (2015). The authors used an archetypes-based approach to model the material inflows associated with the transactions. All these identified archetypes were given a mass: (e.g., sandwich), category (e.g., food), mass (e.g., 0.10 kg), a breakdown by multiple material types and all sources and assumptions. The modelled purchases associated with procurement generate annual outcomes of 22,587 GJ of energy, 1,477 Gg of CO2 equivalent GHG emissions, and 30,891 kL of water, incurring a cost of 3.46 million AUD.

The authors discovered that the predominant material flows within the campus are mainly influenced specifically by food and food packaging waste stemming from both on and off-campus retail activities. Based on these findings, the paper proposes a set of recommendations for universities and large organisations to adopt and transition towards a CE. Although one of the initial studies to comprehensively model material flows on campus, the recommendations provided are not specific to particular flows. The suggestions include a transition to services rather than purchasing products, advocating for a shift in responsibility to providers who benefit from using durable and recyclable products. Furthermore, the paper recommends the establishment of local reuse centres to maximise circularity and realise cost savings through the reuse of valuable materials (Stephan et al., 2019).

3.3. Managing material flows

As discussed, concerning analytical tools HEIs have primarily utilised MFA to map out material flows to derive CE strategies from the insights given. While MFA has proven effective in providing insights into material movement and quantities within campuses, there is a consensus among researchers that further exploration is necessary to enhance its application within the unique context of HEIs (Blomsma & Brennan, 2017; Mendoza et al., 2019a, 2019b; Serrano-Bedia & Perez-Perez, 2022).

To address these challenges, Binder (2007b) aims to answer the question of how MFA can be adapted to these complex decision-making processes. Similarly, Hopff et al. (2019) emphasises that achieving circularity extends beyond technical choices; organisational structure and processes significantly influence its implementation. According to the authors, circular campus management encompasses a blend of material flows, organisational considerations, user behaviour change, and systems.

The two studies conducted by Binder (2007a, 2007b) provide an intriguing perception of why MFA fails as an analytical framework to guide organisations into making better-informed decisions on CE and effectively implementing CE strategies. There is consensus that MFA is often not integrated well into the complex decision-making processes of these types of environments, coupled with its exclusion from the relevant assessment methods employed by decision-makers (Brunner, 2002; Lindqvist-Oestblom et al., 2001).

For this purpose, the idea of moving towards material flow *management*, rather than analysis, arises as a more fitting approach for the unique environment of HEIs (Barles, 2009; Binder, 2007a). Wageningen University & Research (WUR) exemplifies this transition, aiming to move from conventional 'waste management' to the more holistic 'material flow management'. Emphasising the importance of real-time data, WUR underscores the requirement for tailored policies to improve circularity performances on campus (WUR, 2021).

Governance involves collaboratively creating goals and targets to guide actions toward desired outcomes, whether at the regional, organisational, or company level. These goals provide specific directions for stakeholders to work towards, motivating them to strive for results and facilitating the monitoring of progress (Lester & Neuhoff, 2009; Morseletto, 2020). These goals not only motivate actors to strive for results but also facilitate monitoring advancements by guiding effective measurement (Milios, 2018). According to Brunner (2002), the implementation of assessment tools is crucial for monitoring progress towards established goals. Specific targets play a pivotal role in this monitoring process, serving as smart indicators aligned with the overarching goal. This is why the right analytical framework could help in advancing circular campus management.

In practical terms, this goal-oriented approach involves setting targets, such as reducing waste by a certain percentage by a specified date, derived from insights gained through tools like MFA. However, merely communicating these goals without a clear organisational plan may leave stakeholders uncertain about how to accomplish them (Frick et al., 2004). Therefore, the development of comprehensive organisational strategies becomes imperative to translate these goals into action (Binder, 2007b; Hilty & Rautenstrauch, 1997). The relevance of these goals lies not only in their establishment but in their translation into actionable steps aimed at improving sustainability performance over time.

3.3.1. Stakeholder involvement

The need for a management perspective on material flows arises from recognising that stakeholders and the involved organisation are not inherently rational and consistently cooperative entities; their interests significantly impact the process (Binder, 2007a; Hinz, 2006). According to Enzler (2006), examining physical material flows alone is not sufficient for reaching efficient cooperation between several stakeholders. By not taking organisation and information flows into account, cooperation options are only utilised to a limited extent in corporate practice.

Given the diverse backgrounds and expertise levels of stakeholders, the success of material flow management is contingent upon factors such as motivation, knowledge, assertiveness, and influence. This management perspective becomes indispensable due to the inherent challenges faced by stakeholders in effectively communicating and optimising material flows within a complex organisational framework, both internal and cross-company. It can also benefit greatly by including specialists from different disciplines and educational levels (Brunner, 2002).

When considering cross-company dynamics, HEIs, are heavily reliant on imported products for sustaining campus facilities. In this context, suppliers play a pivotal role in shaping the overall circularity performances of the organisation (Hopff et al., 2019). The procurement processes, influenced significantly by tendering policies and design choices from suppliers, determine the feasibility and effectiveness of applying circular principles. Consequently, the effective adoption of CE strategies faces challenges due to the diverse interests of stakeholders and the agreements made with them, as highlighted by Hopff et al. (2019) and Winans et al. (2017).

3.3.2. Product life cycle

Similar to stakeholder inclusion, the principle of a product life cycle emphasises that each product undergoes a comprehensive journey, and organisations should recognise and understand this trajectory. Purchased products go through a life cycle that begins with extracting raw materials, followed by production, and culminating in sales. In the context of HEIs, the products procured are predominantly consumed on campus and eventually discarded. Subsequently, the responsibility for the material's life shifts to the waste disposal company.

While internal material flow encompasses the movement of substances within a single company, cross-company material flow delineates the trajectory of material throughout the entire value-added chain. This cross-company material flow management aligns with the product life cycle, encompassing stages such as raw material input, manufacturing, distribution, utilisation, and consumption, ultimately concluding with disposal, as articulated by Hinz (2006). Importantly, each phase of the product's lifespan introduces a distinct set of involved stakeholders.

3.4. Chapter conclusion

This chapter is dedicated to answering the following sub-question: *How can Higher Education Institutions contribute towards the advancement of a Circular Economy?*

In this chapter, the investigation into the role of HEIs in advancing the CE has uncovered multifaceted dynamics at play. HEIs hold substantial potential as drivers of sustainability beyond their academic functions. Through their engagement with local stakeholders, municipalities, and industries, HEIs not only influence regional CE landscapes but also serve as catalysts for societal change.

However, a critical examination of the challenges inherent in managing material flows within campus operations reveals the complexities involved. While MFA has provided insights into these flows, the practical integration of these insights into decision-making processes remains elusive.

This gap highlights the necessity for a paradigm shift towards the management of material flows, emphasising strategic goal-setting, stakeholder collaboration, and a nuanced understanding of product life cycles. Moreover, the examination of stakeholder dynamics underscores the importance of effective communication and cross-company interactions in achieving sustainable outcomes.

Therefore, by embodying the management of material flows, HEIs can transition towards circular campus operations, inspiring sustainable behaviour in other organisations, enterprises, industries, and their own community.

4
Methodology

This chapter covers the methodology. In Section 4.1, the framework guiding this thesis is introduced and the method of material flow management (MFM) is explored, shedding light on its meaning and principles. Section 4.2 takes a closer look at the management structure of TU Delft. Subsequently, the evaluation of the MFM through interviews is detailed in Section 4.3. Finally, Section 4.4 provides a cohesive summary of the key findings.

4.1. The management of material flows

Mendoza et al. (2019a) underscores the common challenge faced by HEIs in identifying a suitable analytical framework and indicators to assess CE solutions effectively. As highlighted in Section 3.2.1, the adoption of MFA and other assessment tools to evaluate circularity strategies in HEIs is not adapted well enough to the complex management structure of these types of organisations (Binder, 2007a, 2007b). Existing models are predominantly static, offering data from a single year. While this approach can provide initial insights into problematic waste flows, it falls short when aiming for objective-oriented management. It cannot track progress and assess the impact of implemented strategies over time.

To solve these challenges, the idea of material flow management (MFM) arises, which researchers have tried to conceptualise in the past, but its application remains very limited. It's crucial to highlight that, in contrast to the well-established MFA framework, MFM has not been fully conceptualised and is not as widely applied at this point. A search on the Web of Science using "Material Flow Management" in the title, yields a total of 33 papers, while "Material Flow Analysis" has 484 in total. Among these 33 papers, the term material flow management is often used loosely. It's essential to discern between the general management of material flows, sometimes referred to as material flow management, and the specific concept of Material Flow Management, which delves into its meaning and application through research. As the concept of MFM is still in its early stages, there is considerable flexibility in defining what an MFM model should encompass and the functions it should perform. According to the Wageningen University & Research (WUR), implementing MFM is a complex task which remains uncommon in the Netherlands (or worldwide), and there are no off-the-shelf solutions available yet (WUR, 2021).

At the heart of MFM lies the mapping out and quantifying of material flows (Hilty & Rautenstrauch, 1997; Hinz, 2006). MFA, therefore, serves as a specific tool and methodology within the broader context of MFM, focusing on quantifying and analysing the physical flows of materials. According to Enzler (2006), MFM stands apart from MFA by prioritising stakeholder needs during analysis and planning. Serving as an umbrella term for related methods, MFM primarily involves the analysis and optimisation of material and energy flows and acknowledges the need for diverse applications across different levels, ranging from entire regions as system boundaries to individual companies (Hinz, 2006). Furthermore, it underscores the importance of material management for the benefit of sustainable development (Heck, 2011; Held, 1994). Notably, MFM recognises the value of integrating stakeholder and network analyses with the technical aspects of mapping material flows. Given the unique approach of the CE, which focuses on restructuring material flows, MFM and related tools naturally emerge as distinct methods that support CE implementation and prove valuable for planning activities within the CE framework (Yong, 2007).

Within the broader context of CE, indicators play a vital role in assessing the overall performance and progress towards circularity goals (Delahaye et al., 2023; Elia et al., 2016). Indicators can measure key aspects such as resource efficiency, material circularity rates, waste diversion rates, and the adoption of circular business models. These indicators provide valuable insights into the effectiveness of circularity strategies, enabling stakeholders to identify areas for improvement and refine their approach towards achieving a CE (Calzolari et al., 2022; Corona et al., 2019).

4.1.1. The Material Flow Management Framework

In response to the complexities identified in the CE implementation within HEIs and the limitations of existing MFM frameworks, a novel framework is proposed. Illustrated in Figure 4.1, this framework encompasses two parallel processes aimed at both analysing and managing material flows within the campus environment. The circles' upper parts represent the technical analysis, while the lower parts represent management. It is important to maintain a clear distinction between the two.

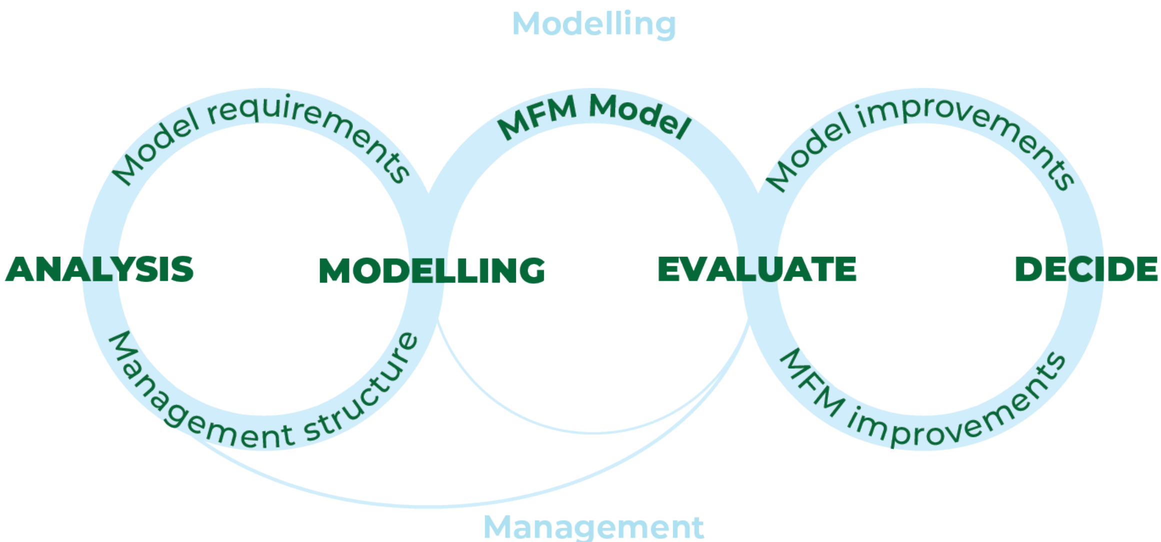

Figure 4.1: The Material Flow Management Framework

Analysis phase

The Analysis phase entails an examination of the management structure governing material flows within the campus. Various stakeholders across different domains influence decisions regarding products and waste, effectively acting as Material Flow Managers within their respective areas. Through a first analysis of material flow categories and their associated stakeholders, the management structure can be understood, leading to the identification of model requirements.

Modelling phase

The Modelling phase entails the actual modelling process, drawing upon MFA as the cornerstone for MFM. This phase encompasses acquiring relevant data, establishing waste flows, and effectively visualising the scope of the system. Derived from insights garnered in the Analysis phase, specific model requirements emerge, guiding the inclusion of material flow categories and relevant data necessary for modelling and visualisation tailored to stakeholder needs. A comprehensive explanation of the modelling process will be discussed in Chapter 4.

Evaluation phase

The Evaluation phase unfolds on two fronts. The implementation of CE strategies hinges on various factors, including the availability and reliance on data, how data is presented, and its utilisation by key decision-makers within TU Delft. It must be tailored to the specific needs and behaviours of the stakeholders involved to maximise effectiveness. This thesis study marks the initial attempt to create an MFM model designed with such considerations. During the Modelling process, which encompasses data collection and the quantification of material flows, an analysis is conducted to ascertain the availability and reliability of data at TU Delft. This involves assessing whether the data is precise and reliable or is based on assumptions.

Through interviews, the study aims to identify current obstacles to implementing CE strategies and explores how information and data can play a role in overcoming these challenges. Further details on this approach are provided in Section 4.3. Section 4.2 provides an initial overview of TU Delft's organisational structure concerning procurement. This exploration will help determine which roles within the organisation are likely to derive the most benefit from using an MFM model and are, therefore, the focal points for interviews.

4.2. Management structure

This section is dedicated to delving into the organisational structure of TU Delft concerning decision-making related to circularity. The objective is to gain insights into the effectiveness of the mechanisms employed by the organisation in identifying, evaluating, and monitoring the implementation of sustainability strategies.

In addition, to provide context to the organisational structure, an overview is presented of the university's commitment to advancing circularity and sustainability, as highlighted by Mendoza et al. (2019b). TU Delft has explicitly committed to advancing sustainability on its campus. In the upcoming years, the university is set to embark on initiatives aimed at achieving a carbon-neutral, circular, and climate-adaptive campus. These efforts emphasise improving biodiversity and enhancing the overall quality of life within the campus environment. This context sets the stage for a more in-depth exploration of how the principles of CE are implemented and can be optimised within the TU Delft (TU Delft, n.d.).

4.2.1. Introduction to TU Delft campus

Established in 1842, TU Delft is renowned as the oldest and largest public technical university in the Netherlands. It houses nearly 40 technological and scientific disciplines, spanning diverse specialisms distributed across its eight faculties and numerous research institutes. With a student population surpassing 27,000 and a workforce of 6,600 individuals contributing in various areas, TU Delft stands as a prominent and multifaceted institution within the academic landscape (TU Delft, 2022).

Spanning 73 buildings and covering a substantial area of 161 hectares, TU Delft's campus is sizeable, providing a comprehensive environment for academic and research activities (TU Delft, 2018). The university's campus is equipped with a diverse array of research facilities, unique in the Netherlands, catering to a wide range of disciplines. These facilities, which include wind tunnels, a chip facility, a high-voltage laboratory, and a nuclear reactor, as well as capabilities for serious gaming and product evaluation, are utilised for research collaborations with businesses and industry.

Sustainable campus strategy

TU Delft aspires to be the world's leading climate university, and in pursuit of this goal, it has established an ambitious objective to transform its campus into a circular environment by 2030. This initiative involves integrating all resource and waste flows within the campus into circular processes and adhering to the principles of 'reduce, reuse, recycle.' Emphasising a demand reduction, the re-purposing of waste flows, and exclusive reliance on renewable sources for production, this strategic approach aligns with the vision of sustainability outlined by (van den Dobbelsteen & van Gameren, 2022).

In the designated time frame, the university aspires to uphold the adoption of sustainable and circular principles in the procurement and contracting of all new materials, products, or services. The central focus lies on extending the lifespan of raw materials while simultaneously minimising their environmental impact. Circular guidelines are obligatory for both procurement and construction initiatives, with circularity measured through key performance indicators (KPIs). Reflecting this commitment, TU Delft has implemented various initiatives:

- TU Delft is actively implementing the Eat-Lancet diet across all its canteens. The Eat-Lancet diet is a scientifically formulated dietary plan that emphasises a balanced and sustainable approach to food consumption. This transition reflects the university's commitment to promoting healthier and environmentally friendly eating habits among its community.
- In a move towards reducing single-use plastic waste, TU Delft has adopted the reusable Billie Cup as an alternative to disposable coffee cups. It is a reusable option, aiming to minimise the environmental impact associated with the use of traditional throw-away cups (Tessa van Mourik, 2023).
- TU Delft has committed to sustainable practices by embracing geothermal energy as a renewable source of power. This strategic adoption of geothermal energy is a significant step towards reducing the university's carbon footprint by shifting away from the use of fossil energy. Furthermore, this initiative underscores TU Delft's commitment to research excellence in sustainable energy. The infrastructure serves as a living laboratory, providing valuable data and insights that contribute to ongoing research efforts aimed at enhancing the efficiency and applicability of geothermal systems (TU Delft, 2023).
- Recognising the importance of a structured approach to sustainability initiatives, TU Delft has established a dedicated Sustainability Project Team (SPT). This team plays a central role in overseeing and managing various sustainability projects across the university. Their coordination ensures that sustainability efforts are cohesive and aligned with the institution's overarching goals (TU Delft, n.d.).
- TU Delft has taken a decentralised approach to sustainability by appointing local sustainability coordinators for each faculty. These coordinators serve as key figures within their respective academic units, fostering sustainability initiatives tailored to the specific needs and dynamics of each faculty (TU Delft, n.d.).

In addition to these efforts, TU Delft is involved in an extensive and ongoing venture. They have established a tangible experimental area on campus known as the Green Village. Acting as a living lab on the TU Delft Campus, it focuses on the built environment, providing a space for testing at various levels, from neighbourhoods to streets and buildings. This area serves as a hub for living, working, and learning. Addressing technical, business-economic, socioeconomic, and regulatory/policy challenges,

The Green Village supports innovative entities in expediting their transition from theory to practical implementation to achieve meaningful impact (The Green Village, n.d.). As outlined in TU Delft's 'Vision, Ambition, and Action Plan,' the overarching objective is to extend the concept of a living lab throughout the campus, aiming to cultivate innovation and facilitate implementation (van den Dobbelsteen & van Gameren, 2022).

The ambitious goals and initiatives undertaken by TU Delft underscore its commitment to becoming a more sustainable university. The university's dedication and determination are evident in its impressive rise in the QS World University Ranking, securing the 14th position in 2024 compared to the 23rd position the previous year (QS World University Rankings, 2023). This notable improvement positions TU Delft as a compelling case study for examining sustainable practices in higher education institutions.

Carbon footprint of the TU Delft

In van Mastrigt and Tax (2023)'s study, it was revealed that in 2022, the university was responsible for 103.000 tons of CO2 emissions. Of this, 13.600 tons originated from direct emissions, primarily due to gas consumption for heating and electricity generation. Approximately 89.000 tons came from indirect sources, including construction activities, building services, and the use of instruments and equipment within the university. This means that indirect emissions comprised a significant portion, totalling 87 % of the overall emissions. Figure 4.2 illustrates the five major categories at TU Delft and their corresponding indirect emissions.

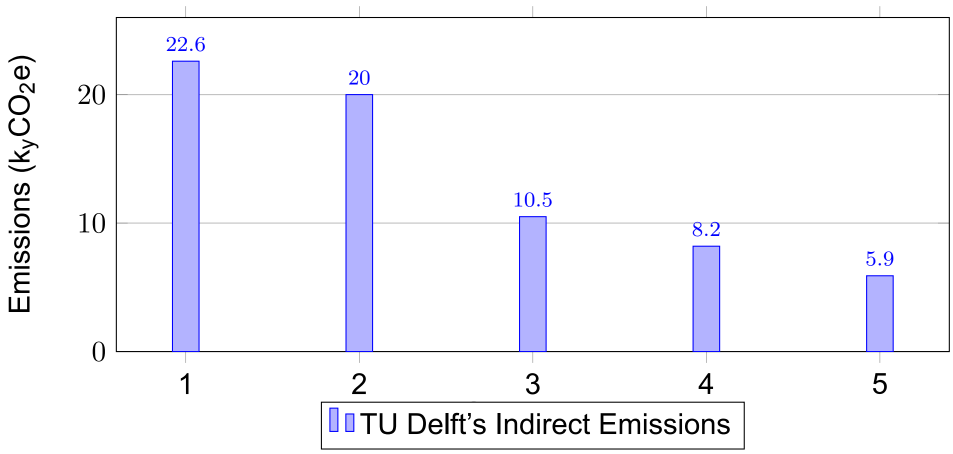

Figure 4.2: TU Delft's Indirect Emissions of 2022 by Category (k_yCO_2e)

Buildings and building-related installations and services (1) encompass cleaning, food and catering, and utility management. Specific services (2) include obtaining, leasing, and maintaining instruments and equipment, including metalworking, plastics, and laboratory materials. Additionally, it included (electro)technical consumables necessary for the university's technical infrastructure.

Automation and telecommunication (3), include the emissions from the digital operations of the university, encompassing the footprint of purchasing, renting, and maintaining hardware such as computers, printers, and network equipment, as well as the acquisition and maintenance of software, infrastructure, and the use of telecommunications, both mobile and fixed.

Office and business management resources (4) include maintaining and running a typical (research) workplace, involving office supplies, paper, computer accessories, office and laboratory furniture, and printed materials, as well as those associated with business insurance, advertising, and logistics. The fifth category is not related to procurement in any way and is called 'Work as secondment and temporary personnel' (5).

Except for the last category, it's evident that each category is, in some way, linked to procurement. All these products necessitate resources for manufacturing and are transported to TU Delft. Once on campus, they are utilised and eventually discarded, contributing to carbon emissions. CE emerges as the appropriate framework to address these resource challenges, considering the entire supply-chain dependency on various suppliers that collaborate with TU Delft.

This sentiment can be seen in the recommendations provided by van Mastrigt and Tax (2023) in their study. To mitigate these emissions, they propose that the university should adopt sustainable procurement and real estate policies. Furthermore, they emphasise the importance of collaboration with suppliers who prioritise sustainability, adhering to principles of reduction, reuse, and recyclability in material acquisition.

4.2.2. Integral management

The TU Delft follows the principle of integral management, which entails a comprehensive and coordinated approach. This approach ensures that both primary tasks (such as academic research, education, and knowledge transfer) and support services are managed in an integrated manner to achieve the overall (circularity) goals and objectives of the institution. In integral management at TU Delft, decision-making and responsibility are distributed across three administrative levels: the Executive Board, faculties, and departmental directors. This decentralised structure allows each level of administration to have a role in shaping and implementing policies related to the university's core functions. An overview of the organisational structure can be found in Appendix A. The key administrative bodies involved in integral management include:

Executive Board

The highest level of leadership at the university, responsible for overall strategic decision-making and coordination. The Executive Board oversees the entire institution and ensures alignment with its mission and goals.

Faculties

These are academic units within the university, each focusing on specific disciplines or fields of study. The deans, responsible for leading the faculties, play a crucial role in managing academic activities, encompassing research and education, within their respective domains. Furthermore, the Faculty Management Team (MT) includes multiple Department Chairs and the Faculty Secretary, as well as other Directors. The composition varies across faculties.

In total, there are eight faculties at the TU Delft: Architecture and Built Environment (Arch), Civil Engineering and Geosciences (CEG), Electrical Engineering, Mathematics & Computer Science (EEMCS), Industrial Design Engineering (IDE), Aerospace Engineering (AE), Technology, Policy and Management (TPM), Applied Sciences (AS) and Mechanical Engineering (ME).

Even though faculties operate within the framework set by the Executive Board, there remains space for them to make distinctive decisions that align with their unique values and priorities. The MTs of the faculties maintain a degree of autonomy. One notable instance of faculty autonomy is exemplified by the Faculty of Architecture, which made a significant shift towards sustainability by transforming its canteen into a fully vegetarian establishment in 2021 (TU Delft, 2021). This decision reflects the faculty's independent choice to align its offerings with specific values, diverging from the standard practices across other faculties.

Another area showcasing this autonomy is the variance in waste separation methods. While several buildings diligently segregate paper, PMD (Plastic, Metal, and Drink cartons), coffee cups, and residual waste, other buildings may only provide bins for residual waste and coffee cups. This discrepancy in waste separation practices underscores how faculties exercise decision-making power in the implementation of operational procedures.

Concerning sustainability, a novel role has been established in each faculty known as the Local Sustainability Coordinator (LSC). As a TU Delft staff member, you have the opportunity to contribute to the sustainability of your department or faculty and enhance the campus's overall sustainability. In various faculties and departments, an LSC is appointed to serve as an ambassador affiliated with the Sustainability Project Team (SPT).

Departmental Directors

These are units within faculties that focus on specific academic disciplines or research areas. Departmental directors are responsible for managing the day-to-day operations, research projects, and educational programs within their departments.

University Corporate Office

The support for the primary processes is organised within the University Corporate Office. This centralised office provides support services that are essential for the functioning of the entire university. It includes administrative, financial, human resources, and other support functions to ensure the smooth operation of the institution.

In regards to implementing circularity strategies and goals, one of the university services that have a large influence is Campus Real Estate & Facility Management (CREFM). CREFM develops and manages the real estate and grounds of TU Delft. In addition, it provides all the products and services needed to sustain campus operations, such as the canteen, office supplies, furniture and more. The organisational structure of CREFM can be found in Appendix A.

Finance is responsible for developing the financial strategy and policy of TU Delft. Finance also takes care of business control, procurement, treasury management, tax matters, insurance and (operational) activities concerning financial information reporting.

4.2.3. Management Structure of material flows

In general, a management structure describes how roles, power and responsibilities are assigned and coordinated, and how information flows within the organisation. TU Delft has a comprehensive management structure that regulates various aspects of its operations. However, this study focuses specifically on a subset of this overarching framework, concentrating on the management of material flows in the context of CE initiatives. This segment of the management structure relates primarily to facilities management, excluding considerations related to the built environment. Figure 4.3 presents an illustrative depiction of TU Delft's management structure tailored to material flows, providing a simplified yet thorough understanding of its key components.

Importantly, alongside well-known stakeholder groups that significantly influence material flow management, less conventional groups are also included. These include the TU Delft Community and Contract Partners. While they may not officially hold positions in TU Delft's management, they possess the capacity to influence material flows in their own right, as explained below.

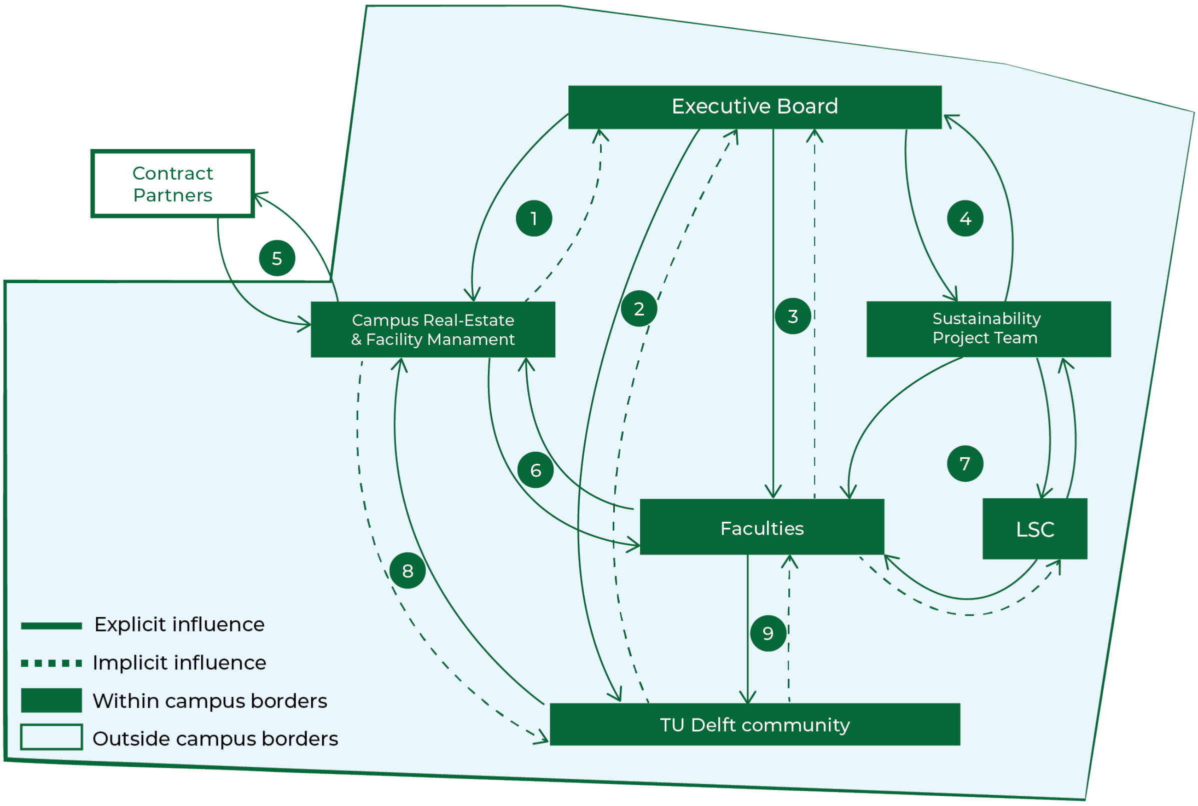

Figure 4.3: Overview of the Management Structure of Material Flows

Figure 4.3 illustrates arrows indicating various forms of management or influence between entities. Dotted arrows signify interactions of lesser significance. The interactions between entities are numbered from one to nine, each explained below:

1. The EB ensures that the CREFM aligns with TU Delft's ambitions and goals, reporting closely to them. Larger initiatives by CREFM require approval from the EB.
2. Students and staff must adhere to TU Delft's rules and regulations, overseen by the EB. However, the TU Delft community can also influence the EB through various channels.
3. Faculties are bound by rules and regulations set by the EB and must contribute to the ambitions and goals but can also exert influence on the EB in certain circumstances.
4. The SPT advises the EB on CE strategy implementation, being more specialised on this area. The SPT also abides by the EB's rules and regulations and contribute to the ambitions and goals in their respective area of influence.
5. CREFM selects new contract partners, including suppliers and waste management companies, through a tender process, significantly impacting TU Delft's circularity performance. A more detailed explanation can be found in sub-section 4.2.5.
6. Choices made by CREFM affect the circularity performance of Faculties. While Faculties have some autonomy, they must work with the options provided by the contract partners.

7. Each Faculty has a LSC guiding sustainability and circularity decisions, operating within the SPT. While unable to directly control Faculties, the SPT provides advisory support.
8. The criteria established during the tender process reflect the preferences of the TU Delft community, which partially influence CREFM's decisions.
9. Faculties have the most direct influence on the TU Delft community, as they spend most of their time within their respective Faculty. Consequently, they play a central role in motivating sustainable behaviour within the community.

By delineating these interactions, a clearer understanding of TU Delft's management structure for material flows emerges, highlighting the interconnectedness among various stakeholders and their roles in fostering circularity on campus.

4.2.4. Inflow categories of TU Delft

Different types of products and materials are needed to sustain TU Delft's campus operations. When excluding the built environment and purely focusing on the facility management-related product of the TU Delft, the university has seven inflow categories as depicted below. In addition, some examples of waste generated from the inflow categories are named and the assigned waste bin in which it is disposed of.

1. **Canteen**:
   - *Main waste items*: Food waste, packaging, foodware
   - *Waste streams*: GFT, PMD, Glass
2. **Cleaning**:
   - *Main waste items*: Plastic bottles and containers, chemical waste, cleaning cloths
   - *Waste streams*: PMD
3. **Electronics**:
   - *Main waste items*: Computers, larger office equipment, batteries, electronic components, larger research equipment
   - *Waste streams*: Electronic
4. **Furniture**:
   - *Main waste items*: Desks, chairs, lamps, cabinets, tables, sofas
   - *Waste streams*: Electronic, Debris
5. **Lab Equipment**:
   - *Main waste items*: Glassware, wipes, gloves, chemicals, smaller research equipment
   - *Waste streams*: Glass, PMD, Hazardous, Electronic
6. **Office Supplies**:
   - *Main waste items*: Paper, pencils, printer cartridges, staplers
   - *Waste streams*: Paper/cardboard, PMD, Electronic
7. **Vending**:
   - *Main Types of Waste*: Plastic wrappers, bottles, aluminium cans
   - *Waste Streams*: PMD

8. **Off-campus**:
    - *Main waste items*: Food and food packaging
    - *Waste streams*: GFT, PMD

Canteen

The food and beverage services at TU Delft represent a significant aspect of campus life, with various outlets catering to the diverse needs of students, staff, and visitors. Understanding the flow of materials and waste within these operations is essential for developing sustainable practices in line with the principles of the CE.

The food and beverage inflows at TU Delft manifest through various channels. Primarily, the university's canteens serve as significant contributors, offering lunches (and occasionally dinners) to all campus visitors. Moreover, the current catering operator manages multiple coffee corners dispersed across the campus. Beyond the canteens and coffee corners, the same catering operator oversees catering services for events and meetings. It is noteworthy to differentiate between meetings, typically involving smaller groups, and events, which can attract larger crowds ranging from several individuals to hundreds. For extensive events, external catering services are engaged to accommodate the larger number of attendees.

Furthermore, TU Delft has two restaurants that offer sustenance throughout the entire day, including evenings. The Faculty Club, situated in the Aula, and X, positioned within the sports and culture centre, play pivotal roles as sources of canteen and catering inflows. Lastly, the campus has several food trucks, operated under the same catering umbrella, providing food and beverages specifically around lunchtime. In summary, regarding canteens and catering, the TU Delft has the following inflow sources:

1. Cafeteria
2. Coffee corners
3. Events
4. Food trucks
5. Meetings
6. Restaurants

Figure 4.4 provides an overview of the waste generation process within the Cafeteria, where lunch and other meals are prepared by staff. Subsequently, individuals purchase, consume, and dispose of waste as necessary. The waste generated from these operations primarily comprises packaging, food waste, and food ware, which includes plates, cutlery, cups, and similar items. Although swill bins for food waste disposal are available in some canteens, there is a notable absence of dedicated methods for separating food waste across the university. Consequently, a significant portion of food waste finds its way into residual waste bins, as highlighted in previous research conducted by Stephan et al. (2019).

Cleaning materials

Maintaining cleanliness at TU Delft is not only crucial for hygiene but also presents an opportunity to embrace sustainable practices. Within this realm, the choice and management of cleaning materials play a pivotal role. Currently, cleaning materials have been associated with a linear consumption model, where products are used and disposed of after a single use, leading to significant waste generation.

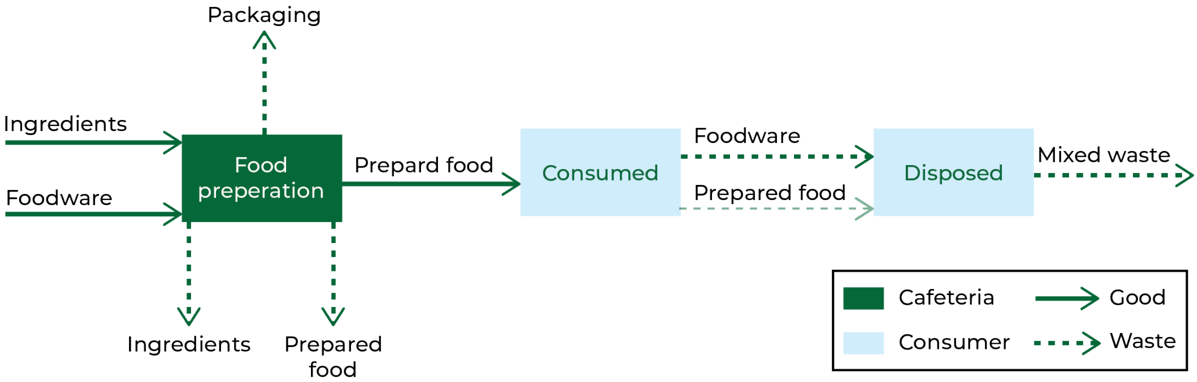

Figure 4.4: Process of Preparing and Buying Food in the Cafeteria

The primary sources of waste in cleaning operations at TU Delft stem from the packaging of cleaning products and the disposal of used materials. Plastic bottles, often used to contain various cleaning agents such as disinfectants, all-purpose cleaners, and degreasers, contribute to plastic waste accumulation. On average, the TU Delft consumes approximately 19,300 bottles of various cleaning products annually. Additionally, the plastic bags utilised for waste collection during cleaning activities also contribute to waste generation.

Beyond the disposal of packaging, the environmental impact of cleaning products themselves must be considered. Many conventional cleaning agents contain chemicals that can be harmful to both human health and the environment. Furthermore, the wastewater generated during cleaning operations may contain pollutants that can negatively impact local ecosystems if not properly managed.

Electronics

The category of electronics at the university encompasses a range of devices utilised for building maintenance, including freezers, batteries, computers, printing machines, and light bulbs, with these items having a longer lifespan compared to consumables like cleaning materials or food. This longevity contributes to electronics being a significant component of the university's material stock over an extended period.

As indicated by a study conducted by Stephan et al. (2019), the 'electronics' inflow category stands out with the highest embodied energy, water, and greenhouse gas emissions, as well as associated costs. This high impact is attributed to various factors. Firstly, the extraction and processing of raw materials, such as metals (e.g., gold, copper, aluminium) and minerals (e.g., rare earth elements), used in electronics, are energy-intensive and environmentally impactful, with mining and transportation contributing to embodied GHG emissions.

Electronic waste contains various hazardous substances, including heavy metals and polychlorinated biphenyls (PCBs), which, if improperly processed, can be released into the environment, leading to environmental challenges, as well as health problems (Sinnadurai & Charles, 2009). Furthermore, it's estimated that for every kilogram of electronic equipment produced, five kilograms of waste is generated during the manufacturing process, requiring 25 kilograms of raw material extraction (UNEP, 2002). Additionally, the energy consumption during the use phase of electronic devices is a significant contributor to their overall emissions.

The significant environmental impact of electronics throughout their lifespan underscores the need for careful consideration and the implementation of smart strategies to mitigate their effects. Encouraging the adoption of CE principles can contribute to reducing the environmental footprint of electronics. In addition, efforts aimed at designing more energy-efficient devices in combination with energy consumption reduction strategies can help decrease emissions of electronic products throughout their lifespan.

Lab equipment

Laboratory activities at TU Delft involve a diverse array of equipment and materials, each contributing to the university's research and educational objectives.

The materials used in laboratory equipment, including plastics, metals, glassware, and electronic components, can have significant environmental implications. Laboratory equipment encompasses a wide range of instruments, from basic tools to sophisticated machinery, all essential for conducting experiments and analyses. Maximising the utilisation and lifespan of these assets is critical to reducing resource consumption and minimising waste generation.

Laboratory activities often generate various types of waste, including hazardous chemicals, disposable consumables, and obsolete equipment. Implementing robust waste management practices, such as proper segregation, storage, and disposal procedures, is essential to minimise environmental contamination and ensure compliance with regulatory requirements.

Furniture

Much like the inflow category electronics, furniture in general has a long product cycle within the buildings of the TU Delft. Most of the furniture that is bought goes via the main contracting party. Still, faculties and departments are allowed to buy furniture from other suppliers and companies. The procurement and deployment of furniture within the TU Delft involve the facility teams of buildings and faculties, known as local FM. These teams play a crucial role in assessing the need for new furniture and overseeing their placement. Additionally, CREFM has established a Furniture Expertise Team, which provides support to the local FM in their furniture-related decisions.

Each faculty and department within the university enjoys a certain degree of autonomy and influence in determining their furniture preferences. Moreover, they manage the procurement and deployment of furniture using their allocated budgets. The responsibility and ownership of furniture vary depending on the type, with some being under the responsibility of the university service CREFM, while others are owned by specific faculties and their departments. Regardless, both the faculties, particularly their MT, and CREFM exert significant influence on the overall circularity performance of the furniture.

Office supplies

Office supplies encompass a diverse range of products essential for daily operations in academic and administrative settings. Paper products such as printer paper, notebooks, and envelopes are commonly used for documentation and correspondence, but they contribute to waste generation through discarded or unused materials. Writing instruments like ballpoint pens, pencils, and markers also add to waste when they run out of ink or become damaged and are being disposed of. Desktop accessories such as staplers, paper clips, and binders, while aiding the organisation, generate waste.

Off-campus sources

In a comprehensive study conducted by Stephan et al. (2019), the authors discerned that a significant proportion of waste emanates from off-campus sources, specifically from food-related waste flows and their accompanying packaging. Notably, this crucial data cannot be derived from the university's internal purchase records. Instead, it hinges on the behaviours of campus visitors, encompassing students and staff, who may bring their own food and beverages, complete with packaging, onto the premises.

Recognising the unique context of TU Delft compared to the Australian campus studied in the referenced research, it is essential to acknowledge that the fundamental challenge of accurately mapping out off-campus-related inflows persists. Although the specifics of the TU Delft scenario may differ, the broader implication remains relevant: off-campus inflows significantly contribute to waste generation, introducing complexities in terms of precise modelling and analysis.

Vending

Within the TU Delft, the inflow category Vending is done by a different company than Catering & Canteen. In general, the TU Delft has three types of vending machines that are placed within the buildings:

- Coffee machines
- Beverages
- Snack foods

Firstly, there are various types of coffee machines available on campus, some exclusively providing coffee, while others offer a range of hot beverages like chocolate and tea. Until July 2023, the coffee machines dispensed hot drinks in coffee cups made from a combination of cardboard and a layer of plastic. These cups were prevalent and easily accessible. However, as part of a new circularity strategy implemented by TU Delft in July 2023, a reusable cup, the Billie Cup, was introduced, as mentioned in Section 4.2.1. This initiative aims to reduce waste generated by coffee cups, which cannot be recycled effectively due to the combination of plastic and cardboard (Renewi, 2020).

In addition to coffee machines, TU Delft has separate vending machines for beverages, including sodas, water bottles, and other cold drinks. The waste generated from these machines typically consists of plastic (PP, PET, and other materials) and aluminium from the cans. Another type of vending machine on campus offers snack foods, ranging from candy bar wrappers like Mars and Snickers to popcorn and healthier options such as nuts and energy bars. The waste generated from these snacks is predominantly plastic when discarded.

4.2.5. Procurement procedure

Procurement, in essence, is the comprehensive process of discovering, negotiating terms, and obtaining goods, services, or works from external sources. This often involves engaging in tendering or competitive bidding procedures. The primary objective of procurement is to ensure that the buyer acquires the desired goods, services, or works at the optimal price, taking into account factors such as quality, quantity, delivery time, and location.

As highlighted in Sub-section 4.2.4, HEIs heavily depend on imported products to support campus facilities. Consequently, the suppliers engaged by the TU Delft play a pivotal role in shaping the circularity performance of the institution. The (design) decisions and practices of these suppliers directly impact the overall sustainability and circularity of the products integrated into the campus infrastructure. Therefore, the selection of suppliers and the subsequent agreements developed between them and TU Delft hold paramount significance.

Whilst universities operate as public law institutions, they have to adhere to European regulations. In addition, when a tendering assignment is equal to or higher than the European threshold values, the assignment is carried out via an official European tender procedure (Rijksoverheid, n.d.). This provides guidelines and rules that govern various aspects of procurement, emphasising transparency, fair competition, and accountability. For all the inflow

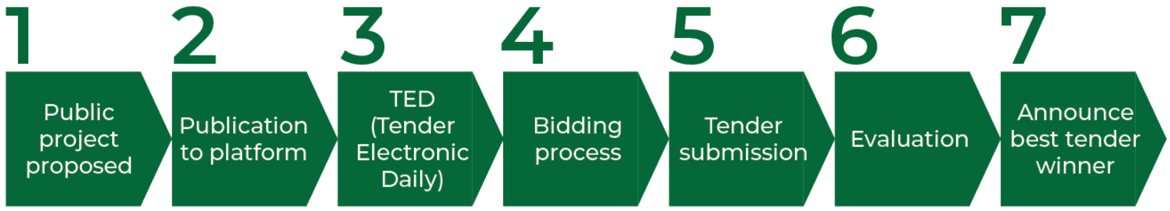

Figure 4.5: The Standard Procedure of Public Procurement EU

categories as mentioned in Sub-section 4.2.4, a public procurement process must be done to find a supplier. Figure 4.5 shows this procurement process.

In addition to their primary objectives, universities have the opportunity to integrate sustainability and circularity criteria into their procurement processes (Meehan & Bryde, 2011). Knowing how much impact suppliers have on our environment, there has been an increase in research on concepts such as 'sustainable procurement' or 'circular procurement' to navigate the environmental impact of the product purchased. Still, these concepts are still in its infancy.

4.3. Semi-structured interviews

Relevant stakeholders at TU Delft were involved in semi-structured interviews, selected as the method for evaluating the effectiveness of the MFM model in supporting their roles. In total, 10 interviews were conducted, with each session recorded and transcribed for thorough analysis. Subsequently, a summary of individual interviews is crafted and presented to the participant for validation.

The semi-structured interview format incorporates predefined questions to guide the discussion framework. This approach allows for flexibility and depth as the conversation is shaped by the interviewee's knowledge, potentially leading to the exploration of additional topics. The interviewer has the freedom to follow the interviewee's responses, enhancing the qualitative richness of the data. It is essential to recognise that not all questions in the interview protocol may be covered, and new inquiries may arise during the interview. While offering flexibility and qualitative depth, this method acknowledges its lower validity and potential for bias as downsides. Through analysing the dynamics of TU Delft (Section 4.2), two types of interviewees were chosen:

- Local Sustainability Coordinators (LSCs)
- Members of the Facility Team CREFM

Given that LSCs function as local ambassadors within their respective faculties or buildings, they are well-positioned to recommend CE strategies to the MT team. Members of the FM team, particularly CREFM, play a crucial role in selecting suppliers and determining the types of products used on campus. Therefore, a group of decision-makers will be interviewed to explore top-down strategies and rules applied both campus-wide and for specific buildings, encompassing these two significant dynamics.

It's important to note that while LSCs and FM members are employees who could benefit from utilising the MFM model, they may not be the only ones. As illustrated, various organisations and departments are actively working to implement sustainability strategies, indicating a broader interest and involvement beyond these roles. However, due to time constraints, other groups have been excluded from this thesis study.

The interview aims to glean insights from LSCs and FM members at TU Delft regarding their roles in advancing circularity within their respective spheres of responsibility. It is structured into two parts. The initial segment delves into general questions surrounding circularity, exploring how participants perceive the impact of their roles on overall circularity, their understanding of circularity concepts, and the challenges encountered in implementing circularity strategies. The interview further delves into their perspectives on shaping decision-making processes related to circularity and sustainability. Additionally, coordinators are queried about specific information, resources, or support pivotal to fulfilling their roles, with a discussion on the potential contributions of information and data exchange to circularity strategy implementation.

The second part transitions into an unstructured discussion, testing a model's relevance and features tailored to the interviewees' roles. This section involves a more free-flowing conversation, presenting participants with real numbers and facts from the MFM model pertinent to their specific roles. The objective is to assess the relevance of provided information, identify functionalities crucial for the model's effectiveness in supporting their roles, and understand their preferences for utilising the model. Additionally, coordinators share their insights on preferred methods of visualising data, offering opinions on specific graphs or visualisations. This phase aims to gather valuable feedback for refining and optimising the model.

To analyse and interpret the data obtained from the interviews, a systematic approach was followed. Initially, participants were asked for consent to record the interviews, facilitating accurate transcription of the audio recordings. Subsequently, transcripts were generated from these recordings, capturing the entirety of the discussions. These transcripts served as the primary data source for analysis.

The analysis process involved coding the transcripts for themes using an inductive approach. This method allowed for the emergence of new codes during the interpretation phase, based on the content found within the transcripts. Each segment of the text was systematically reviewed, and relevant themes or patterns were identified and assigned codes. These codes were then organised and analysed to derive key insights and findings from the data.

4.4. Summary of key findings

As discussed in Chapter 2, the complexity of HEIs suggests that the method of MFA is not suitable for this specific context. Previous scholars have noted that, in dynamic contexts with multiple stakeholders and diverse opinions and interests, a more comprehensive approach involving stakeholder and network analysis is necessary. This insight underscores the preference for MFM over MFA, as MFM proves more suitable in contexts featuring various actors and perspectives, emphasising an objective-oriented approach.

Recognising the integral connection between the effectiveness of MFM and the management structure, the roles of actors within TU Delft become paramount. Within TU Delft, hierarchical structures emerge, featuring both top-down and bottom-up influences. The Executive Board, operating from the top-down, implements rules and directives. Simultaneously, faculties wield significant influence, boasting a distinct internal anatomy.

In this context, CREFM plays a pivotal role as they manage facilities across the university. While faculties can collaborate with CREFM, it is CREFM that facilitates the procurement process and chooses the suppliers. Recognising the importance of these products in the overall circularity and sustainability performance of the university, this collaborative effort becomes crucial in steering TU Delft towards its CE objectives.

5
Modelling

This chapter provides an answer to the following sub-question: *How can material flows be modelled to implement and assess Circular Economy strategies in the context of the TU Delft?*

Section 5.1 outlines the chosen modelling method, which draws from both the developed Material Flow Analysis (MFA) method and existing literature. The delineation of system boundaries, a crucial aspect of the modelling approach, is elaborated upon in Section 5.2, where spatial and temporal boundaries are defined. Subsequently, Section 5.3 elucidates the criteria for selecting materials and goods within these system boundaries.

The process of data collection is summarised in Section 5.4, followed by an explanation of data categorisation and classification in Section 5.5. The quantification of material flows is detailed in Section 5.6, providing insight into the magnitude of these flows within the system. Section 5.7 delves into the methodology for modelling and visualising material flows, offering a comprehensive understanding of their dynamics. Next, the significance of achieving a balance between the inputs and outputs of material flows is briefly discussed in Section 5.8. Lastly, this chapter closes by providing a short conclusion to this chapter's sub-question in Section 5.9.

5.1. Modelling approach

What became evident in Section 4.1 is that at the core of MFM lies the method of MFA. In this thesis study, MFA guidelines are therefore employed to model the material flows of the TU Delft. In essence, MFA is a systematic and analytical approach used to comprehensively study the flow of materials through various processes and systems. It serves as a critical tool in environmental management, industrial ecology, and sustainability studies. By quantifying material inputs, outputs, and stocks within a defined system, MFA helps identify inefficiencies and opportunities for resource management (Brunner & Rechberger, 2004).

Typically, the initiation of an MFA involves the initial steps of problem definition and the establishment of clear objectives. Following this, decisions regarding the selection of relevant materials, determination of system boundaries, and identification of involved processes are made. Subsequently, an examination of how these materials interact within the designated system follows. The calculation of substance flows and stocks are then undertaken, with due consideration of any associated uncertainties (Brunner & Rechberger, 2004).

Ultimately, the results are effectively presented to aid in the visualisation of conclusions and to facilitate decision-making aligned with the predefined objectives. It is noteworthy that these procedural steps, do not need to adhere strictly to a sequential order, allowing flexibility to tailor the process to the specific requirements of the analysis (Brunner & Rechberger, 2004). This is in line with the overall design cycle approach that is utilised for this thesis.

Drawing from both the insights from Stephan et al. (2019) and the method articulated in Brunner and Rechberger (2004), a modelling approach has been crafted, visually represented in Figure 5.1. This approach unfolds across four phases: First, the system definition is established, as explained in both Section 5.2 and Section 5.3. Following this, the identification and quantification of material flows take place, a process detailed in Section 5.4, 5.5, and 5.6. Subsequently, the third phase focuses on the modelling and visualisation of these material flows, as explained in Section 5.7 and 5.8. Lastly, the fourth step involves interpreting and discussing the results, an important aspect addressed in Chapter 6.

5.1.1. Choice for software

The choice of software was based on two criteria: the software must be capable of visualising material flows and managing/integrating multiple data sources. Additionally, it is desirable that staff members, specifically LSCs and FM members, find it easy to work with.

One of the programs that Brunner and Rechberger (2004) suggests in his manual is Microsoft Excel. The primary advantage of this approach lies in its widespread familiarity among users. Many individuals are already acquainted with this software, and it is commonly pre-installed on personal computers, eliminating the need for additional software purchases for MFA.

Since the release of *the Handbook of Material Flow Analysis*, Microsoft has introduced another program named Power BI. This platform offers enhanced capabilities for data analysis, making it particularly valuable for the intended purpose. This software can also be installed on the laptops and computers within the TU Delft when requested through the ICT service. Like Microsoft Excel, it can visualise material quantities, but more importantly, it can easily integrate multiple data sources. Therefore, it is more suitable in that way than Excel.

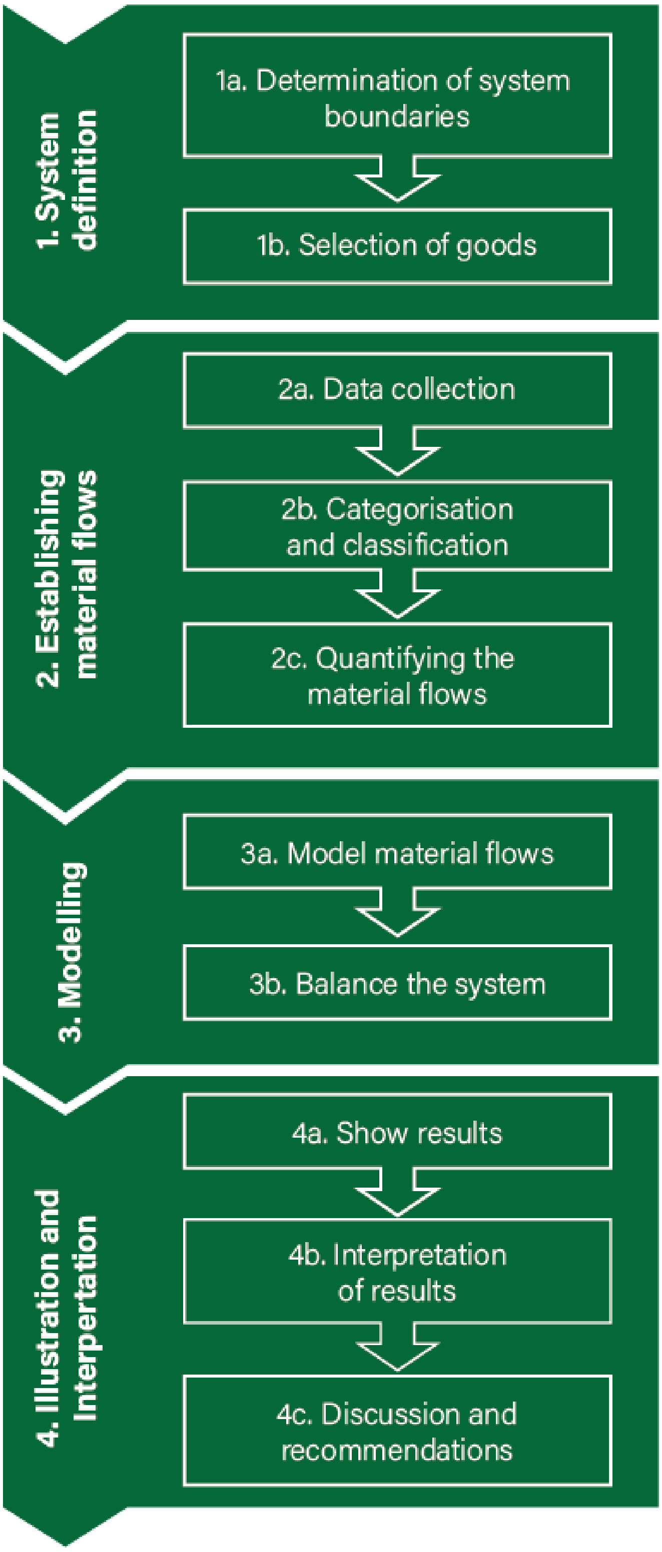

Figure 5.1: Modelling Approach

5.2. Determination of system boundaries

In the context of this thesis, the case study centres on the campus of TU Delft. Specifically, the focus extends to comprehensively understanding the lifespan of materials within the campus setting. This encompasses the entire journey of purchases, products brought into the campus, their usage, and eventual disposal. Subsequently, the disposal process involves the items being discarded in bins within the campus, followed by their management by the waste disposal company.

Spatial system boundary

For this thesis, the campus of the TU Delft is chosen as a case study and therefore also as a spatial boundary. This physical boundary is shown in Figure 5.2.

Figure 5.2: An Overview of the TU Delft's System Boundaries

From the analysis conducted in Section 4.2, it becomes apparent that the various buildings within the system of the TU Delft are important and act as smaller sub-systems. Therefore they are also included in the system boundaries. In general, the buildings can be grouped into four types: faculties, research, educational, and others. Table 5.1 shows the list of buildings within the scope of this thesis and their corresponding numbers.

Table 5.1: Building Numbers and Corresponding Names

Nr	Building name	Nr	Building name
3	Science Centre	34	Mechanical Engineering
5	Kluyver Laboratory	34b	P&E Laboratory
5a	RoboHouse	35	Education Building 35
6	Hortus Botanicus	36	Electrical Engineering, Mathematics & Computer Science
8	Architecture and Built Environment	36	ESP Lab
12	Chemical Engineering	37	X
15	Kramers Laboratory	42	InHolland University
19	STUD	43	WKT
20	Aula	45	VSSD
21	TU Delft Library	45	Wind Tunnel LS
22	Applied Physics	46	TNO
23	Civil Engineering and Geosciences	50	Reactor Institute
25	Greenvillage	58	Applied Sciences
26	Bouwcampus	60	Logistics and Environment
28	Van Mourik	61	Vliegtuighal
29	Echo	62	Aerospace Engineering
30b	Campus and Real Estate	64	Wind Tunnel HS
31	Technology, Policy & Management	66	The Fellowship
32	Industrial Design Engineering	67	Industrial Catalysis Lab
33	PULSE	153	HollandPTC
33b	Coffee & Bikes		

Every building is unique and accommodates a diverse set of individuals, adding an extra layer of intrigue to the study. For example, the TU Delft campus houses a total of eight faculties, each forming its unique community connected to various studies and people. This also leads to differences in facilities as mentioned in Section 4.2.

Temporal system boundary

The chosen period for this thesis encompasses the period from the year 2017 to 2023. The choice of 2017 as the starting point provides a baseline for understanding the initial conditions or circumstances, while the endpoint of 2023 signifies the conclusion of the study period, allowing for a comprehensive evaluation of changes, patterns, or impacts that may have occurred over these years.

In addition, the years 2019 through 2022 are distinct due to the prevalence of COVID-19 in the Netherlands during that period. The safety measures implemented in response to the pandemic had a notable impact on campus dynamics, resulting in reduced on-site presence of individuals. This, in turn, affected procurement activities and generated changes in waste streams. Therefore, it is necessary to incorporate more data from ”regular” years to detect material consumption and waste handling patterns.

5.3. Selection of goods

A substance is any chemical element or compound composed of uniform units. All substances are characterised by a unique and identical constitution and are thus homogeneous. Next to substances, the term ’goods’ is used often (Brunner & Rechberger, 2004). Brunner and

Rechberger (2004) defines goods as: "*economic entities of matter with a positive or negative economic value. Goods are made up of one or several substances*".

A distinction can be made between 'upstream' flows and 'downstream' flows. Specifically, upstream flows denote goods brought to TU Delft, which are products that are composed of various materials and substances. Downstream flows encompass waste streams, collected by the waste disposal company, and exiting the TU Delft system. These waste streams consist of multiple upstream goods. An overview of the TU Delft as a system boundary and its corresponding material flows in Facility Management is shown in Figure 5.3.

The university service CREFM plays a pivotal role in facilitating the provision of goods and services essential for the functioning of the university. This encompasses various aspects, including procurement, maintenance, and waste management. Therefore they influence these flows significantly.

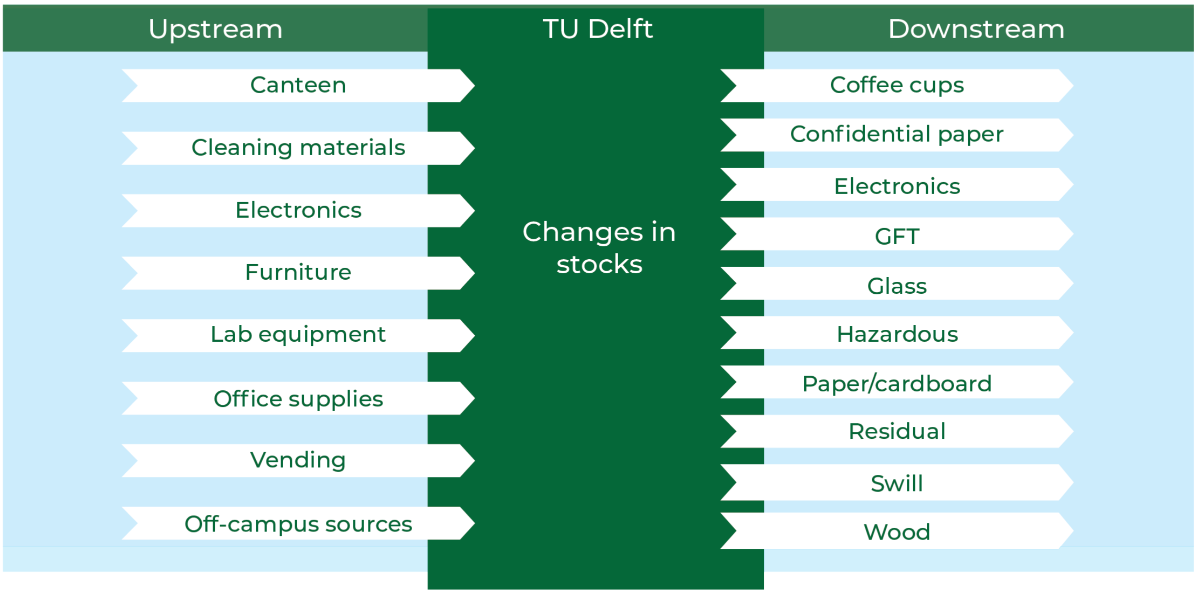

Figure 5.3: Upstream and Downstream Flows within the TU Delft

Upstream

As this thesis focuses on HEIs, in particular the TU Delft, the goods under consideration are everyday products such as cleaning supplies, food items, and coffee cups that are brought to TU Delft and utilised by the campus community. While the built environment also contributes to the upstream of materials, it is excluded from the scope of this study.

Take, for example, a Coca-Cola aluminium can purchased by TU Delft and stored in a vending machine until it finds a buyer on campus. After it has been consumed, the final destination of this can, while not certain, is likely to be the PMD or residual waste bin collected by the waste disposal company. This trajectory is illustrated in Figure 5.4 which shows two examples of products within the vending category.

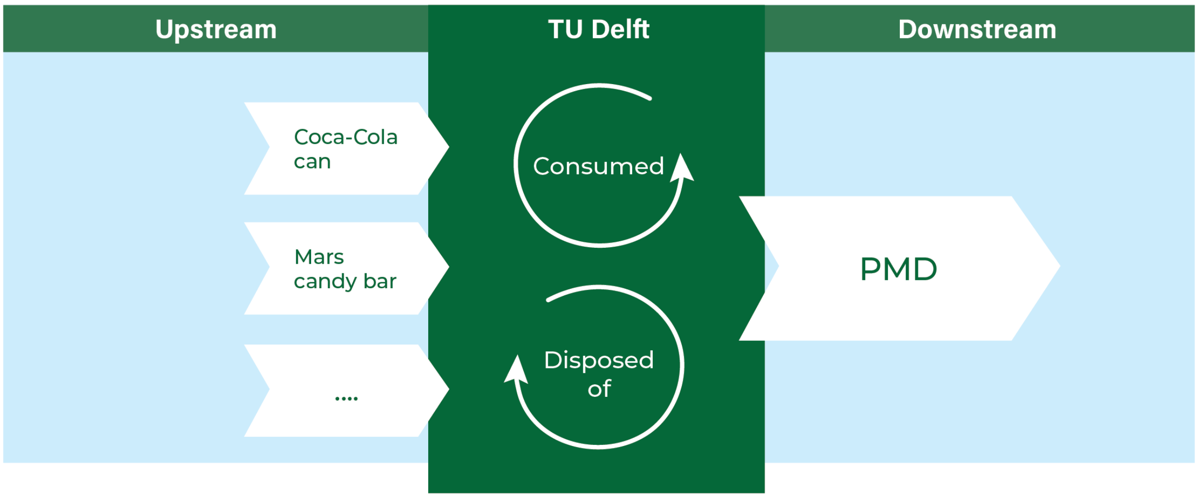

Figure 5.4: Trajectory of Vending Goods

Apart from soda cans and candy bars, there's a variety of goods that are essential for the maintenance of TU Delft's facilities. The following categories of incoming goods have been identified within TU Delft as shown in Figure 5.3.

- Canteen
- Cleaning materials
- Electronics
- Furniture
- Lab equipment
- Office supplies
- Vending
- Off-campus

Downstream

The downstream, also known as waste streams, play a crucial role in the complex "puzzle" that implies the material balance. Modelling all the upstream flows enables an estimation of the downstream size. However, the complexity of HEIs introduces a challenge, as the upstream and downstream may not perfectly align. There could be instances where students or staff members dispose of a significant amount of personal waste brought from home, or vice versa, as shown by the study of Stephan et al. (2019). Consequently, the primary objective is to model the material flows with precision, allowing organisations to create valuable insights. Within the TU Delft system, the following waste streams can be identified:

- Coffee cups
- Confidential waste
- Electronic waste
- Film/plastics
- GFT
- Glass

- Paper/cardboard
- PMD
- Residual waste
- Swill
- Wood

As this thesis is not focused on the built environment, it is crucial to highlight that waste streams labelled 'debris' and 'construction waste' have been purposefully left out of consideration for the scope of this study.

5.4. Data collection

During this research, various types of data were utilised for creating the MFM model. Table B.1 in Appendix B provides an overview of the diverse data sources employed in the study. From Section 2, it became evident that while the TU Delft campus serves as the system boundary, the faculties and buildings within the system are also crucial entities. Therefore, it is essential to distinguish between the buildings. Naturally, given that this is a mass-based approach, the inflows and outflows need to be quantified as accurately as possible to provide a comprehensive overview. For the material inflows, this also entails including the material(s) of the products. The material determines the correct waste bin for disposal. Lastly, for assessing improvement and making comparisons between different periods, it is crucial to include date data to model flows over time accurately. Table 5.2 shows the two category inflows and whether the data includes the correct information for modelling.

Table 5.2: Data Categories Overview

Category	Mass	Building	Material composition	Date
Downstream	Yes, with some assumptions	Partly	No	Yes
Vending	No	Partly	No	Assigned month

As shown, the data that was collected from the two sources is incomplete. The downstream data, while containing mass per waste stream, revealed an inconsistency upon closer examination of the assigned weights. It became apparent that the mass was not consistently measured but instead assumed. Further details and clarification on this matter are provided in Section 5.6.

5.4.1. Data cleaning

An example of data cleaning involves the products from vending machines. Initially, 184 different products were identified from both beverage and food vending machines over the period 2017-2023. However, upon closer analysis, inconsistencies in naming conventions were discovered, resulting in the same product being registered under different names. For instance, a snack from the company Raw containing apricots, sunflower seeds, and pumpkin seeds appeared in three different variations:

- Raw Snack Abrikoos pitten
- Raw Snack Abrikoos pitten BIO

- Raw Snack Apricot Seeds BIO

Although not problematic, this variability in naming made the data unnecessarily cluttered. After cleaning up the data, the number of distinct products was reduced from 180 to 123.

5.5. Categorisation and classification

The categorisation and classification step involves enhancing raw data, such as vending purchase data, by systematically labelling it with additional information. This includes identifying the location or building where products were purchased, labelling products based on their materials, and linking them to specific waste streams determined by waste management. This organised and labelled dataset enables more informed decision-making.

An example of how data labelling is used visually is depicted in Figure 5.5. Having easy access to explore and compare multiple data sheets at a glance is valuable. In this example, a slicer is created allowing users to select specific buildings, years, and months. To achieve this, the original dataset has been assigned labels for buildings and dates, which can then be divided into years and months (or even days for some datasets).

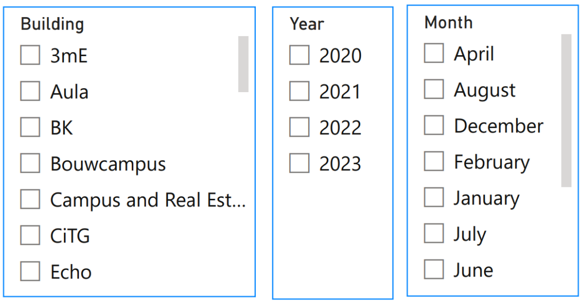

Figure 5.5: The Slicer Function including Buildings, assigned Year and Month

5.5.1. Transforming data

Data transformations are mainly done in the Power Query environment of Power BI. Power Query is a powerful tool within Power BI that facilitates data transformations. It allows users to manipulate and refine data from various sources to create a unified and meaningful dataset for analysis. In comparison to Microsoft Excel, Power BI excels in its capability to seamlessly connect and transform data sheets.

The advantage of Power BI becomes apparent due to its ability to efficiently handle diverse datasets containing information from various time periods, as observed in vending and downstream data. This flexibility is crucial as users often require a comprehensive overview that includes data from different buildings and dates. Consequently, a pivotal step involves converging various datasets into a unified dataset utilised within the model, as illustrated in Figure 5.6.

After appending the data, steps are taken within Power Query to clean the data and merge queries. This involves removing inconsistencies, handling missing values, and restructuring the data as needed. While manually performing these tasks for multiple databases can be time-consuming, Power Query offers automation capabilities. Users can leverage the Advanced Editor function to write and execute custom code that streamlines the data preparation process. The code used for these transformations can be found in Appendix C, providing transparency and enabling users to replicate the process or make adjustments as necessary.

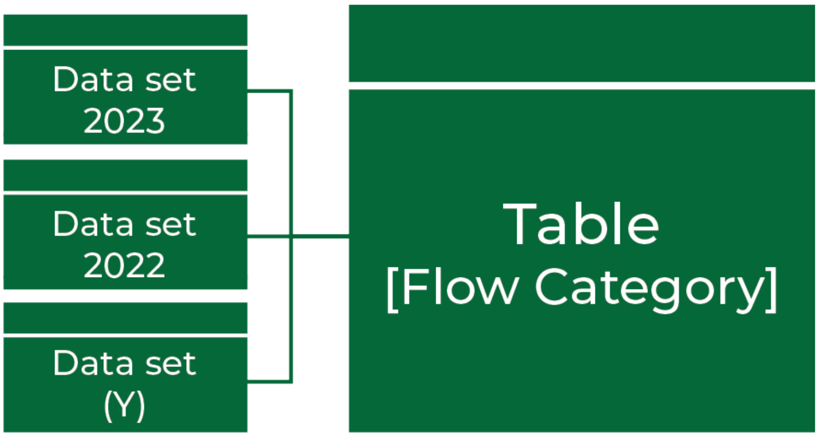

Figure 5.6: Combining Different Datasets into one Table

5.5.2. Labelling

The process of merging queries in Power Query is used for the labelling data. When tables are merged in Power BI, information from different sources is combined based on matching criteria, such as postal codes or addresses. This process results in a new table that includes relevant details from both original tables. For example, rows may display an address alongside its corresponding building name.

Buildings

Adding labels, especially the designation of buildings, is a crucial step. This involves categorising all buildings, as detailed in Table 5.1 in Section 5.2. The rationale behind this is twofold. Firstly, it allows for a detailed breakdown of waste generation at the TU Delft, offering insights on a building-by-building basis for meaningful comparisons. Secondly, the MT of individual buildings and CREFM can implement targeted strategies tailored to specific locations. In the context of buildings, postal codes serve as unique identifiers suitable for merging queries. While ideally, this step may be unnecessary if buildings are included in the contact partners' dataset, their absence necessitates merging queries. Figure 5.7 visually represents a simplified version of the process of merging queries, based on the unique postal code.

Table A

Waste stream	Postal code
Paper/carton	2628 CC
Paper/carton	2628 BX

+

Table B

Building	Postal code
Aula	2628 CC
TPM	2628 BX

=

Table C

Waste stream	Postal code	Building
Paper/carton	2628 CC	Aula
Paper/carton	2628 BX	TPM

Figure 5.7: The Process of Merging Queries

Within this example, table A comprises data on waste streams alongside their corresponding postal codes, while table B contains information regarding building transformations, including postal codes and building names. Through merging these tables based on postal codes, a new integrated table (table C) is generated, encompassing both waste stream data and building transformation details. This integrated table enables users of the model to select specific buildings for comparison or obtain an overview of individual buildings.

Date

An essential aspect of data analysis is the comparison of dates, where users typically prefer the convenience of easily filtering data by date. In downstream waste data, the exact collection date is recorded, while vending machine data often only includes the month of replenishment on campus. Despite both datasets containing date information, they aren't inherently compatible for filtering by specific years or months as they're not directly linked. As a result, manually filtering all the datasets required for comparison becomes a time-consuming task. Moreover, there's a higher likelihood of errors occurring when accidentally selecting dates across datasets that do not align.

To streamline this filtering process, a recommended approach involves creating a dedicated date table. This table acts as a standalone dataset containing various date-related columns, such as precise dates, corresponding years, month numbers, and month names. By establishing this separate date table, users gain the ability to effortlessly filter data based on a range of date-related criteria. All datasets are then connected to this date table, enabling seamless filtering by date. Figure 5.8 provides an overview of this mechanism.

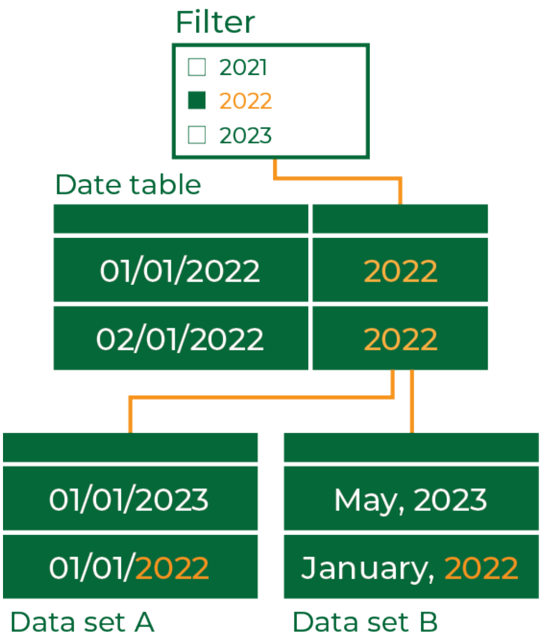

Figure 5.8: Filtering by Date

Material and waste stream

Naturally, the materials composing a product determine its distinct waste stream, as outlined in Section 5.3. Products need to be labelled with their constituent materials and the corresponding designated waste stream, as shown in Table 5.3. It is worth noting that while, ideally, an aluminium can should be discarded in the PMD bin, this isn't always the case. Nevertheless, each product is assigned to its "ideal" waste bin.

The composition of the products is primarily sourced from online databases such as PS in foodservice (n.d.), as the supplier itself lacked this type of data. These databases provide information such as material composition and, occasionally, mass.

Table 5.3: Product and Associated Material and Waste Stream

Product	Material	Waste stream
Kanjers Stroopwafels	Mix plastic/aluminium	PMD
Chaudfontaine still	PET	PMD
Cola-Cola can	Aluminium	PMD

The process of integrating data follows the same method as the one depicted in Figure 5.7. Products are connected with their respective materials, which, in turn, are associated with the corresponding waste stream.

5.6. Quantifying the material flows

Within this model, two distinct flow categories are examined: downstream and vending products. It is essential to understand that while the waste disposal company collects waste from TU Delft, no detailed information regarding the composition of the waste is available. For vending products, the focus is on modelling the weights of packaging, under the assumption that campus visitors typically discard empty packaging, as illustrated by Figure 5.9.

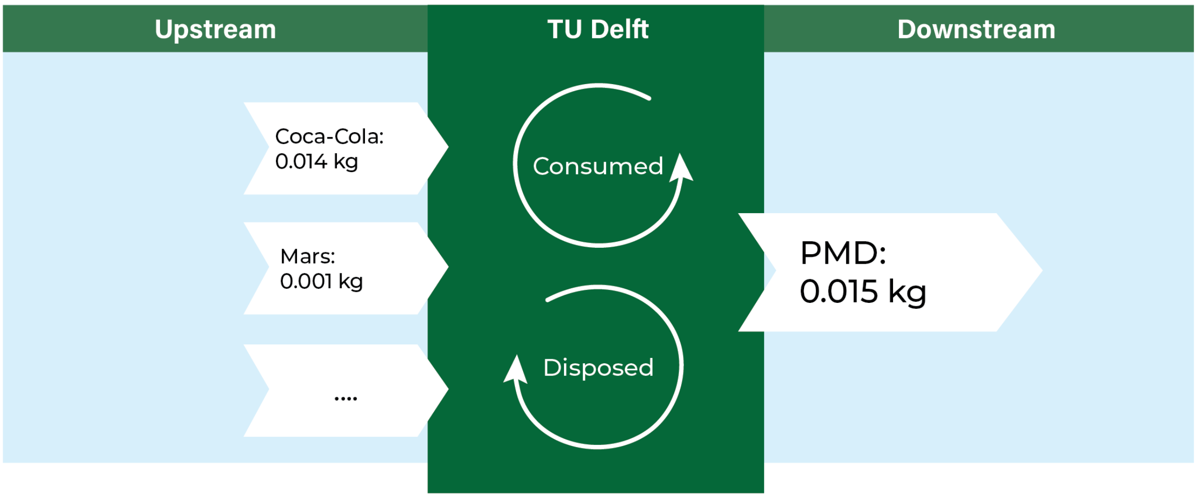

Figure 5.9: Quantification of Vending Products and Corresponding Waste Stream

Downstream

Until November 2023, all the data originates from the same waste disposal company. Within their database, contract descriptions of collected waste were already associated with a certain weight, indicated by columns containing assigned weights. The company has three methods for assigning mass to contract descriptions:

- Assumed weight (a fixed average)
- Weighbridge
- Weighting system on the vehicle

However, from the dataset, it remains unclear which calculation method is utilised when assigning weight to the collected waste.

Vending

The vending data obtained from the supplier did not include weight information for the products and their packaging. The company was unable to provide complete data on material composition and weight. Consequently, online databases were consulted to estimate the weight of the items. However, due to time limitations, certain weight assumptions had to be made in addition to the weight found for some products:

- Similar products have the same weight: For example, a Coco-Cola can 0.33 L was assumed to have the same mass as other variants such as Coca-Cola Zero or Cherry, as well as for other brands with the same measures (e.g., Fuze tea).
- Standard weight for candy wrappers: Candy wrappers that contain both aluminium and plastic were assumed to weigh 0.001 kg based on available data. This mass was then applied uniformly to all candy wrappers.

These assumptions were necessary due to the unavailability of specific weight data for vending products in the dataset and the difficulty in obtaining comprehensive data, particularly for 123 products. While these assumptions facilitate the inclusion of weight information in the analysis, it's important to acknowledge that they may reduce the precision of the model, as actual masses for these products may vary. A list of all vending products and their assigned weight can be found in Table B.2 in Appendix B.

5.7. Model material flows

It is important to present the results of an MFA in a comprehensive way. The relevant results of the study have to be condensed into a clear message that can be presented in an easily comprehensible manner. The main goal of the presentation is to stage this message to make it clear, understandable, reproducible, and trustworthy (Brunner & Rechberger, 2004). According to Brunner and Rechberger (2004) users have the flexibility to present MFA results using a variety of formats, including tables, figures, graphs, flowcharts, and Sankey diagrams. The choice of layout and content for displaying the results is entirely at the discretion of the user, allowing for customisation to best convey the information effectively.

Visualisations

Visualisations of data make trends and patterns in the data much more apparent such as clustering, the distribution of the data, and correlation within the data (Van Long & Linsen, 2011). According to Lowe and Matthee (2020) organisations their objective regarding data analysis is to recognise such patterns, underscoring the need for data visualisation to achieve strategic goals.

Offering a visual interface that enables user interaction facilitates intuitive data comprehension, allowing users to discern underlying patterns without the need for prior programming expertise (Lugmayr et al., 2017). The interactive nature of visualisation empowers users to explore datasets visually to help users detect patterns in data (Chen et al., 2019; Cho et al., 2014). As a result, visualisation tools should facilitate users in delving into specific areas of interest within the data (Zou et al., 2016). In Power BI, a variety of visualisation formats can be utilised to present the quantification of material flows.

By combining these visualisation types with calculated measures and filters in Power BI, comprehensive and insightful dashboards can be created for the analysis of the material quantities. These visualisations enable stakeholders to quickly grasp key insights, identify patterns, and make data-driven decisions to optimise material use and sustainability. Appendix C, Table C.1, presents an array of visualisation types employed for modelling material flows. In summary, the utilised elements and visualisations encompass bar charts, pie charts, time-series graphs and numeric representations.

Measures

Measures in Power BI are essentially calculated fields that allow you to perform calculations on your data dynamically. These calculations can be simple arithmetic operations like addition or subtraction, or they can involve more complex formulas and functions. Measures are particularly useful for performing calculations that are not directly stored in your dataset but are derived from the existing data. In the context of material flows, measures are valuable for analysing and understanding the flow of materials within a system. Measures can help quantify these flows, calculate key performance indicators (KPIs), and uncover insights into the efficiency of material use.

For example, the measure function is used for calculating the adopted R-strategies across different waste streams. The concept of R-strategies, elaborated in Section 2.2, encompasses strategies centred around reduction, reuse, and recycling, prioritised in a specific order. Data sourced from the waste disposal company provides insights into their average utilisation rates for waste recovery, recycling, and disposal. For instance, in the case of the residual waste stream, the company indicates a breakdown where 73% of the waste is recovered (via incineration) for energy generation, 5% is recycled, and the remaining 22% is destined for landfill Renewi (2020).

These percentages, detailed in Appendix B, Table B.3 for all waste streams, serve as foundational data for deriving new values through measures. New datasets can be formulated to delineate the application of R-strategies across various waste streams, which is important for monitoring circularity. The accompanying code for these calculations is provided in Appendix C for reference and reproducibility.

5.8. Balance the system

A fundamental aspect of MFA involves developing straightforward and dependable models to represent real-world scenarios. Adhering to the mass-balance principle is key in this process. This principle states that the mass of all inputs into a process must equal the mass of all outputs of the same process, accounting for any accumulation or depletion of materials within the process itself (Brunner & Rechberger, 2004).

If the inputs and outputs do not balance, it indicates that one or more flows are either missing or inaccurately determined. This principle extends to both individual processes and entire systems (Brunner & Rechberger, 2004). This principle was employed by Stephan et al. (2019) to estimate the proportion of waste originating from off-campus sources. Their analysis revealed that out of the total waste generated, amounting to 2280 metric tons, 1514 metric tons were identified as non-campus-related waste. These findings underscore the substantial contribution of waste brought in by students and staff from external sources, emphasising the significance of comprehensive waste management strategies. To attain such insightful conclusions, it is imperative to accurately quantify and model all inflow categories. Presently, only the vending category has been modelled, while the outflows are predominantly understood.

5.9. Chapter conclusion

This chapter provides an answer to the following sub-question: *How can material flows be modelled to implement and assess Circular Economy strategies in the context of the TU Delft?*

From the preceding chapters, it became evident that the static nature of MFA lacks utility within the specific context of TU Delft. While MFA visualisation and modelling are predominantly interpretable by researchers, the management of material flows involves a diverse array of stakeholders, as revealed through the analysis of TU Delft's Management Structure.

Therefore, a more user-friendly and comprehensible approach to modelling material flows was sought. Power BI software emerged as a suitable tool for transforming material flow data into easily understandable formats such as bar charts and other visualisations.

However, while CE principles advocate for "*narrowing, slowing, and closing material loops*", MFA serves as the foundational framework from which methods are derived. Bearing this in mind, a new modelling approach was devised, comprising four distinct steps: system definition, establishment of material flows, modelling, and illustration & interpretation. Adhering to these steps ensures the effective modelling of material flows within TU Delft's context.

6

Results I: The MFM Model

This chapter addresses the research question: *What noticeable results can be derived from modelling material flows in the context of the TU Delft*? To explain the MFM model and interface in more detail, section 6.1 is provided. Section 6.2 presents interesting results related to the downstream modelling, while section 6.3 provides insights into notable results related to vending. Finally, section 6.4 provides an overview of the challenges identified during the modelling phase in terms of data availability and usefulness, and offers suggestions for improvement.

It is essential to acknowledge that the results showcased in this chapter do not encompass the entirety of the findings derived from the modelling process. Rather, selected findings are presented to provide an overview of the capabilities of the model. These specific findings were curated for presentation during the second part of the interview process, allowing interviewees to engage and provide feedback. Consequently, the creation of an initial draft of the MFM model played a pivotal role in facilitating this interaction. For every result, a more detailed Table is provided in Appendix D.

6.1. Overview of the Model

The result of an MFA study is usually a detailed overview of the materials within the system boundary: how much is produced, consumed and discarded, and its trajectory within the system boundary. Sankey diagrams are most commonly used. However, while this has proved useful in some cases, this thesis study moves away from the standard MFA tool to explore the concept of material flow management. Rather than a static overview of material flows, an interactive display that provides real-time data and is adaptable to stakeholder needs is required to bridge the gap between science and actionable steps. As mentioned in chapter 4, Power BI software is used to quantify and visualise material flows and other types of information in a more user-friendly way. An overview of the dashboards created is shown in Figure 6.1. The blue visualisations are downstream related and the orange one vending.

At the core of this model lies the concept of integrating multiple years and providing users the flexibility to select and compare specific periods. Moreover, given that the system boundary of TU Delft encompasses various subsystems, buildings, and faculties, it's crucial to enable users to zoom in on these components. Hence, a pivotal decision was made to incorporate a slicer tool into the model, as explained in section 5.5. This slicer empowers users to navigate the model dynamically, altering its overview based on the chosen years and buildings.

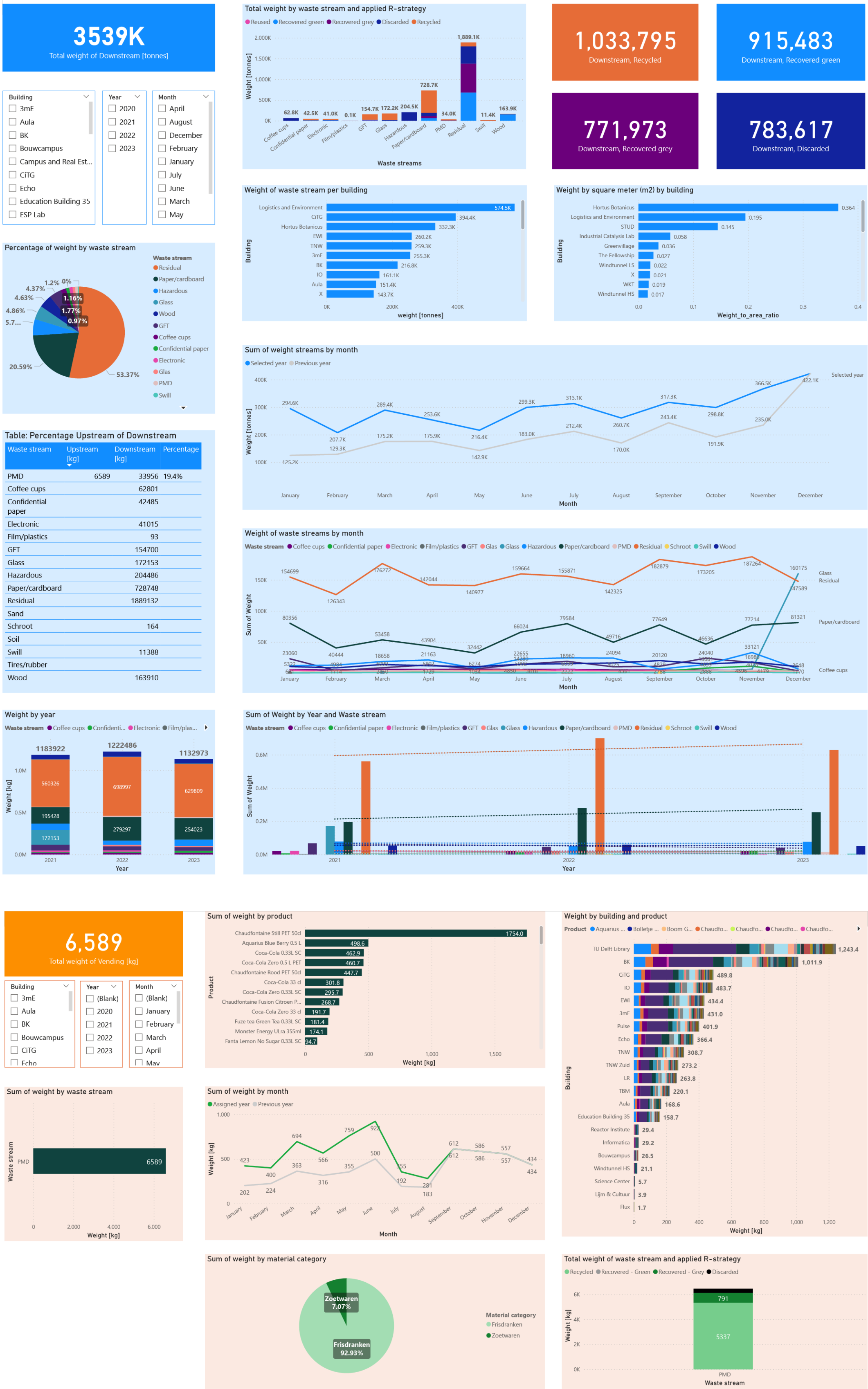

Figure 6.1: An Overview of the MFM Model

Figure 6.2: The Narrative

To explain the overall interface of the model, a brief narrative is constructed, as depicted in Figure 6.2. Let's imagine the user's journey: initially, they seek insights into the development of TU Delft as a whole and wish to compare various circularity metrics, such as overall waste generation. This entails starting with an overview of TU Delft and potentially zooming in on the data for the year 2023. Subsequently, the user may desire to delve deeper into the circularity performances of a specific building, such as the Aula, which is one of TU Delft's generic education buildings. This narrative involves seamlessly navigating between different years and selecting the Aula as the focus system.

Figure 6.3 illustrates the various functionalities of the selection tool. Initially, when no specific items are selected, it indicates that all data from all years and buildings are displayed. This aggregated view provides a comprehensive overview of the TU Delft campus as a unified system, facilitating comparisons of circularity performances across different buildings.

Subsequently, the selection narrows down to the year 2023, focusing solely on data pertinent to this particular year. Finally, the Aula is chosen as the new observation system, leading to the exclusion of data from other buildings. This targeted selection offers a more granular view, allowing for a detailed examination of material trajectories and behaviours within the specific context of the Aula. How the model's interface adapts to these different selections is illustrated in Figure 6.4.

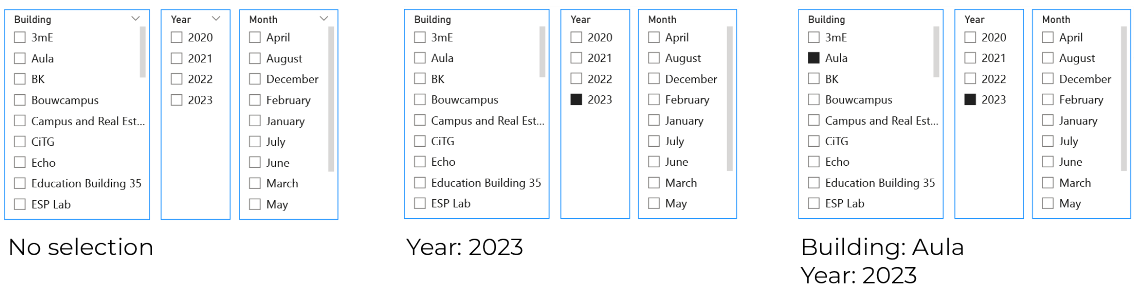

Figure 6.3: The Slicer Function

Figure 6.4: The Interface Changes

The interface changes when different items are selected, as depicted in Figure 6.4. Comparing the first and second interfaces, the overall layout remains largely unchanged, with only the quantities of material flows varying. The number of buildings and the types of waste streams remain consistent.

As shown, selecting the Aula reveals distinct alterations. The number of waste streams decreases, along with their corresponding weights. This is because the Aula does not generate all the waste streams present in TU Delft as a whole. Additionally, the ability to compare between buildings is no longer available, as only the Aula has been selected. Nevertheless, this selection highlights that focusing on a single building provides valuable insights into specific circularity metrics.

6.2. Noticeable results from downstream

The data utilised to quantify and visualise downstream flows originates from the dataset provided by Renewi. It is imperative to acknowledge that while this dataset offers valuable insights into waste consumption and management across various buildings, it is not fully accurate, as explained in Section 5.6. The dataset spans from the year 2021 to November 2023, after which there was a transition to a new contract partner for waste handling. In the subsequent subsection, data from the year 2022 will be the focal point.

6.2.1. Total downstream by building

In Section 4.2, the importance of faculties and buildings as significant sub-systems within the overarching system of TU Delft was underscored. While the campus serves as the system boundary, all buildings outfitted with products and producing waste are regarded as sub-boundaries. Consequently, a compelling aspect emerges in comparing buildings, indicating a form of resource utilisation and waste generation performance across various buildings and faculties. Figure 6.5 illustrates the total weight (in tonnes) by building for the year 2022.

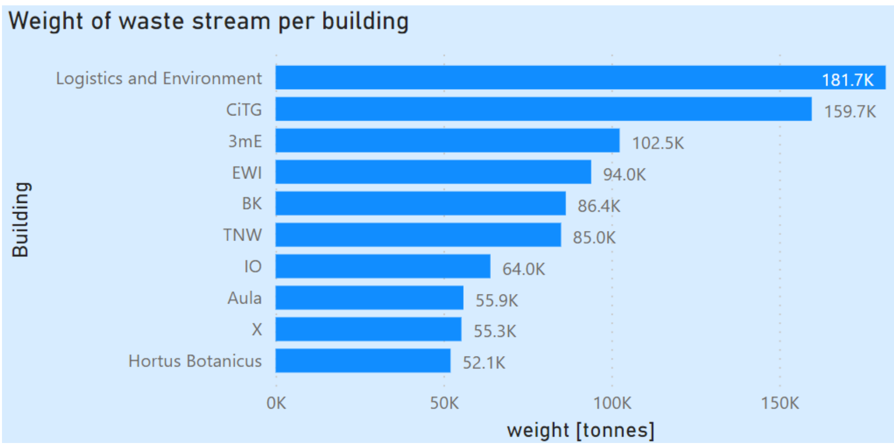

Figure 6.5: Weight of Waste Stream by Building (2022)

The analysis of the data revealed insightful findings regarding the distribution of weights across various buildings within the campus. Notably, the Logistics and Environment (L&E) building emerged as the most significant contributor, constituting 14.87% of the total weight. This can be explained by the fact that the L&E Department facilitates the procurement, storage, and distribution of laboratory supplies, chemicals, and gases used by the various laboratories at TU Delft. The location also handles the entire amount of hazardous waste, as well as coffee cups, confidential paper, electronic waste, and a significant portion of the GFT stream and wood.

Next, the Civil Engineering and Geosciences (CiTG) building exhibited substantial weight, comprising 13.06% of the total, indicative of its considerable presence within the university's facilities. Buildings such as Mechanical Engineering (ME) with a weight of 102.5 tonnes, Electrical Engineering, Mathematics and Computer Science (EWI) with a weight of 94.0 tonnes, and Arch with a weight of 86.4 tonnes also demonstrated notable weights. Additionally, the results highlighted a diverse range of contributions from other buildings, showcasing the intricate interplay of departments and facilities within the institution. While certain buildings exhibited comparatively lower weights, their inclusion in the analysis provides valuable insights into the overall distribution and utilisation of campus resources.

6.2.2. Weight-to-area ratio

Naturally, due to the significant diversity among buildings and their respective uses, solely comparing total waste weight may not be the most equitable approach, although it does highlight the largest contributors to waste generation. One way to achieve a more fair comparison is by calculating a ratio based on square meter area. This is depicted in Figure 6.6. This approach operates under the assumption that larger buildings, typically accommodating more people or providing additional workspace, are likely to generate more waste.

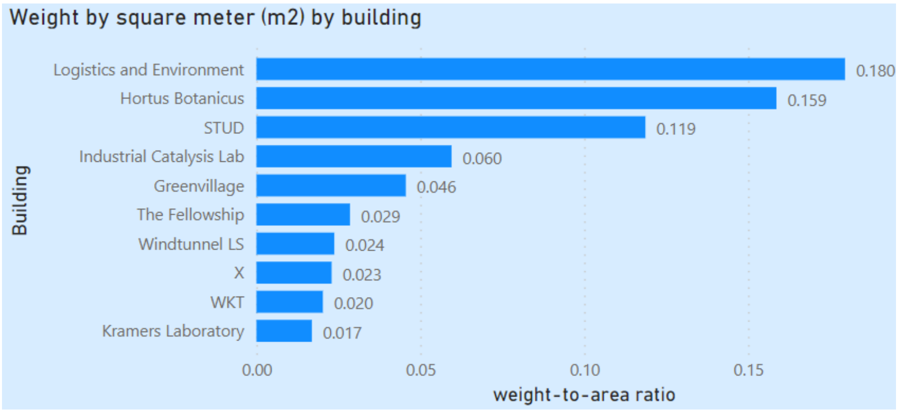

Figure 6.6: Weight-to-area Ratio by Building (2022)

However, it's important to recognise that building usage is far more intricate than mere size, so the limitations of this ratio should be acknowledged. Whilst no data could be acquired on the population size per building, this ratio was not used. Otherwise, this may have been a more fair comparison. Nonetheless, it offers some insight into a building's waste generation performance. While comparing very small buildings to large ones may not be entirely fair, as larger buildings naturally accommodate more people and thus generate more waste, the ratio still provides valuable information.

According to the data, the building that generated the highest waste per square meter in 2020 was L&M, with a weight of 0.180 kg/m^2. It was closely followed by Hortus Botanicus, with a weight of 0.159 kg/m^2, and STUD, with a weight of 0.119 kg/m^2. Conversely, the building that generated the least waste per square meter in 2020 was the ESP Lab, with a weight of 0.001 kg/m^2, followed by EWI, with a weight of 0.004 kg/m^2.

When comparing these values to the total weight of waste generated by buildings, CiTG registered 0.013 kg/m^2, Arch 0.011 kg/m^2, and 3mE 0.007 kg/m^2, indicating their respective contributions to the university's overall waste generation.

6.2.3. Total weight by waste stream

The analysis of waste streams and their recovery/recycling status unveils several significant findings, shedding light on the effectiveness of waste management strategies within the studied context. Figure 6.7 illustrates the distribution of waste streams on the x-axis and their corresponding total weights in kilograms on the y-axis, as collected from the model. The utilisation of stacked bar graphs provides a visual representation of how each waste stream is managed by the waste disposal company, thereby clarifying the connection to R-strategies, encompassing various approaches such as reducing, reusing, recycling, and recovery. These

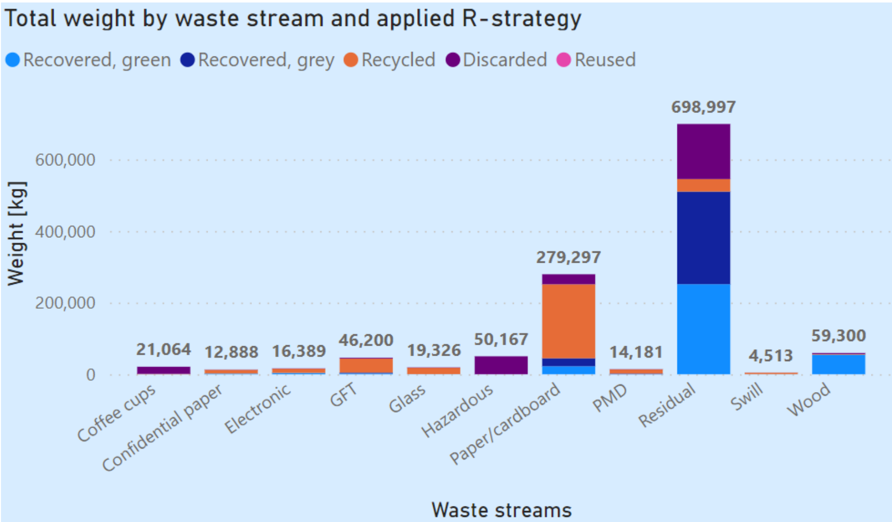

Figure 6.7: Total Weight by Waste Stream in the Year 2022

insights are sourced from Renewi's booklet ”From Waste to Product” (Renewi, 2020). Important to note is that these are averages based on measurements and reporting done by Renewi. Overall, Renewi applies two R-strategies: recycling and recovery. Recovery, in this context, refers to the recovery of energy during waste processes and is further divided into two subgroups: green recovery and grey recovery.

A notable challenge arises in the management of residual waste, with a total of 699 tonnes collected in 2020. Of this, merely 35 tonnes (5%) undergo recycling, while 75% is incinerated for energy recovery and the remaining discarded. Similarly, the paper and cardboard waste stream significantly contributes to TU Delft's overall waste generation, accounting for 279 tonnes in 2020, which constitutes 23% of the total waste. However, this waste stream demonstrates better recycling endeavours, with 22.3 tonnes recycled and an additional 22.3 units recovered.

In addition to these waste streams, wood (59 tonnes), hazardous materials (50 tonnes), and GFT (46 tonnes) also contribute to waste generation, representing 4.85%, 4.1%, and 3.78% respectively—unfortunately, the absence of recycling or recovery efforts for hazardous waste results in its complete disposal. Similarly, coffee cups collected during the year exhibit poor recycling and recovery options, leading to a substantial quantity (20 tonnes) being discarded.

Electronic waste management presents both environmental challenges and opportunities. A considerable effort is observed in managing electronic waste, with a substantial portion being recycled (3,605.58 kg) and recovered for grey energy (327.78 kg). At Coolrec's processing sites, these devices are dismantled, shredded, and sorted into different partial streams, predominantly metals and plastics, which are then made suitable for further recycling. Depending on the quality, these separated streams can serve as raw materials for various new metal and plastic products (Renewi, 2020).

6.2.4. July's peak at Architecture

Upon examining various faculties, one that stood out significantly in terms of waste generation was Architecture (BK), as depicted in Figure 6.8. The blue line represents the selected year, 2022, revealing a peak of 11.7 tonnes of waste generated, which surpasses the average by 4.5 tonnes. Notably, the majority of this waste comprises residual waste (85%). The grey line

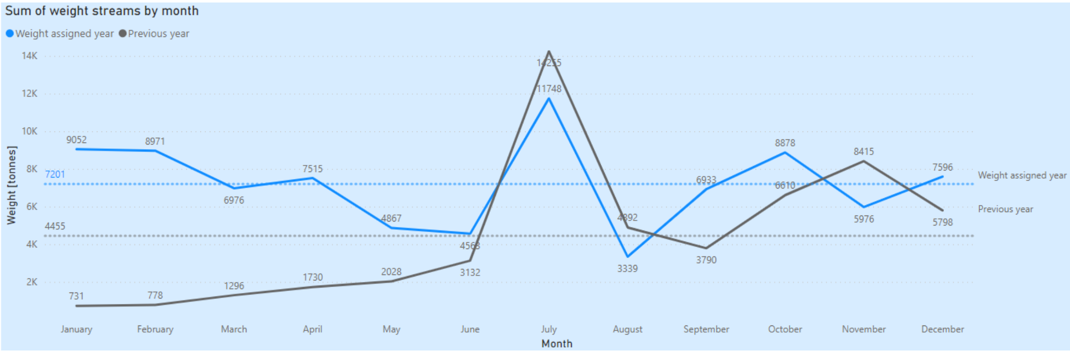

Figure 6.8: Total Weight throughout 2022, Faculty of Architecture and the Built Environment

represents the year before the selected year, indicating 2021. It exhibits a similar pattern to 2022, resulting in a peak of 14.2 tonnes of waste, again predominantly consisting of residual waste. The findings regarding the fluctuation of waste throughout the year were also presented to the local sustainability coordinator of Arch to provide further clarification.

6.2.5. Paper waste analysis at Mechanical Engineering

Figure 6.9 presents a breakdown of the total waste generated by the Faculty of Mechanical Engineering (3mE) in the year 2022, categorised by the waste stream. Notably, the Faculty exhibits a distinctive pattern in waste generation, particularly in paper waste compared to residual waste, when compared to other buildings on campus.

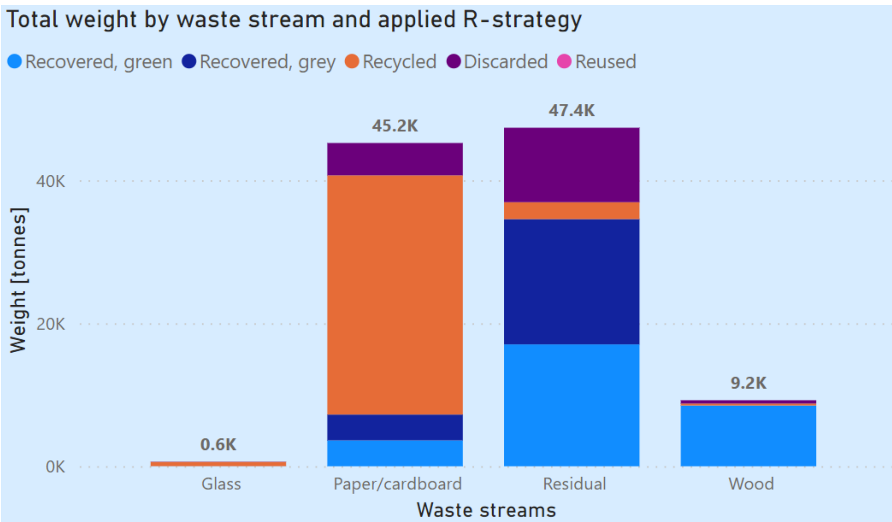

Figure 6.9: Waste Generated by the Faculty of Mechanical Engineering (2022)

Upon examination, it is evident that paper/cardboard waste constitutes a substantial portion, accounting for 44.1% of ME's waste stream, whereas residual waste comprises 46.2%. In contrast, the average distribution across buildings is notably different, with paper/cardboard waste representing 22.9% and residual waste 57.2%. This disparity prompts an intriguing analysis of the factors contributing to this difference.

This raises compelling questions: Does ME excel in waste segregation practices, leading to a reduced percentage of residual waste? Alternatively, does ME simply generate a significantly higher volume of paper waste compared to the average building? Further investigation is warranted to elucidate the underlying causes of this disparity and to inform potential waste management strategies at ME.

6.2.6. Total weight of waste by year

Figure 6.10 presents a comprehensive overview of waste generation across different waste streams for the years 2020, 2021, and 2023. It aims to explain the trend of waste generation over the years. However, it's imperative to acknowledge certain factors that may affect the accuracy and interpretation of this data.

Firstly, 2021 coincided with the COVID-19 pandemic, which could have significantly influenced waste generation patterns. Consequently, caution must be exercised when drawing conclusions from the data for this year, as it may not be entirely representative. Furthermore, in November 2023, TU Delft switched its waste management contract and supplier, leading to a lack of data for December 2023. To address this gap, the approach taken was to estimate December's waste generation by averaging the consumption of waste across the previous eleven months. While this method provides a solution to the missing data, it introduces a level of uncertainty to the accuracy of the 2023 data.

Additionally, an observation from 2022 indicates a peak in waste generation in December, likely attributed to end-of-year activities leading to increased disposal. Consequently, it's reasonable to anticipate that December 2023's waste generation could potentially surpass the current estimates. Therefore, while Figure 6.10 offers valuable insights into waste generation trends, it's crucial to consider the previous nuances and limitations when interpreting the data, particularly for the years 2021 and 2023.

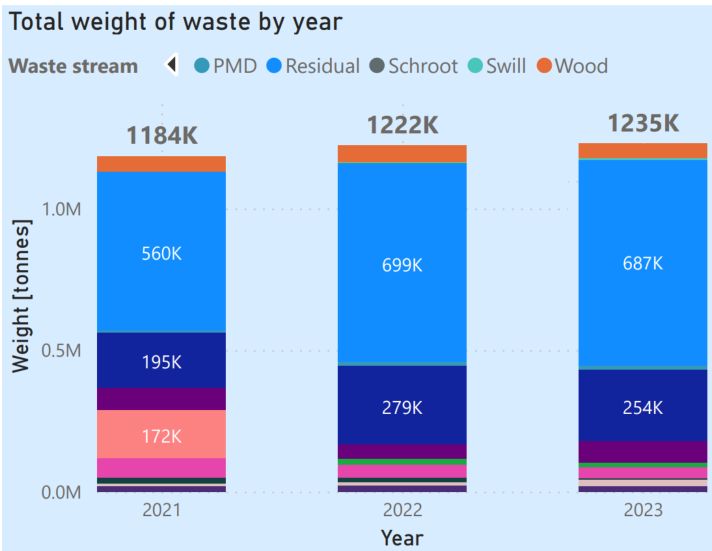

Figure 6.10: Total Amount of Waste Generated by Year

Comparing the data between 2022 and 2030 reveals a slight shift in waste generation patterns. Specifically, there's an increase of 13 tonnes in total waste, coupled with a decrease of 12 tonnes in residual waste. When considering the population size during these years, a trajectory can be calculated. The calculations can be found in Appendix F.

In 2022, the average weight of residual waste per capita annually stood at 20.72 kg. This figure represents the amount of waste each individual generates over the course of a year. By contrast, in 2023, this figure decreased to 22.40 kg per capita per year.

Examining the total waste generated, in 2020, the figure stood at 36.23 kg per capita annually. By 2023, this had marginally increased to 36.66 kg per capita per year.

Concluding from these trends, it's projected that by 2030, each person will generate approximately 18.09 kg of residual waste and 39.69 kg of total waste annually. These figures suggest a continuing trend towards higher total waste generation, with a reduction in residual waste.

6.3. Introduction to results of vending

Vending, while constituting a relatively minor inflow category in terms of mass, holds significance as one of the prominently visible aspects for campus visitors. To provide a comprehensive overview of pertinent information, a dedicated dashboard tab has been created specifically for vending analysis.

Purchase data for vending operations was acquired from the contracted partner, Maas B.V., spanning from the year 2018 to 2023. This dataset includes information linked to individual vending machines situated within buildings, along with the corresponding replenishment months. However, it is important to note that obtaining precise information regarding the assigned weights of the vending products proved challenging, with success varying across items. Consequently, it is essential to acknowledge that the numerical figures presented in this section may not be entirely accurate; instead, certain values are assumed.

Despite these limitations, the analysis of vending data offers valuable insights into consumption patterns and preferences, contributing to a broader understanding of resource utilisation within the campus environment

6.3.1. Total vending by building

Similar to the downstream analysis, a comparison between buildings is conducted to assess vending waste distribution, as depicted in Figure 6.11, illustrating the total weight of packaging in 2022. Remarkably, the TU Delft Library and the Faculty of Architecture and the Built Environment (BK) stand out as the primary locations where campus visitors purchase vending products. In 2022, the TU Delft Library accounted for 722.5 kg of vending waste, representing 20.9% of the total vending waste. Following closely, the Arch's contributed 640.7 kg of vending waste. In comparison, the next building, CiTG, generated 312.7 kg of vending waste, which is notably lower than Arch's contribution. This discrepancy underscores a significant variance.

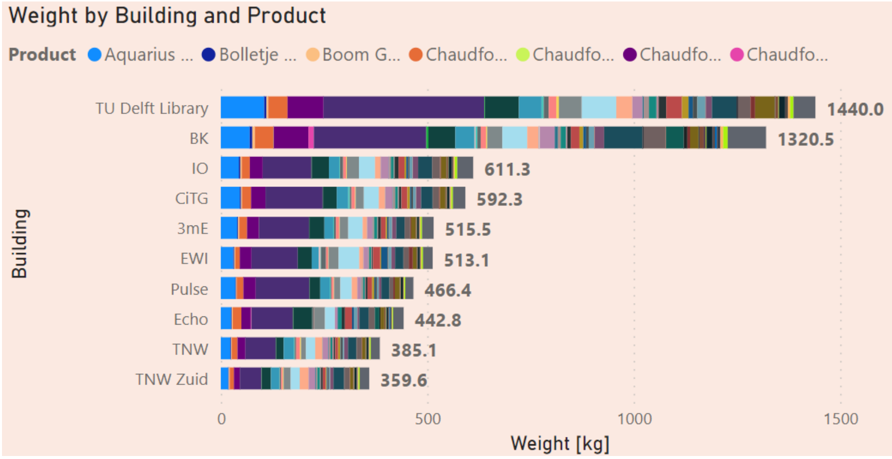

Figure 6.11: Total weight of vending items by building (2022)

6.3.2. Contribution of products

Figure 6.12 illustrates the total weight of various products available in vending machines for the year 2022. Particularly noteworthy is the substantial contribution of simple water bottles to overall vending waste. A staggering 813.9 kg of waste was generated from still water alone.

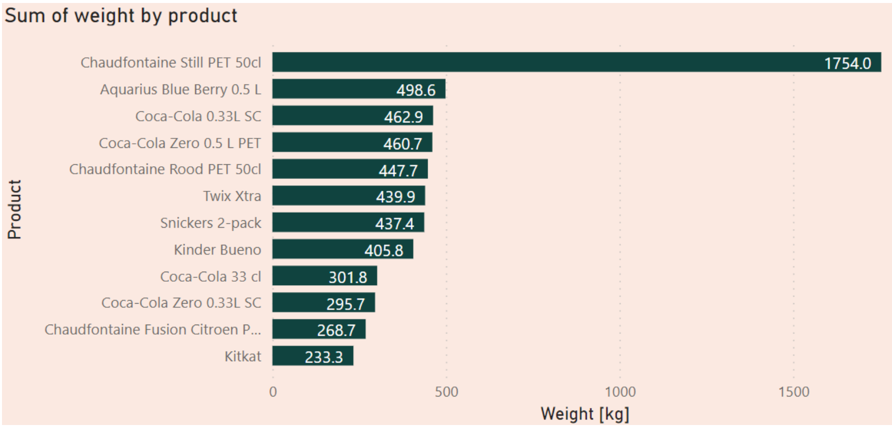

Figure 6.12: Total weight of vending items (2022)

Following closely, sparkling water emerged as a significant contributor to overall waste generation, accounting for 232.5 kg in 2022. Similarly, aluminium cans from Coca-Cola were among the largest contributors, totalling 230.3 kg. These findings highlight the impact of specific product categories on vending waste generation, suggesting targeted interventions or alternative sustainable solutions.

6.4. Challenges encountered during Modelling

To achieve results as depicted in the previous sections, various challenges were encountered during the modelling and visualisation of material flows, particularly in data acquisition, flow quantification, and other phases of the process. It became evident that the accuracy and completeness of the model heavily rely on the availability and granularity of data. These obstacles have been translated into actionable recommendations aimed at addressing these challenges in Chapter 10. The following challenges were met:

6.4.1. Lack of standardised data collection

During the data acquisition phase, it became apparent that TU Delft lacked efficient organisation in terms of data. The data necessary for a mass-based analysis of material flows was dispersed across multiple organisations and within TU Delft itself. Stephan et al. (2019) recommends systematic and consistent procurement data collection for universities and large organisations. TU Delft, given its significant procurement activities, holds the leverage to request additional metadata, including product weight and volume, to streamline material flow analyses. Implementing such practices could enhance research efforts and deepen understanding of procurement-related material footprints.

6.4.2. Lack of data on separation behaviour

All the data was modelled to reflect the ideal waste disposal scenario. For instance, a bottle made of PP would ideally be disposed of in the PMD waste bin, and thus, it was modelled accordingly. However, it is important to note that in reality, this ideal scenario may not always hold true, and items could end up in different bins than intended. Therefore, it is crucial to gather data on waste separation to understand the actual trajectories of materials in practice. In addition, no data can be obtained yet on off-campus related flows.

6.4.3. Comparison rate

Efforts to obtain data on student and staff numbers for buildings through CREFM, ESA, and HR were unsuccessful. It is imperative to address this gap by ensuring readily available data on student and staff populations per building for analysis.

Emphasis on population data is crucial as TU Delft intends to expand as a university (TU Delft, 2022). In light of this expansion and the commitment to circularity objectives, decisions regarding effective development comparisons must be made. If circularity is adopted as an objective and circularity performance is to be monitored, the availability of population data becomes even more pertinent.

6.5. Chapter conclusion

This chapter provides an answer to the following sub-question: *What noticeable results can be derived from modelling material flows in the context of the TU Delft?*

The modelling method outlined in Chapter 5 ensures a more user-friendly and objective-oriented approach. Still, several noteworthy findings emerged. The use of various visualisation techniques allows for the exploration of diverse datasets. For instance, examining waste consumption patterns in the Architecture and Built Environment department reveals intriguing trends, such as a peak in waste generation in July. Similarly, dedicated visualisations of vending products provide valuable insights into the primary contributors to the PMD stream, such as plastic water bottles.

In addition, it was revealed that L&M was the largest contributor to waste, accounting for 181.7 tonnes in 2022. This underscores the need for improvements in waste management practices, particularly concerning hazardous waste, electronics, and paper cups. Furthermore, a significant portion of residual waste continues to be disposed of, suggesting a linear waste handling approach. Analysis of waste generation patterns between 2022 and 2023 indicates a lack of significant progress toward transitioning to circular campus operations.

Therefore, the findings underscore the importance of ongoing efforts to enhance waste management practices and move toward more sustainable campus operations.

7 Results II: MFM in the Context of the TU Delft

This chapter presents the interview results that answer the sub-question: *What are the drivers and barriers for material flow management at the TU Delft*? Section 7.1 discusses the first part of the interview, which aimed to identify current barriers to implementing CE strategies. The themes identified during the interviews are discussed in order of importance. Section 7.1 explains the results of the second part of the interview. It discusses how the MFM Model can be used as an analytical framework to assist LSCs and FM members in implementing CE strategies. Finally, it provides suggestions for improving the current MFM Model based on the interviews. An overview of the interview is available in Appendix E.

7.1. Drivers and barriers for CE implementation

The structural organisation has been previously discussed in Section 4.2, shedding light on the organisational dynamics. Through interviews, it becomes evident that these dynamics play a pivotal role in the implementation of CE strategies. They can be perceived as both drivers and barriers in this process. Across TU Delft, certain entities wield considerable influence in driving sustainability-led change, notably the Executive Board (EB), the Campus Real-Estate and Facility Management (CREFM), and The Sustainability Project Team (SPT). Additionally, University Services (US) such as Human Resources (HR) and Finance hold influence over decision-making processes from a top-down approach within their particular reach.

Moreover, significant dynamics unfold within faculties. While faculty management teams (MTs) possess ultimate decision-making authority regarding implementations, they are obliged to adhere to the guidance set forth by the EB. Furthermore, certain decisions are entrusted to CREFM, such as supplier contracts, which in turn significantly impact the circularity performance of both faculties and the campus at large.

Top-down Management Duality

Through the interviews, the initial understanding of certain dynamics, established during the Analysis Phase has been confirmed. Initiatives implemented across TU-wide platforms carry significant weight, as every faculty and internal organisation must adhere to the policies of the organisation. This dynamic presents both drivers and barriers. On the one hand, LSCs express relief at the prospect of TU-wide initiatives, feeling that the burden of implementation is lifted from their shoulders. They appreciate knowing that certain aspects of sustainability are already being addressed at a higher level. An example of such an initiative that will be implemented on a campus-wide level is the new mobility plan, as mentioned by some interviewees.

> *"As a faculty, we don't have anything further to do with that [the mobility plan], so we just follow it"*.

As a result, LSCs no longer have to worry about mobility-related matters. Another participant echoes this sentiment, emphasising HR's important role in managing the mobility plan, thereby relieving the faculties of this responsibility. This sense of delegation is reflected by another LSC who finds it reassuring that these types of initiatives are being handled by other organisational units such as the SPT.

However, some LSCs also express frustration at the challenge of obtaining similar directives in areas where a similar force for change is needed. Overall, there is a collective desire for top-down support and alignment to further propel sustainability efforts across TU Delft, as LSCs feel they lack the authority to enforce certain changes. Examples such as waste management and canteen operations, which are managed TU-wide, are areas where LSCs sometimes wish to have more influence. The feeling of lack of influence in certain domains is reflected in the following quote:

> *"I observe certain activities within my building that I would like to see handled differently, but these matters are typically managed at a broader level, which adds complexity to the situation."*

Support from Management Teams

Importantly, despite faculties ultimately being required to align their actions with the directives of the EB, they maintain their unique preferences which leads to a significant degree of flexibility within the faculties. In this context, MTs are tasked with implementing the overarching objectives set forth by the board. However, it is noted that faculties vary in their approaches. Some LSCs observe that this diversity introduces complexity. One of the LSCs states that "*what works for one faculty doesn't necessarily work for another building*", highlighting this discrepancy. Within this range of flexibility, the MT members represent the highest form of governance within the faculties. The implementation of CE strategies at the faculty level is paramount, as noted by the interviewees.

The interviews reveal that LSCs play a crucial role in spearheading sustainability-driven change. They provide guidance to the MT in making decisions related to circularity and sustainability, actively participating in discussions and informing the MT about sustainability concerns and areas for potential improvement, demonstrated by the following quote:

> *"It's also about creating an overview of what is happening centrally and what can still happen locally. Thus, it involves coordinating actions within the faculty and providing an overview concerning the TU-wide initiatives. I consider it a quite important role."*

The quote from one of the LSCs highlights the discernible dynamics between TU-wide initiatives and those specific to individual faculties. It is important to note that, while LSCs typically play a supportive role, the ultimate decision-making authority lies predominantly with the MT within each faculty. The extent of influence wielded by LSCs varies across faculties. Still, it becomes evident that securing support for sustainability initiatives is of utmost importance, as mentioned by both FM members and LSCs, as exemplified by the following quote:

> *"Stakeholder support, especially from the MT, is paramount. Aligning organisational plans without backing from department chairs or the dean is essential for the success of such initiatives."*

This underscores the crucial role played by management at higher hierarchical levels. LSCs guiding members of the MT and explaining the significance of specific changes are essential steps in this process. Creating this support is a challenge for some, as mentioned by a large part of the LSCs.

Autonomy of Faculties

Interviewees discussed the challenge of balancing centralised directives with local decision-making. They highlighted the tension between top-down directives and the faculties' autonomy. While it is important to follow university-wide regulations, it is unclear when it is better to maintain faculty flexibility and when top-down initiatives are more effective. In some cases, tension arises as some faculties assert their desire for autonomy. As explained by one of the LSCs:

> *What I encounter a lot is that they [MT of faculties] want to have some kind of autonomy, at least to a certain extent, and then find it quite troublesome that there is a [university] service that is going to determine what is going to happen here in the building.*

On the other hand, establishing university-wide goals and initiatives can help mitigate problems that arise when faculties want to implement sustainability initiatives themselves. As mentioned by some interviewees, the mobility plan at TU Delft was spearheaded from the top down and effectively addressed mobility challenges previously faced within faculties. This approach ensures consistency across faculties, making it easier to implement sustainable practices as some groups of people resisted changes to mobility policies.

Although sustainability is said to be important, creating a sense of urgency around sustainability issues remains a challenge. Often, sustainability initiatives take a back seat to primary education and research processes. It can be challenging to communicate the urgency of implementing CE principles to MTs. One of the LSCs echoed a similar sentiment, suggesting that sustainability could be effectively integrated into primary processes if there is sufficient willingness among individuals.

As one of the FM members explains, in an ideal scenario, the necessity for top-down directives would subside, and faculties would proactively seek guidance to improve their sustainability performances. This would require motivating faculties and fostering a culture of sustainability engagement. This is a great challenge still as noted by multiple interviewees.

Implementing CE principles often entails challenging existing habits and norms. As some interviewees pointed out, this becomes evident in situations such as furniture procurement, where faculties may need to adjust to the presence of different types of standard furniture in a single room if more of the preferred type is unavailable. This raises the critical question of how to motivate faculties to opt for the more sustainable, potentially less visually appealing, option.

Involving the Community

Whether discussing campus-wide initiatives or changes within faculties, a recurring challenge is securing support and acceptance for these endeavours. This involves not only garnering approval from the EB or MTs but also engaging all other members of the campus community. One of the LSCs noted that while this role grants certain competencies from the EB and the

SPT, the challenge persists in how to involve and motivate individuals to adopt sustainable behaviours. Establishing a sense of ownership among both staff members and students remains a challenging task as echoed by other interviewees. This challenge is illustrated by a quote concerning the campus-wide implementation of the 19-degree policy by CREFM:

> *"The standard agreement is to set the thermostat to 19 degrees. This is something that CREFM can manage centrally, but if every employee keeps the knob open, it's like mopping with the tap running. Therefore, the behavioural component, regarding how each individual employee can contribute to the overall agreements, is the question."*

Therefore, both staff and students must be actively motivated to adopt sustainable behaviour. One of the FM members explains that there is a lot to be gained in how the building's facilities and services are used. While it is mainly CREFM that provides the options, it is the students and staff who should also be making sustainable choices. The following quote from one of the FM members illustrates the importance of the (purchase) behaviour of campus visitors:

> *"That's where you have relatively high leverage [the supply choice]. So, that's one aspect—procurement and the development of supplier management. And then, how much is purchased, that's where the profits are mainly to be made."*

Definition and Measurement

One of the barriers for implementing CE strategies is the lack of a clear and universally accepted definition, making it difficult for people to understand how to apply it in their operations. During the conducted interviews, it was clear that respondents hesitated to describe what, according to them, the concept of CE means. However, a recurring principle mentioned by many was the concept of responsible management of products and materials, often emphasising the importance of reusing.

> *We discussed this the other day: what is circularity and how do you measure it? Sustainability is still relatively easy to measure in terms of CO_2, but circularity is tricky. That's why I know it's an issue.*

As a result, there appears to be a lack of consensus across organisations regarding the definition of CE and, more importantly, how to translate it into action. The recurring question raised was: how do we measure it?

> *So we [the TU Delft] want to be 100% circular, but what does that entail exactly? The R ladder? Well, I still don't know. I don't have an example of which I think: "Here it is completely quantified". Maybe it can't be, or it's not possible yet.*

Some interviewees noted that quantifying environmental impact, such as measuring CO_2 emissions, helps align goals effectively. However, the lack of clarity surrounding circularity poses barriers for employees who may not fully understand how to improve it. This confusion spans across various roles within the TU Delft, from policy-makers to local FM members.

Within FM specifically, there appears to be a need for a clearer understanding of what CE entails and how campus operations can enhance their circularity performance.

Embedded and Coordinated Roles

The role of LSCs presents several barriers, with some facing difficulties in their positions. Most LSCs note that colleagues still struggle with their roles, attributing this to a lack of full integration within the organisation. It's important to note that perceptions vary among LSCs. Multiple interviewees acknowledge that the role is still evolving and needs further development to achieve full integration within the organisation, with hopes of increasing their impact. They also recognise the challenge of implementing change due to time constraints. One interviewee explains the dilemma of having limited time to dedicate to the role:

> *"As an LSC, you can accomplish a lot, but I only have eight hours a week for this. And sometimes, I'm already in meetings for three-quarters of that time. If it were a full-time job, I believe we could make significant progress."*

This sentiment is echoed by another LSC who suggests that the role should be a dedicated position rather than an additional responsibility alongside other duties. They also question why other organisations have full-time sustainability coordinator positions while TU Delft does not. This sentiment is echoed by other LSCs.

For LSCs who feel less secure in their roles, collaborating with knowledgeable individuals on specific topics and engaging with fellow LSCs is considered crucial. Additionally, diversifying teams by including individuals from local FM or Information and Communication Technology (ICT) departments proves to be effective for some. This broader network allows for coverage of a wider range of sustainability-related topics, as local FM members play a pivotal role in translating goals into action. Two LSCs who already benefit from such a team note the value of having additional support and expertise from various domains.

A key idea raised by one of the LSCs is the importance of defining roles within the organisation. This is to prevent complacency and ensure that initiatives are taken forward. Without clear roles, there's a risk that staff will become indifferent, assuming that the SPT will take care of everything. So the challenge is to keep everyone engaged and committed to sustainability and circularity efforts.

Communication

Effective communication plays a pivotal role in advancing sustainability and circularity initiatives within an organisation. However, it appears that there is a lack of comprehensive information regarding ongoing efforts in these areas:

> *"What are we doing collectively to contribute [to the environment]? Communicating this clearly will help significantly."*

This sentiment resonates with many interviewees, indicating a need for improved communication strategies. One LSC highlighted the presence of sustainability initiatives on campus but emphasised the importance of better dissemination of this information. Individuals should be aware of where to access such details and understand their roles in contributing to sustainability efforts. Clear communication about ongoing and future initiatives is essential to engage both students and employees in actionable steps towards sustainability.

Another specific form of communication which is lacking is the communication of sustainability, and therefore circularity objectives. The significance of clearly defined overarching goals cannot be overstated, as they ensure alignment, provide clarity on objectives, and foster a collective understanding of the purpose and potential improvements. This sentiment is echoed by other LSCs as well.

One interviewee underscored the necessity for all stakeholders to share a common vision and stressed the importance of alignment among all leadership roles within the faculty and emphasised.

7.2. Opportunities for the MFM model

The second part of the interview aimed to assess whether the proposed MFM model could assist LSCs and FM members in their roles and potentially address the barriers outlined earlier. Alternatively, it sought to determine if the MFM offers guidance or support in other areas. Therefore, this section provides common realisations and potential opportunities for the MFM model as identified from these interviews. Similar to the previous section, the overlapping opportunities are mentioned.

Better informed decision-making

The quote, "*How is that possible? Where do these differences come from?*" encapsulates the initial reaction of an LSC upon seeing the MFM model for the first time. It reflects the general sentiment shared by many interviewees as they delved into the model's insights. It became evident that the information presented often led to a sense of astonishment about certain numbers and prompted a search for explanations.

For instance, the revelation that the TU Library and the Faculty of Architecture were the largest consumers in vending raised eyebrows and provoked speculation. Longer opening hours at the TU Library and the possibility of students congregating more within their faculty at Architecture were proposed as potential reasons. Although these theories remain unverified, they sparked intriguing discussions. Similarly, the observation of a larger paper waste stream in Industrial Design Engineering and Mechanical Engineering was met with speculation about the nature of design-related tasks in the curriculum. However, it is essential to note that these hypotheses are not validated. Overall, the model's insights ignited curiosity and prompted the need for further investigation. As one interviewee expressed:

> "*It touches upon things, I find it very interesting to see that, because things come up that I had never expected.*"

This sentiment resonated across all interviews, emphasising the value of the model in stimulating critical thinking and inspiring future research endeavours. Showing certain compelling facts and figures to the interviewees sparked new ideas for potential CE strategies or initiatives. One noteworthy observation made by the LSCs was the significant contribution of water bottles to the overall vending machine waste. In response to this, one LSC proposed a solution: removing all bottled water from the vending machines and installing more water taps across campus. The sentiment echoed by one of the LSCs encapsulates the utility of the MFM model in this context:

> *"I find this [the MFM model] especially useful because based on this we can start making alternative choices."*

Similarly, other LSCs suggested launching waste reduction campaigns focused on discouraging the use of water bottles, aiming to raise awareness about their impact on waste generation. The objective of such campaigns is to inform and encourage individuals to opt for reusable alternatives, thereby reducing reliance on single-use plastics. Hence, the MFM model provides valuable insights into the current state of resource consumption and management, inspiring discussions on potential improvements among interviewees.

Monitoring developments

The interviews shed light on a more tangible application of the MFM model: monitoring specific objectives and the impact of implemented strategies, as discussed in the previous section. It was evident that in addition to the proposed CE initiatives, there was a perceived importance in monitoring the outcomes of these strategies. A clear example of how the MFM model could be utilised was provided by one interviewee:

"Suppose you initiate a campaign encouraging individuals to bring your own bottle. After implementing this campaign for a year, you can monitor the results to observe any decreases".

This sentiment was echoed by several interviewees, highlighting the importance of data-driven insights for a technical university like TU Delft, where students and staff are inclined towards factual evidence:

"It is important to note that this is a technical university with quite a blue-oriented audience, both men and women, who are data-driven."

Hence, the MFM model appears to be a valuable tool in providing an initial overview of resource consumption and management. It allows users to assess the current situation and identify areas for improvement. Furthermore, it facilitates the evaluation of the effectiveness of various initiatives and the progress towards specific goals, which were frequently mentioned by interviewees. While there is ongoing development of a CO2 monitoring system, similar efforts are desired for monitoring circularity within TU Delft. However, the challenge lies in defining and quantifying circularity, a concept not yet standardised like sustainability.

Addressing this challenge, some interviewees proposed using baseline measurements to establish reference points for future assessments. They emphasised the importance of assessing the current situation, tracking developments, and making comparisons over time. Overall, whether it pertains to sustainability or circularity, interviewees stressed the significance of setting clear objectives and subsequently monitoring progress towards those objectives. Effective visualisation of data plays a crucial role in this process, as it enables clear and comprehensible tracking of numerical insights to evaluate our efforts, as underscored by one of the interviewees.

Underpinning arguments

One of the barriers expressed by interviewees is the difficulty in gaining support from higher-level stakeholders within the organisation to enact change. The question arises: How can individuals in such positions be motivated to grasp the importance of certain initiatives and issues? Interviewees mentioned that they want to use the model and the data provided to as a tool to substantiate why certain decisions should be made, as illustrated in the following quote:

"This enables me to initiate discussions. I can engage with FM and other stakeholders, advocating for changes based on the data insights. For instance, I can propose to our management that we revise our policy by discontinuing the sale of plastic water bottles altogether, emphasising the savings and impact it would have. Such data-driven arguments hold significant value for our management team."

One interviewee explains that the MFM model helps substantiate the necessity of certain changes. Real data from the model can address specific inquiries posed by MT members, thereby aiding LSCs in guiding them effectively. It highlights that garnering support from the MT can be facilitated by providing data on the current situation and the changes that still need to be made. Another interviewee provides a concrete example, envisioning the use of the model to illustrate faculty developments every quarter. This approach allows for discussions on policy effectiveness and reveals previously unknown insights during meetings.

Creating a sense of ownership

As emphasised by interviewees, fostering engagement across the entire TU Delft community is paramount for achieving collective goals and objectives in sustainability and circularity. This encompasses not only the MTs, FM members, and the EB, but all members of the TU Delft community. Several interviewees stressed the significance of this inclusive approach.

One way the MFM model can address these barriers is by translating complex data into actionable insights for crafting targeted campaign strategies. By effectively communicating the rationale behind certain changes related to circularity and sustainability, the model could foster a sense of ownership among community members. When individuals understand the impact of their decisions, they are less likely to overlook the significance of their actions.

> *Make it understandable to the consumer. If you do that, then... or we'll take that away for that reason, because look what we're all doing together. I think that just makes people proud and happy. So what is it that makes people say, "Why are we doing this together? And what is the result?*

Furthermore, providing clear explanations for university initiatives enhances transparency and strengthens community engagement, as highlighted by one of the interviewed LSCs. Effective communication not only articulates organisational objectives but also substantiates the rationale behind specific actions, thus encouraging sustainable behaviours among community members.

A key aspect underscored by interviewees is the importance of transforming raw data into compelling narratives that resonate with people and earn their interest in sustainability. Therefore, leveraging the insights generated by the MFM model can facilitate the development of engaging and informative campaigns. By aligning these campaigns with organisational actions, the model has the potential to inspire the community to embrace sustainable practices and take ownership of their impact.

Involving Contact Partners

Through interviews, it became evident that the contract partners, comprising suppliers and the waste management company, wield significant influence over TU Delft's circularity performance. This sentiment is encapsulated in the following quote from one of the LSCs:

> *"If you're still bringing in all kinds of goods from companies that don't care about sustainability at all, then you're throwing a stone in the pond and nothing happens."*

This underscores the pivotal role of suppliers and their sustainability practices in the procurement process.

As emphasised by interviewees, gaining a thorough understanding of the operational system is key to selecting suitable suppliers for campus products. Access to data on purchased items is crucial in this regard. Therefore, it's imperative to secure this data from suppliers, particularly during the contracting phase. By incorporating such requirements into contracts, organisations can ensure that suppliers furnish necessary data. The quote below from an FM member demonstrates how the MFM Model with contract partners could be applied:

> *"In the upcoming years, we want to reduce our intake until we no longer acquire new [products]. The problem is that we often don't know how this is organised, and how much furniture is new versus secondhand. So, making agreements with suppliers and holding them accountable, or holding ourselves accountable, is really difficult. Such a model, even though it still needs further development, could definitely help to establish objectives and communicate them to the suppliers."*

Furthermore, interviewees expressed a desire to monitor developments more closely. Utilising data from suppliers for internal monitoring systems can help ensure that suppliers align with set ambitions. Hence, the MFM Model proves to be a valuable tool for initiating discussions about current performance and identifying avenues for improvement.

7.3. Suggestions for the MFM model

During the interviews, participants had the chance to discuss potential improvements for the model. It's worth noting that while some suggestions were made, many found it challenging to provide direct advice due to their unfamiliarity with the method. Nevertheless, several interesting improvement ideas emerged.

Consideration of population size for comparison

The population size encompasses all students and employees at TU Delft who occupy and utilise the facilities within the buildings. As mentioned in Section 6.2, the building area was included in the analysis, and it was noted that further research is needed to determine the fairest comparison. Just as a larger building area typically results in more waste generation and service usage, a larger population within the building is likely to have a similar effect. While a larger building area may not necessarily lead to higher occupancy, it's worth exploring the inclusion of student and staff populations for a more comprehensive comparison.

Incorporation of opening hours for comparison

Some interviewees suggested incorporating opening hours into the ratio, such as weight-to-area, especially for buildings like the Aula that have longer operating hours. This adjustment would mean that buildings with longer open hours would have a lower ratio.

Expansion to include other flow categories

As outlined in Section 4.2, TU Delft has seven inflow categories or upstream flows. However, this thesis study only modelled vending. Several interviewees expressed interest in having similar information for the other inflow categories.

Improved explanation of the R-ladder

Not all interviewees grasped the principles of the R-ladder, indicating a need for clarification. Some suggested incorporating this explanation into the model to enhance understanding for all types of users.

Potential use for contract partners

One interviewee proposed extending the model's usability to contract partners. Currently, only members from TU Delft were interviewed, but it would be intriguing to explore whether the model could be adapted for use by users outside the TU Delft community as well.

7.4. Chapter conclusion

This chapter aims to answer the following sub-question: *What are the drivers and barriers for material flow management at the TU Delft*?

The MFM and CE implementation at TU Delft are driven by a combination of top-down directives and grassroots efforts within individual faculties. Key drivers include the support from influential entities such as the EB and the CREFM, which provide direction and resources for sustainability-led change. Additionally, MTs within faculties play a crucial role in translating overarching sustainability objectives into actionable strategies tailored to their specific contexts. LCSs guide MT members in decision-making processes, fostering support for sustainability initiatives within faculties.

However, several barriers hinder the smooth implementation of CE strategies. These include challenges in defining and measuring circularity, as well as the lack of clear communication and community engagement strategies. Despite efforts to involve the entire campus community, motivating individuals to adopt sustainable behaviours remains a challenge. Moreover, securing data from contract partners, such as suppliers, for internal monitoring systems poses difficulties in assessing and improving circularity performance.

In addressing these barriers, it is crucial to leverage the existing top-down support while empowering grassroots efforts within faculties. This requires clear communication of sustainability objectives, active engagement of the community, and collaboration with contract partners to ensure data transparency and accountability. By overcoming these challenges and building on existing drivers, TU Delft can further advance its material flow management and accelerate progress towards a CE.

8 Discussion

This chapter discusses the results of the initial implementation phase of the study, which aims to illuminate pathways to overcome the hurdles hindering the successful implementation of CE strategies. Section 8.1 outlines the academic contributions of this thesis study, while Section 8.2 delves into the interpretation of interviews conducted during the evaluation phase. Subsequently, Section 8.3 scrutinises the interpretation of the modelling results compared to the established ambition for circularity. In Section 8.4, the implications tied to this thesis study are explored, followed by a discussion of the study's limitations in Section 8.5. Finally, Section 8.6 offers suggestions for future research efforts.

8.1. Academic contribution

This study aims to bridge the identified gap in the literature concerning the lack of a suitable analytical framework for HEIs to implement CE strategies. However, it extends beyond simply acknowledging the gap. It delves into the reasons why existing frameworks may not be universally applicable, acknowledging the diverse interpretations and applications of CE concepts. It recognises that the first step lies in understanding the unique character of HEIs as large, complex organisations with intricate decision-making processes involving numerous stakeholders, resulting in unique management structures revolving around material flows.

This led to the conceptualisation of the Material Flow Management framework, an adaptation of the well-established MFA framework, tailoring it to the specific needs of HEIs and integrating a network analysis approach. Unlike standard MFA studies, this research prioritised creating an interactive dashboard that presents material data in a more comprehensive and user-friendly manner. This approach promotes the generation of meaningful insights that can inform the development of more targeted and effective CE strategies.

The study acknowledges that CE implementation is both context- and actor-dependent within HEIs, with complex management structures further influencing its success. Therefore, it underscores the crucial role of consulting key decision-makers when interpreting and applying the results generated by the adapted MFM Model. Additionally, it recognises the need for further research to explore the factors hindering HEIs from progressing towards circularity. Identifying such barriers will not only inform improvements to the MFM Model itself but also guide necessary changes within the university's management structures. Ultimately, enhancing both the MFM Model and existing management structures is crucial for HEIs to successfully implement effective CE strategies.

While further research is essential to refine the MFM framework, this study serves as a pivotal step forward in empowering HEIs to embrace data-driven management of their material flows combined with a network approach. The MFM framework equips HEIs with the necessary tools to make informed decisions and implement targeted initiatives aimed at promoting sustainability and circularity within their operations and organisational structure.

Moreover, the insights gained from this study not only contribute to academic discourse but also have practical implications for HEIs seeking to adopt sustainable practices. Through continued collaboration, innovation, and dedication to driving positive change, HEIs can lead the way towards a more circular and sustainable future.

8.2. Interpretation of the Interviews

This section provides an interpretation of the results and the findings from the literature and other research. The interpretation focuses on the results of the evaluation phase, and the interviews conducted. In total, seven main challenges were identified for the implementation of CE strategies within TU Delft according to some LSCs and FM members.

The challenge of top-down management duality encapsulates the dual nature of top-down initiatives: while they have considerable power, they also have limitations. In particular, local changes can be delayed while waiting for campus-wide directives, which hinders timely implementation. Faculties play a crucial role in driving CE change on campus. In addition to top-down directives, the CREFM, SPT and LSCs influence faculty MTs, thereby influencing sustainability performance. LSCs emphasise the importance of gaining the support of MTs, as described in the section on support from management teams.

Similar challenges face other organisations seeking to change, particularly in motivating faculties to adopt sustainable practices while respecting their autonomy. The struggle to adopt more sustainable behaviours permeates all levels of the TU Delft community, including building occupants who may be engaged in unsustainable practices. Moreover, there seems to be a broader challenge in defining CE comprehensively, which hinders its effective implementation. The question remains what circularity entails.

Furthermore, the integration of certain sustainability functions, in particular the LSC function and CE expertise, is a challenge. Finally, effective communication of CE initiatives is essential to ensure widespread awareness and individual engagement across the TU Delft community. Going forward, the following sections will explore these issues in more detail and analysis.

8.2.1. Comparison to prior studies

Creating an understanding of CE

Similar to the findings of Mendoza et al. (2019a), the conducted interviews in this thesis study revealed a varied understanding of the CE concept among participants. While all interviewees demonstrated some awareness of CE principles, none could articulate its implications within their specific roles. This suggests a lack of discussion surrounding CE within the relevant areas of responsibility. This lack of clarity poses significant challenges for envisioning and implementing CE within organisations. This sentiment is echoed within FM, where there is a lack of alignment on the definition and vision of a circular campus. Therefore, TU Delft would benefit greatly from creating CE goals and targets and communicating them throughout the university.

However, as demonstrated by the literature review, CE is context-dependent. While overarching goals help to direct everyone towards the same objective, it is also important to gain a better understanding of how to apply CE principles in specific domains. This is also acknowledged in the study of Saidani et al. (2017). For instance, the application of CE principles may differ between vending and furniture in the inflow category, as they have significantly different lifespans at TU Delft.

Circularity goals and indicators

In terms of quantifying CE initiatives, the EB currently lacks established measurable targets, hindering efforts to monitor progress towards achieving circular campus management operations. The need for meaningful KPIs aligns with the findings of Mendoza et al. (2019a), highlighting the significance of such metrics in measuring progress on environmental sustainability initiatives.

It's essential to recognise that while the MFM Model can incorporate and visualise predefined targets and KPIs, it doesn't inherently generate the appropriate circularity indicators. While it can quantify material flows and integrate established targets, the specific targets themselves need to be developed separately. In the model, certain KPIs related to the R-framework have been integrated, such as the amount of waste recycled, recovered, or discarded, providing a foundation for KPIs. In addition, more general indicators such as cumulative waste generation or vending purchases per building have proven to be valuable, evoking positive feedback from interviewees. Furthermore, interactions with the MFM Model have sparked ideas on how to utilise waste, demonstrating the effectiveness of quantifying and visualising resource use. However, as indicated by interviewees, these KPIs require improvement, particularly in terms of better comparisons between different periods.

In contrast to the findings of Mendoza et al. (2019a), who highlighted data gathering as the main challenge in creating CE-related KPIs, this thesis study identified the primary difficulty in defining what CE encompasses and how to quantify it, as indicated by the interviewees. This difference could be attributed to several factors. Firstly, the participants in this thesis study held more specific and novel roles compared to those in Mendoza et al. (2019a). Additionally, the study by Mendoza et al. (2019a) encompassed a broader range of individuals within the university setting. Furthermore, it is possible that universities in the Netherlands, including TU Delft, are more advanced in terms of data acquisition and management, thus affecting the challenges encountered in CE-related KPI development.

However, challenges related to data gathering were found during the Modelling phase. To address these challenges, recommendations outlined in Chapter 6 emphasised the importance of centralising data repositories and standardising data sheets to streamline the data-gathering process. These measures are essential for facilitating effective monitoring and evaluation of CE progress within TU Delft.

Engaging faculties

During the analysis phase, it became clear that the faculties play an important role in the overall sustainability performance of TU Delft. Therefore, an important aspect of the modelling was to distinguish between campus-wide and building-specific information. As shown in chapter 6, this provided insight into the total waste production of the buildings and the comparison, which led to interesting findings, as confirmed by the interviews. However, while these findings are intriguing, translating them into actionable steps remains imperative. This raises the question: what management mechanisms can be employed to facilitate this translation into tangible initiatives?

If the EB were to establish TU-wide CE goals and targets, these could be cascaded down to individual buildings, thereby holding MTs accountable for implementing CE strategies. This approach serves as an effective mechanism to incentivise faculties to enhance their sustainability efforts. This method resonates with recommendations given in the studies by Mendoza et al. (2019a) and Bocken et al. (2016). Additionally, LSCs play a pivotal role in this process, serving as sustainability advisers to the MTs.

As motivating faculties is an important task, both the EB and faculties could benefit from establishing robust sustainability teams to serve as advisory boards. Some LSCs already have such teams in place and attest to their effectiveness. Conversely, LSCs lacking support structures may feel constrained in their ability to effect change and may perceive a lack of time to dedicate to their roles. Furthermore, some express a desire for additional sustainability knowledge to bolster their effectiveness.

Although a direct link between sustainability advisers for a faculty's MT is not explicitly outlined in the literature, Mendoza et al. (2019a) highlights the importance of establishing CE-committed leadership teams. These teams, made up of senior managers and operational staff, are critical to driving effective change from both the top down and the bottom up. This highlights the critical role of committed leadership teams in driving sustainability initiatives.

Creating a sense of ownership throughout the community

One of the major problems is that people within the TU Delft community don't feel a direct need to engage in sustainable behaviour. The challenge of community engagement in sustainability initiatives has been highlighted in previous studies, including Mendoza et al. (2019a), which identifies sustainable behaviour by students, suppliers and researchers as a significant barrier. There is a direct correlation between this challenge and one of the opportunities identified for the MFM Model. Many interviewees highlighted the need to translate data into engaging campaigns to encourage sustainable behaviour change among students and staff. Providing data can help individuals understand the impact of their choices, thereby fostering a sense of ownership of sustainability issues. This need was expressed at both campus-wide and building-specific levels.

Furthermore, establishing sustainability and circularity objectives can enhance the sense of unity in addressing these challenges. In this regard, the MFM Model plays a crucial role by providing insightful data and quantifying these targets, as discussed in the previous subsection. Clear communication of this information is also vital, as shown through the interviews, as it remains a barrier to implementing CE change. Improving campus circularity and community engagement and strongly related to each other, which are both important roles that HEIs play in the advancement of CE, as shown in the literature review.

8.2.2. Main differences compared to prior studies

The study of Mendoza et al. (2019a), that was focused on the University of Manchester revealed several challenges hindering the implementation of CE practices:

- Lack of awareness and understanding of the CE concept, principles, benefits, and their relevance to the university context.
- Absence of suitable analytical frameworks, data gathering systems, and Key Performance Indicators (KPIs) to effectively identify, evaluate, prioritise, implement, monitor, and manage CE solutions.
- Inadequate leadership teams, unclear allocation of responsibilities, insufficient stakeholder engagement, and ineffective policies targeting CE as a key strategy for long-term sustainability.

Interestingly, while most challenges align with those encountered at the TU Delft, there appears to be less emphasis on the allocation of responsibilities, as evidenced by its limited mention in interviews. Although participants did highlight the lack of embeddedness of the LSC function, the discussion around the allocation of responsibilities was sparse. This discrepancy may stem from the focus of this thesis study, which primarily centred on LSCs and FM members.

In contrast, the work of Mendoza et al. (2019a) encompassed a broader array of employees and decision-makers, including local FM members operating at the operational level rather than solely at the strategic level. This broader inclusion may provide insights into why the issue of responsibility allocation was more prominent in their study compared to the present research. In addition, as mentioned previously, organisations are complex and unique, so it is not surprising that there are differences in encountered challenges.

8.3. Interpretation of the Model results

This section provides an interpretation of the results and the findings from Chapter 6, the MFM Model. It examines the current situation and circularity performances and compares them to the ambitions set by the TU Delft.

8.3.1. A circular campus

In the Vision, Ambition, and Action Plan of TU Delft, the university's overarching objective is articulated: a carbon-neutral, climate-adaptive and circular campus, with a contribution to the quality of life and biodiversity, by 2030 (van den Dobbelsteen & van Gameren, 2022). Specifically focusing on circularity, it entails integrating campus activities into the CE. It involves procuring materials, products, and services through sustainable, circular processes, maximising the lifespan of available raw materials without causing harmful environmental emissions. Additionally, the document expresses a desire to further incorporate the R-ladder within the organisation as much as possible, following the hierarchy. This means to aim for the highest order of the R-strategies as much as possible and avoid the lower boundaries, such as energy recovery and recycling.

To achieve a circular campus that implements R-strategies to the highest degree possible, it is necessary to make changes in vending and downstream flows, as modelled and discussed in Chapter 5. Transitioning to such an operational system will lead to changes in waste generation, waste separation, and the use of single-use plastics, among other things. These changes can be analysed using the model results to identify significant changes.

8.3.2. Comparison with results

The goal set forth is to transform into a circular operating campus by 2023. It's important to recognise that this is an ambitious target, necessitating significant shifts in material consumption and handling practices.

A suitable metric for assessing progress towards this goal is the total amount of waste generated per capita. If TU Delft is indeed progressing towards circular campus practices, one would expect to observe a notable decrease in total waste generation. This can be examined by comparing data from 2022 and 2023, as depicted in Figure 6.10 in Section 6.2. Notably, due to the disruptive effects of COVID-19, earlier years were deemed unrepresentative, hence focusing on 2022 and 2023 as reference points.

Upon analysing the overall waste generation, it becomes apparent that rather than decreasing, it has shown an upward trajectory, indicating no discernible change in waste generation patterns. For instance, projecting from the 2022 baseline, it's estimated that by 2030, each individual would produce approximately 39.69 kg of waste annually. However, it's important to note that relying solely on data from two years may not be sufficient for accurate trend analysis. Nonetheless, it's evident that there hasn't been a significant shift, perhaps even a slight decrease, in waste generation.

Given the relatively short time frame of seven years, if this trend persists and is reflected across other aspects of circular campus operations, it suggests that TU Delft will not achieve its ambitions. This underscores the importance of reassessing strategies and implementing more impactful measures to align with the desired circularity goals.

These trends are evident in several key findings, such as those depicted in Figure 6.9, where paper/cardboard waste consumption is large. Additionally, the dominance of residual waste as the largest waste stream, as illustrated in Figure 6.7, highlights a persistent challenge. Furthermore, the observation that nearly a quarter of residual waste continues to be discarded is particularly concerning, as it falls outside the scope of the R-strategy framework. Another indicator is the number of single-use plastic bottles and soda cans purchased annually, as depicted in Figure 6.12. Combined, these findings suggest a predominantly linear behaviour in material consumption and waste management practices, indicating a need for more comprehensive strategies to achieve circularity goals.

To achieve the highest level of circularity possible at the present moment, the organisational structure must be strategically aligned towards this goal. As highlighted by several interviewees, a unified direction is essential – as one LSC aptly puts it, "*all arrows need to point in the same direction*." However, there still exists a notable misalignment among stakeholders' aspirations. Moreover, challenges persist within departments like CREFM, particularly in the integration of CE principles into their tender processes. Additionally, the absence of clearly defined CE objectives disseminated from the EB further underscores the current state of misalignment. In essence, the current management of material flows falls short of effectively propelling the transition towards circularity. Rather than witnessing substantial progress, what prevails are minor, incremental adjustments in material consumption and handling practices.

8.4. Implications

Tailored analytical framework

The MFM framework presents a novel analytical approach designed specifically for analysing material flows within the unique context of HEIs. It acknowledges the nuanced nature of the CE concept, which is both context-dependent and actor-dependent. The literature reveals that many concepts are related to the CE concept, tailored to the system's scope. Industrial Symbioses is designed for the industrial scale, while eco-design is focused on product design. However, there has not been a framework tailored to the context of HEIs until now. This thesis study contributes to existing knowledge by creating a framework that includes the specific context of HEIs.

By prioritising an in-depth examination of the organisational and contextual management structures, the MFM framework ensures a more accurate understanding of the complexities at play. Moreover, the MFM framework acknowledges the dynamic nature of HEIs, where various stakeholders interact within a complex organisational ecosystem. In essence, the MFM framework represents a significant advancement in addressing the analytical challenges specific to HEIs in the context of CE implementation. By providing a comprehensive and contextually relevant analytical tool, it empowers HEIs to make informed decisions and develop targeted strategies for achieving sustainability goals.

Effective implementation of CE strategies

The MFM framework plays a pivotal role in facilitating the effective implementation of CE strategies within HEIs. By bridging the divide between comprehending material flows and devising efficient management strategies, the MFM framework enables a thorough examination of the strengths and weaknesses inherent in HEIs' existing management structures. This insight serves as a cornerstone for crafting targeted interventions aimed at enhancing the circularity of campus operations and optimising CE strategy implementation.

Unlike conventional methods such as MFA, which often rely on complex Sankey diagrams primarily comprehensible to researchers within the field of Industrial Ecology, the MFM framework prioritises clarity and accessibility for diverse stakeholders. This accessibility is crucial in engaging stakeholders in meaningful discussions and garnering support for strategic decisions regarding CE implementation. Furthermore, the MFM framework highlights the importance of effective storytelling in driving change. While accuracy and precision remain fundamental in research contexts, the MFM framework underscores the significance of presenting information in a compelling and persuasive manner to stakeholders. By demonstrating that conveying the right narrative and visualising data effectively can be more impactful than striving for absolute precision, the MFM framework offers valuable insights into navigating the complexities of stakeholder engagement and decision-making processes within HEIs.

Advancement to CE transition

As highlighted in Chapter 3, HEIs play a pivotal role in driving the transition towards a CE. Beyond their traditional roles in education and research, HEIs serve as hubs for cultivating the next generation of business leaders, researchers, and entrepreneurs—individuals who will shape the future landscape of sustainability and innovation. Through research, it became evident that transitioning towards circular campus operations is not merely a practical necessity but also a powerful means of motivating and inspiring students towards sustainable behaviours. The interviews conducted in this thesis study revealed the challenge of instilling a sense of ownership and collective responsibility within the TU Delft community to embrace sustainability initiatives.

The MFM framework emerges as a meaningful asset in this context. By offering improved implementation strategies for CE principles, the MFM framework holds the potential to catalyse broader transitions towards sustainability across various domains. Moreover, the findings suggest that the MFM Model serves as a valuable tool for engaging contract partners in sustainability dialogues, fostering collaboration, and stimulating innovative solutions to sustainability challenges. Therefore, the adoption of the MFM framework not only enhances the efficacy of CE strategies within HEIs but also holds the potential to contribute to the overarching advancement of the CE transition. By leveraging the framework to mobilise campus communities, engage stakeholders, and foster collaborative partnerships, HEIs can drive meaningful progress towards a more sustainable and circular future.

8.5. Limitations of the study

It is imperative to recognise and address the limitations inherent in this study. Despite rigorous efforts, certain constraints may have influenced the depth and breadth of the research findings. The following paragraphs outline the specific limitations encountered:

Conducted interviews

The qualitative insights gathered through interviews with LSCs and FM members provide valuable perspectives. However, the exclusion of other stakeholder groups due to time constraints may limit the generalisability of the findings. Insights from additional groups could have enriched the analysis and offered broader insights into the applicability of the MFM framework and model.

Focus on vending

This study focused predominantly on modelling material flows related to vending operations within the University. While this approach proved advantageous for understanding the dynamics of this specific category, it may not fully generalise to other inflow categories such as furniture and electronics. The unique characteristics and lifespan of different categories necessitate tailored strategies, and extrapolating findings beyond vending operations may require careful consideration.

Data sources

The downstream waste disposal data provided by Renewi and vending-related data from Maas B.V. were crucial for the analysis. However, limitations exist regarding the accuracy and precision of the data. The assigned weights for waste disposal and vending products were determined using various methods, sometimes lacking clarity on the underlying procedures. These estimations may introduce uncertainties and deviations from the actual quantities of waste disposed of or vending products used.

Prior knowledge

As a student of TU Delft with prior involvement in the Green Office, the background analysis of the university's sustainability dynamics was facilitated. This prior familiarity may have influenced the ease with which relevant information was accessed and understood. However, researchers unfamiliar with the organisation may face challenges in conducting similar analyses, potentially requiring additional interviews or consultations with staff members to gain comprehensive insights.

Rebound Effect

The rebound effect, as discussed by Hinz (2006) and Korhonen et al. (2018), poses a challenge to sustainable development by potentially offsetting gains in eco-efficiency. Improved economic efficiency often leads to increased consumption, known as the "Jevons' paradox" and the "boomerang effect." This phenomenon underscores the importance of monitoring material flows using frameworks like MFM to detect and mitigate potential rebound effects. Integrating MFM-derived indicators with metrics assessing CE strategies and environmental impacts is essential for comprehensive monitoring and addressing rebound effects effectively.

Exclusion of environmental impact

In this thesis study, the assessment of environmental impact, particularly in terms of CO2 emissions, was not incorporated. While the MFM framework effectively analyses material-focused processes like vending and downstream waste disposal, it may not be as suitable for activities such as university-related travels. Additionally, in categories with significant environmental impact relative to their weight, such as canteen operations and electronics, the MFM framework's applicability may be limited.

8.6. Suggestions for Future Research

The following suggestions outline potential avenues for future research based on the insights and limitations identified in this study. These recommendations aim to guide future investigations towards addressing gaps in knowledge and expanding upon the findings presented herein.

Applying the MFM Framework to other HEIs

Extending the application of the MFM framework to other universities would provide valuable insights into the efficacy and adaptability of the approach across different institutional contexts. Comparative studies could be conducted to assess variations in material flow patterns, sustainability practices, and challenges among universities of varying sizes, locations, and missions. This broader application would not only contribute to advancing knowledge in the field of sustainable resource management but also offer practical guidance for implementing effective sustainability strategies in HEIs worldwide.

Including other inflow categories

Expanding the scope of research to include additional inflow categories beyond vending would provide a more comprehensive understanding of material flows within the university context.

Conducting more interviews

Increasing the number of interviews with various stakeholder groups, including faculty members, students, and administrative staff, would offer diverse perspectives and enrich the analysis of material flow dynamics and sustainability initiatives within the university.

Including environmental impact

Incorporating assessments of environmental impact, particularly CO2 emissions, into the analysis would enhance the evaluation of sustainability efforts and provide insights into the broader environmental implications of material flow management strategies.

Including water and energy flows

Expanding the analysis to include water and energy flows alongside material flows would offer a holistic perspective on resource utilisation and sustainability performance within the university, facilitating the development of more comprehensive sustainability strategies.

9

Conclusion

This chapter presents the culmination of the research journey undertaken in this thesis, aiming to answer the main research question: "*How can Delft University of Technology effectively implement material flow management to improve circular campus operations?*"

It is evident from the exploration conducted that the concept of CE strategies encompasses a broad spectrum of initiatives aimed at advancing the principles of sustainability and resource management. Within the context of TU Delft, a renowned university fostering innovation and academic excellence, the potential for implementing CE strategies is clear. These strategies serve to advance CE principles within the TU Delft and beyond.

As students of Industrial Ecology, we are taught the importance of thinking from a systems perspective, recognising the interconnectedness of actions within the broader organisational context. HEIs, including TU Delft, clearly hold significant influence in advancing the CE, not only through teaching and research but also by improving sustainability operations on campus, engaging students in CE experimentation, and influencing local businesses to adopt sustainable practices. I experienced firsthand the impact a university can have on shaping one's motivations. It was during my studies at TU Delft that my interest in sustainability was ignited, propelling me to contribute to the same university that first introduced me to the concept of the Circular Economy through my thesis study

During the search for a definition of CE and as I was preparing to apply the MFA method, I encountered a conflict between what I was learning and the method I was applying. While the concept of the CE is expansive, the MFA method necessitated a more constrained perspective. Upon exploring the integration of CE principles within HEIs, it became evident that many struggle with implementation due to the static nature of the available methods, which fail to provide real-time data. Given the intricate decision-making processes inherent to HEIs, involving multiple stakeholders with diverse interests and preferences, the suitability of the MFA approach came into question.

As a consequence, a more management-oriented approach was pursued, leading to the discovery of the concept of material flow management. Although not yet widely applied in this context, the concept holds promise by emphasising the need to manage and analyse material flows. The literature review revealed that the developed framework must be tailored to the organisation and its stakeholders. Subsequently, the first phase, the analysis phase, was conceptualised to understand the structure of material flows and the stakeholders responsible for managing them. With this information in mind, the modelling phase begins. This involves visualising material flows in a more user-friendly and objective-oriented manner, taking into account the various stakeholders. During the Evaluation phase, both the management structure and the model are tested to understand the challenges involved in making campus operations more circular and whether or not the presented model offers any assistance in this regard.

Looking at the results, it can be confidently stated that the MFM model has proven to be useful in supporting key stakeholders within TU Delft in overcoming challenges, such as understanding material flows and monitoring progress once the right CE targets are established. Furthermore, the data obtained from the model can be used to craft a compelling narrative to hopefully inspire the entire TU Delft community to adopt more circular and sustainable behaviour.

Additionally, by gaining a better understanding of management-related challenges, tailored advice can be provided to overcome hurdles in the future. It is a reinforcement loop of knowledge: understanding the management structure and stakeholders' needs regarding visualisations and leveraging knowledge on material flows. Following the initial round of the three phases, it can be confidently said that the concept of managing material flows has evolved into a practical method called Material Flow Management.

So, to address the research question of how stakeholders within TU Delft can utilise the MFM framework, the answer is manifold. It's crucial to understand that it's an iterative process. The MFM framework is employed to comprehend how materials move within the TU Delft organisation and how the management structure around these materials operates. By understanding the system, interventions can be made and focal points identified regarding circularity. By perpetuating the cycle of setting objectives, strategies can be devised to achieve these goals. The MFM model has the potential to monitor developments and motivate stakeholders to adhere to these objectives.

Ultimately, this aims to inspire students, staff, and contract partners to adopt more sustainable behaviour, guiding TU Delft to lead by example in the transition towards a society where circular behaviour is the norm. The iterative nature of the MFM framework ensures ongoing improvement and adaptation, paving the way for the EB, CREFM and the Faculties to truly embody the principles of a circular campus.

10
Recommendations

In this chapter, the concluding recommendations are provided. Section 10.1 presents a series of recommendations primarily aimed at CREFM, aimed at enhancing the modelling of the MFM Model. Additionally, Section 10.2 offers a brief overview of how these recommendations were formulated, as explained in the Executive Summary at the outset of the report.

10.1. Recommendations for Modelling

Challenges were encountered during the modelling phase, particularly in acquiring suitable data and accurately representing material flows. Additionally, Chapter 7 sheds light on the desired functionalities of the MFM model. Consequently, this section presents recommendations aimed at enhancing future modelling endeavours.

Standardised data collection

During the data-obtaining phase, it became evident that TU Delft was not efficiently organised yet in terms of data. The data that would feed a mass-based analysis of material flows is scattered throughout multiple organisations and also within organisations of the TU Delft. Given its significant procurement activities, CREFM possesses the influence to request additional metadata, including product weight and volume, to streamline material flow analyses. Moreover, providing a detailed mass-based breakdown for each product.

By implementing these practices, CREFM could enhance its research efforts and gain a deeper understanding of its procurement-related material footprint. A similar suggestion can be found in the work of Stephan et al. (2019) who recommends systematic and consistent procurement data collection for universities and large organisations.

It is also recommended to use standardised data sources. In the future, when more data sources are included, it is necessary for a uniform way of naming certain aspects such as the building names, the dates, material composition and more. Therefore, Appendix G, Table G.1 shows an overview of what elements a data source must contain to be functional for CREFM. In addition, a standardised Building table is given in Table G.2 which can be used.

Bin audits

The modelling methodology employed in this thesis encompasses quantifying inflows and outflows based on purchase data. While it offers a comprehensive overview of the waste generated and its management within TU Delft and beyond, it lacks detailed information regarding off-campus sources and waste separation behaviour.

This gap is exemplified in the research by Stephan et al. (2019), where bin audits were utilised to delineate waste composition. The authors propose that, alongside procurement data, universities and large organisations can conduct audits on material inflows from campus tenants. Their analysis of waste data revealed a predominance of food scraps and paper cups in these streams, contrary to initial expectations. Therefore, it is recommended that CREFM systematically conducts bin audits to explore the composition of materials within waste bins and translate this information into tangible data for modelling purposes.

Comparison rate

As mentioned in Chapter 5, the approach was chosen to compare buildings by establishing a weight-to-area ratio. This methodology aims to provide a more equitable comparison between buildings, recognising that while absolute values are essential, fair comparisons can offer valuable insights into resource utilisation efficiency.

Efforts were made to acquire data on student and staff numbers for buildings through CREFM, ESA, and HR. However, unfortunately, no such data could be obtained for the population size per building. It is imperative to address this gap by ensuring that data on student and staff populations per building is readily available for analysis.

This emphasis on population data is crucial as TU Delft intends to expand as a university (TU Delft, 2022). In light of this expansion and the university's commitment to circularity objectives, clear decisions need to be made regarding how to compare developments effectively. If circularity is adopted as an objective and performance on circularity is to be monitored in the future, the availability of population data becomes even more pertinent.

Moreover, decision-makers within the TU Delft may also express interest in reporting circularity performances, such as waste consumption per capita by students and employees. This approach would enable assessments not only on total waste generation but also on waste generation trends per capita, thereby indicating potential improvements in circularity efforts over time.

Modelling environment

Drawing from both the study's limitations and the insights learned from interviews evaluating the MFM model, a compelling recommendation emerges: either the SPT Team or CREFM should spearhead the establishment of a unified modelling environment capable of encompassing multiple sustainability metrics and datasets. This initiative could overlap with the refinement of the existing MFM Model using Power BI, thereby leveraging new insights to apply to the model in development.

As underscored in the limitations section, crucial data concerning environmental impact, water usage, and energy consumption are notably absent. To address this deficiency effectively and grasp nuanced trade-offs, it is imperative to consolidate these dimensions within a singular model. Given the complexity of this endeavour, it is best suited for a dedicated Modelling Team equipped to tackle the task at hand. Furthermore, it is paramount to adhere to the core methodology underpinning the MFM Model—Analysing, Modelling, Evaluating, and Deciding—as it guarantees the practical efficacy and relevance of the model within TU Delft's organisational context.

Continuous improvement

The interviews conducted in Chapter 7 highlighted the promising role of the MFM Model in supporting stakeholders with implementing CE strategies. However, areas for improvement were also identified, detailed in Section 7.2.

Central to the effectiveness of the MFM Model is its iterative nature, emphasising the importance of ongoing refinement. The model must continuously evolve to enhance its effectiveness. This process can be facilitated by adhering to the modelling aspect of the MFM Model, as depicted in Figure 10.1.

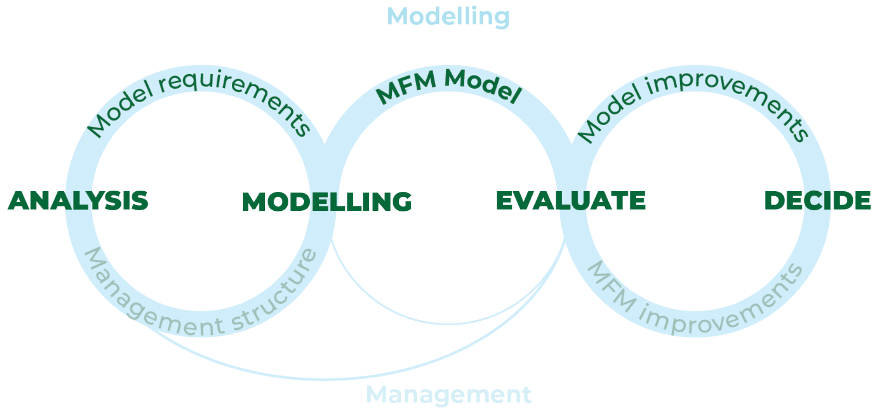

Figure 10.1: The Iterative Cycle of Modelling Improvements

10.2. Recommendations for Management

The analysis of the modelling results outlined in Chapter 8, Section 8.3, underscores that the current management of material flows at TU Delft is insufficient to realise the ambition of operating as a circular campus by 2030. Consequently, recommendations are formulated drawing upon insights from Chapter 7, Chapter 8, as well as the literature review in Chapters 2 and 3.

The Executive Summary, provided at the outset of this report, encapsulates these recommendations tailored for the Executive Board and CREFM. Furthermore, a detailed explanation is offered of how the MFM Model could be effectively applied within the context of TU Delft.

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A

Organisational Structure TU Delft

A.1. Organogram TU Delft

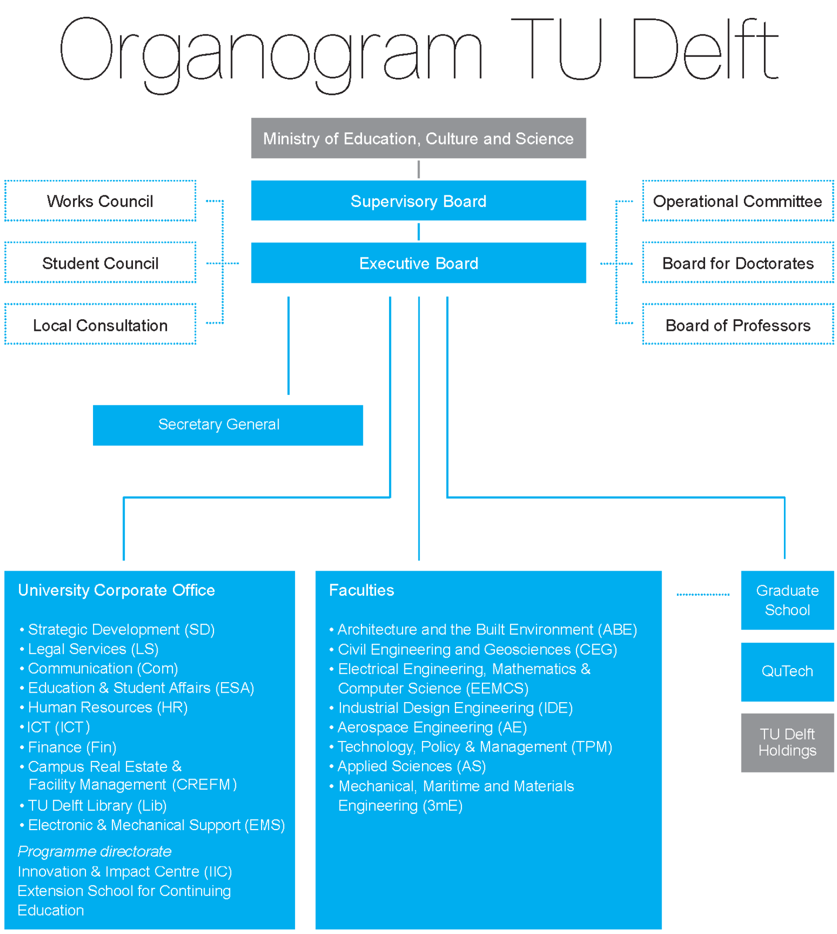

Figure A.1: Organogram of the Delft University of Technology

A.2. Organogram CREFM

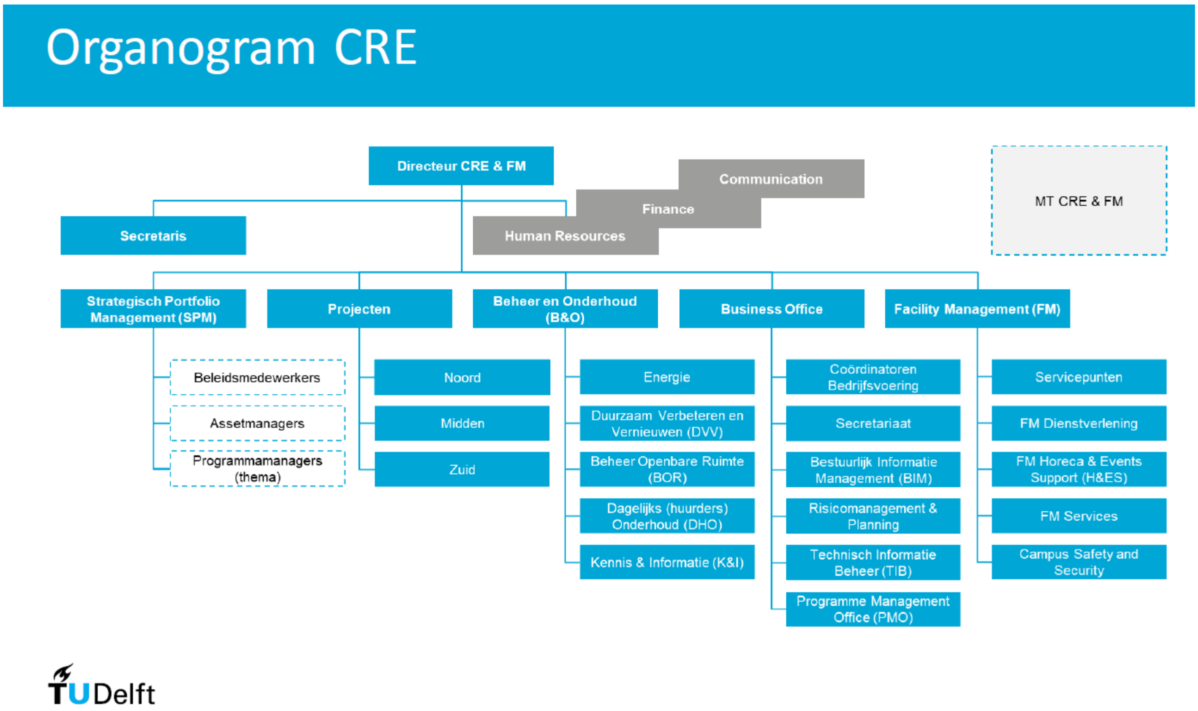

Figure A.2: Organogram of Campus Real-Estate & Facility Management

B
Collected Data

B.1. Data sources overview

Table B.1: Data Sources Overview

Data Category	Description	Data Type	Source
Downstream	Data detailing the types and quantities of waste collected by the waste processing company.	Microsoft Excel Worksheet	Renewi (2021; 2022; 2023)
Vending	Purchase data from vending machines (excluding coffee) detailing transaction information.	Microsoft Excel Worksheet	Maas B.V. (2018; 2019; 2020; 2021; 2022; 2023)
Waste processing	Information on how collected waste is processed, derived from a report provided by Renewi in 2020.	Report	Renewi (2020)
Buildings	Data on TU Delft buildings, including their total area.	Microsoft Excel Worksheet	TU Delft (2023)
Weight of vending	Mass data for specific products available in vending machines, sourced from an online database.	Online Database	PS in foodservice (n.d.)

B.2. Overview of vending products

Table B.2: Overview of Vending Products

Nr	Product	Material	Weight [kg]	Exact?
1	Aquarius Blue Berry 0.5 L	PE	0,03	Yes
2	Aquarius Lemon 0.5 L PET	PET	0,018	Yes
3	Aquarius Lemon Zero 0.5 L PET	PET	0,018	Yes
4	Bio Today Rozijnen Cranberry Koek	Plastic	0,009	
5	Bolletje brosse eierkoek kaneel	Plastic	0,001	
6	Bolletje brosse eierkoek melk	Plastic	0,001	
7	Bolletje brosse eierkoek melklaag	Plastic	0,001	
8	Bolletje eierkoek melklaag	Plastic	0,001	
9	Boom Gevulde koeken	Plastic	0,001	
10	Chaudfontaine Fusion Grapefr. PET 0.5L	PET	0,001	Partly
11	Chaudfontaine Fusion Citroen PET 0.5L	PET	0,025	Partly
12	Chaudfontaine Fusion Lime/Mint PET 0.5L	PET	0,025	Partly
13	Chaudfontaine Fusion Pompelm. PET 0.5L	PET	0,025	Partly
14	Chaudfontaine Rood PET 50cl	PET	0,025	Partly
15	Chaudfontaine Still PET 33cl	PET	0,0165	Partly
16	Chaudfontaine Still PET 50cl	PET	0,025	Yes
17	Cheetos Nibb-it Sticks	Plastic	0,001	
18	Coca-Cola 0.33L SC	Aluminium	0,0122	Yes
19	Coca-Cola 0.5 L PET	PET	0,022	Yes
20	Coca-Cola 33 cl	Aluminium	0,0122	Yes
21	Coca-Cola Cherry 0.33L SC	Aluminium	0,0122	Yes
22	Coca-Cola Cherry 33 cl	Aluminium	0,0122	Yes
23	Coca-Cola Life 0.5 L PET	PET	0,022	Yes
24	Coca-Cola Life 33 cl	Aluminium	0,0122	Yes
25	Coca-Cola Light 0.33L SC	Aluminium	0,0122	Yes
26	Coca-Cola Light 0.5 L PET	PET	0,022	Yes
27	Coca-Cola Light 33 cl	Aluminium	0,0122	Yes
28	Coca-Cola Zero 0.33L SC	Aluminium	0,0122	Yes
29	Coca-Cola Zero 0.5 L PET	PET	0,022	Yes
30	Coca-Cola Zero 33 cl	Aluminium	0,0122	Yes
31	Coca-Cola Zero Cherry 33 cl	Aluminium	0,0122	Yes
32	Cola Zero Cherry 33 cl	Aluminium	0,0122	Yes
33	Crystal Clear Cranberry 0.5L	PET	0,025	Yes
34	Crystal Clear Lemon Light 0.5L	PET	0,025	Yes
35	De Lekkerste Gevulde Koek	Plastic	0,001	
36	De Lekkerste Stroopwafel-duo	Plastic	0,001	
37	Doritos Nacho Cheese	Plastic	0,001	
38	Fanta lemon 33 cl	Aluminium	0,0122	Partly
39	Fanta lemon 33 cl	Aluminium	0,0122	Partly
40	Fanta Lemon No Sugar 0.33L SC	Aluminium	0,0122	Partly
41	Fanta orange 33 cl	Aluminium	0,0122	Partly
42	Fanta Orange Zero 33 cl	Aluminium	0,0122	Partly
43	Fanta Zero Orange 0.33L SC	Aluminium	0,0122	Partly
44	Fisherman fr Original SV	Plastic	0,001	
45	Fisherman fr salmiak SF	Plastic	0,001	

46	Fruit Bowl Strawberry Peelers	Plastic	0,001	
47	Fuze tea Green Tea 0.33L SC	Aluminium	0,0122	Partly
48	Fuze tea green tea blik 0.25L	Aluminium	0,00805	
49	Fuze tea Sparkl.Tea Lem. 0.33L slk	Aluminium	0,0122	Partly
50	Fuze tea sparkling blik 0.25L	Aluminium	0,00805	
51	Fuze tea Sparkling Tea 0.33L sleek	Aluminium	0,0122	Partly
52	Healthy People Goji&Blueberry	Plastic	0,001	
53	Hero B’tween free choco	EVOH	0,00076	Yes
54	Hero B’tween Hazelnoot	EVOH	0,00076	Yes
55	Hero B’tween Pure Chocolade	EVOH	0,00076	Yes
56	Kanjers Stroopwafels	Plastic	0,001	
57	Kinder Bueno	Plastic	0,001	
58	Kinder Bueno White	Plastic	0,001	
59	Kitkat	Plastic	0,001	
60	Lay’s Hamka’s Mini	Plastic	0,001	
61	Leev Bio oercracker sesam pompoen	Plastic	0,001	
62	Leev Bio oercracker kaas sesam	Plastic	0,001	
63	Leev Oercracker Waldcorn	Plastic	0,001	
64	Leev oerkoek choco chip & granen	Plastic	0,001	
65	Lekkerste Gevulde Koek	Plastic	0,001	
66	Levenslust Boost	Plastic	0,001	
67	Lipton Clear GreenTea 0.5L	PET	0,0215	Partly
68	Lipton Ice Tea Sparkling Zero Blik	Aluminium	0,0122	Partly
69	Lipton Icetea Green 33cl	Aluminium	0,0122	Partly
70	Little Miracles Green Tea	PET	0,001	
71	Mars	Plastic	0,001	
72	Minute maid Orange 33cl	Aluminium	0,0122	
73	Monster Energy 355ml	Aluminium	0,0132	
74	Monster Energy ULra 355ml	Aluminium	0,0132	
75	NAKD banana crunch	PP	0,003	Yes
76	NAKD Cherry	PP	0,003	Yes
77	NAKD Crazy Cola	PP	0,003	Yes
78	NAKD Strawberry crunch	PP	0,003	Yes
79	Nestea Green Citrus blik	PET	0,001	
80	Nestea Green Tea Citrus 33cl blik	Aluminium	0,0122	
81	Peijnenburg ontbijtkoek Mono	Plastic	0,001	
82	Peijnenburg Tussendoor Fruit	Plastic	0,001	
83	Peijnenburg Zero mini	Plastic	0,001	
84	Popchips Barbecue	Plastic	0,001	
85	Popchips Original Potato	Plastic	0,001	
86	Pop’d Potatoes Barbecue	Plastic	0,001	
87	Pop’d Potatoes Sea SaL	Plastic	0,001	
88	Propercorn Lightly sea salted	Plastic	0,001	
89	Propercorn sour cream&black pepper	Plastic	0,001	
90	Propercorn sweet&salty	Plastic	0,001	
91	Raw Organic Food Abrikoos pitten	Plastic	0,001	
92	Raw Snack Abrikoos pitten	Plastic	0,001	
93	Raw Snack Abrikoos pitten BIO	Plastic	0,001	
94	Raw Snack Apricot Seeds BIO	Plastic	0,001	

95	Red bull drink SF 0.25cl	Aluminium	0,00805	Yes
96	Red bull energy drink 0.25cl	Aluminium	0,00805	Yes
97	Rocky Rice ChoColate	Plastic	0,001	
98	Rocky Rice ChoColate & Orange	Plastic	0,001	
99	Roobar Cacao Nibs Organic	Plastic	0,001	
100	Roobar Goji berry Organic	Plastic	0,001	
101	Smint mint single	Plastic	0,001	
102	Snelle Jelle Zero	Plastic	0,001	
103	Snickers	Plastic	0,001	
104	Snickers 2-pack	Plastic	0,001	
105	Sourcy Vitaminwater Framb. Gran.appel	PET	0,022	
106	Sourcy Vitaminwater Mango Guave 0.5 L	PET	0,022	
107	Spa Intense 0.5 L PET	PET	0,022	
108	Spa Reine 0.5 L PET	PET	0,022	
109	Spa Touch Of Blackcurrant 0.5L	PET	0,022	
110	Spa Touch of Grapefruit	PET	0,022	
111	Spa Touch of Lemon	PET	0,022	
112	Spa Touch of Mint	PET	0,022	
113	Space Stroopwafels	Plastic	0,001	
114	Sprite 33 cl	Aluminium	0,0122	
115	Sprite Refresh 0.33L SC	Aluminium	0,0122	
116	Sprite Zero Sugar 0.33L SC	Aluminium	0,0122	
117	Sultana Naturel	Plastic	0,001	
118	Tic-tac mint T100	Plastic	0,001	
119	Tic-tac orange T1	Plastic	0,001	
120	Tony’s Chocolonely	Plastic	0,001	
121	Twix	Plastic	0,001	
122	Twix Xtra	Plastic	0,001	
123	Urban Fruit Mango	Plastic	0,001	
124	Vervanger = 10035056	Plastic	0,001	
125	Vita Coco nat. coconut water pineapple	Plastic	0,001	
126	Wasa Sandwich Cheese & Chives	Plastic	0,001	
127	Wasa Sandwich Tomaat/Basilicum	Plastic	0,001	
128	Yogi & Yousef 100% nat.dadels	Plastic	0,001	
129	Zonnatura Rijstwafel duo	Plastic	0,001	

B.3. Waste streams percentages

Table B.3: Waste Streams and Treatment Percentages

Waste Stream	R3 Reuse	R8 Recycling	R8 Incineration - Green	R9 Incineration - Grey	Discarded
Coffee cups	0	0.95	0	0.05	0
Composite	0	0	0	0	1
Confidential paper	0	0.79	0.16	0	0.05
Construction	0	0.45	0.33	0.16	0.06
Debris	0	0.94	0	0	0.06
Electronic	0	0.71	0.22	0.02	0.05
Film/plastics	0	0.93	0	0.01	0.06
GFT	0	0.85	0.05	0.05	0.05
Glass	0	0.93	0.01	0.01	0.05
Gravel	0	0	0	0	1
Hazardous	0	0	0	0	1
Other	0	0	0	1	0
Paper/cardboard	0	0.74	0.08	0.08	0.1
PMD	0	0.81	0.02	0.12	0.05
Residual	0	0.05	0.36	0.37	0.22
Sand	0	0	0	0	1
Soil	0	0	0	0	1
Soil - polluted	0	0	0	0	1
Swill	0	0.89	0.03	0.03	0.05
Wood	0	0.03	0.92	0	0.05

C
Microsoft Power BI

C.1. Automating Table Appending

```
let
    Source = Excel.Workbook(File.Contents("D:\Documents\00␣THESIS\Data␣Model\MAAS␣
        BV\Maas_2020_2021.xlsx"), null, true),
    Tbl_Maas_2020_2021_Table = Source{[Item="Tbl_Maas_2020_2021",Kind="Table"]}[
        Data],

    // Apply Steps for Maas Tables
    #"Changed Type" = Table.TransformColumnTypes(Tbl_Maas_2020_2021_Table, {
        {"YEAR", Int64.Type},
        {"PERIOD", Int64.Type},
        {"EQUIPMENT_NUMBER", Int64.Type},
        {"EQUIPMENT_DESCRIPTIO", type text},
        {"MATERIAL_GROUP", type text},
        {"MATERIAL_DESCRIPTION", type text},
        {"SALES_PRICE", type number},
        {"SHIP_TO_NUMBER", Int64.Type},
        {"STREET_SHIP_TO", type text},
        {"POSTCAL_CODE_SHIP_TO", type text},
        {"PERIOD_QUANTITY", Int64.Type},
        {"PERIOD_AMOUNT", type number},
        {"Gezond", type text}
    }),
    #"Merged to DATE" = Table.CombineColumns(Table.TransformColumnTypes(#"Changed
        Type", {{"YEAR", type text}, {"PERIOD", type text}}, "en-NL"),{"YEAR", "
        PERIOD"},Combiner.CombineTextByDelimiter(" ", QuoteStyle.None),"Date"),
    #"Changed Type to Date" = Table.TransformColumnTypes(#"Merged to DATE",{{"Date
        ", type date}}),
    #"Put MATERIAL DESCRIPTION first" = Table.ReorderColumns(#"Changed Type to
        Date",{"MATERIAL_DESCRIPTION", "Date", "EQUIPMENT_NUMBER", "
        EQUIPMENT_DESCRIPTIO", "MATERIAL_GROUP", "SALES_PRICE", "SHIP_TO_NUMBER", "
        STREET_SHIP_TO", "POSTCAL_CODE_SHIP_TO", "PERIOD_QUANTITY", "PERIOD_AMOUNT
        ", "Gezond"}),
    #"Merged Queries PRODUCT" = Table.NestedJoin(#"Put MATERIAL DESCRIPTION first
        ", {"MATERIAL_DESCRIPTION"}, MaterialDescription_Product, {"Material
        description"}, "MaterialDescription_Product", JoinKind.RightOuter),
    #"Expanded MaterialDescription_Product" = Table.ExpandTableColumn(#"Merged
        Queries PRODUCT", "MaterialDescription_Product", {"Product", "Segment", "
        Material body", "Waste stream", "Weight per unit [kg]"}, {"Product", "
        Segment", "Material body", "Waste stream", "Weight per unit [kg]"}),
    #"Added calculated colum Weight" = Table.AddColumn(#"Expanded
```

```
        MaterialDescription_Product", "Weight", each [PERIOD_QUANTITY]*[#"Weight
        per unit [kg]"]),
    #"Merged Queries BUILDING" = Table.NestedJoin(#"Added calculated colum Weight
        ", {"STREET_SHIP_TO"}, StreetShipTo_Building, {"Street_name"}, "
        StreetShipTo_Building", JoinKind.RightOuter),
    #"Expanded StreetShipTo_Building" = Table.ExpandTableColumn(#"Merged Queries
        BUILDING", "StreetShipTo_Building", {"Building", "Relation", "Type"}, {"
        Building", "Relation", "Type"}),
    #"Filtered Rows" = Table.SelectRows(#"Expanded StreetShipTo_Building", each [
        PERIOD_QUANTITY] > 0),
    #"Changed Type1" = Table.TransformColumnTypes(#"Filtered Rows",{{"Weight",
        type number}}),
    #"Filtered Rows1" = Table.SelectRows(#"Changed Type1", each true)
in
    #"Filtered Rows1"
```

Listing C.1: Power Query Script

C.2. Visualisation types

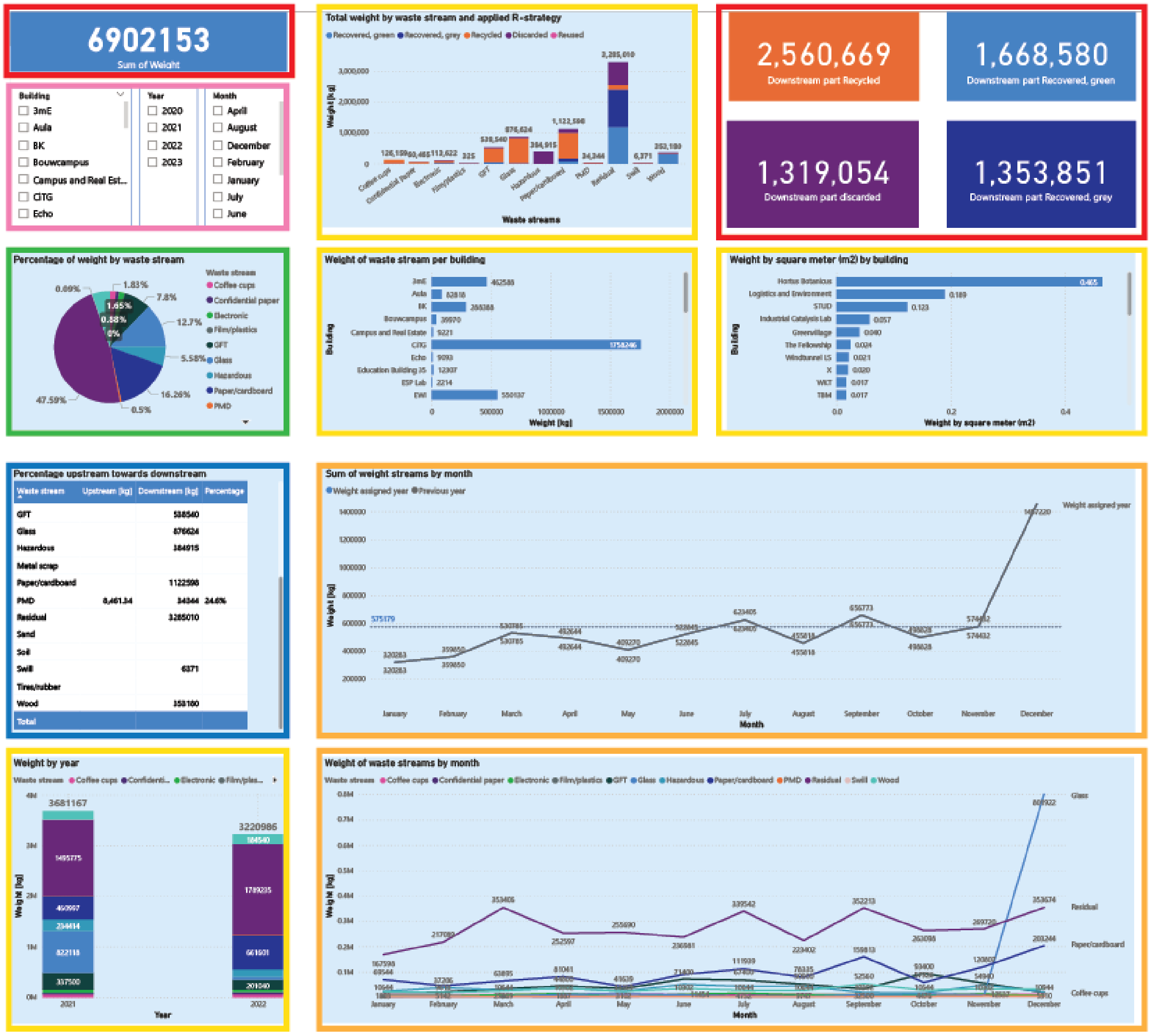

Figure C.1: Types of Visualisation used for the MFM Model

The visualisations employed in the analysis are colour-coded for easy identification:

Pink

The selection tool, showcased in pink, is an essential feature for user navigation. It allows users to zoom in on specific dates and buildings, enabling a closer examination of data without the need to switch between multiple datasets or sheets.

Red

Textual visualisations, denoted by a red frame, present numerical data. Here, the total amount of the assigned weight is displayed.

Orange

Graphs over time are represented in orange. These visuals are particularly effective for illustrating consumption patterns and trends, allowing users to discern whether total waste increases or decreases throughout different periods.

Green
Pie charts, depicted in green, offer insights into the composition of waste. They highlight the proportion of waste types at specific focus points, presenting data in percentages rather than absolute values.

Yellow
Bar charts, indicated in yellow, are frequently employed as they facilitate the comparison of absolute values more easily. These visuals are useful for comparing data across different categories or variables.

Blue
Tables, identified by a blue colour, provide a structured format for presenting detailed information. They are particularly helpful for comparing absolute values across an array of products or categories.

C.3. Measures

Recycle percentage

```
    Downstream part Recycled =
SUMX(
    VALUES('DOWNSTREAM'[Waste stream]),
    SUMX(
        FILTER('DOWNSTREAM', 'DOWNSTREAM'[Waste stream] = EARLIER('DOWNSTREAM'[Waste stream])),
        'DOWNSTREAM'[Weight]
    ) *
    LOOKUPVALUE('WasteSteam_Rladder'[Recycling], 'WasteSteam_Rladder'[Waste stream], 'DOWNSTREAM'[Waste stream])
)
```

Recover percentage - green

```
    Downstream part Recovered, green =
SUMX(
    VALUES('DOWNSTREAM'[Waste stream]),
    SUMX(
        FILTER('DOWNSTREAM', 'DOWNSTREAM'[Waste stream] = EARLIER('DOWNSTREAM'[Waste stream])),
        'DOWNSTREAM'[Weight]
    ) *
    LOOKUPVALUE('WasteSteam_Rladder'[Recover - green], 'WasteSteam_Rladder'[Waste stream], 'DOWNSTREAM'[Waste stream])
)
```

Recover percentage - grey

```
    Downstream part Recovered, grey =
SUMX(
    VALUES('DOWNSTREAM'[Waste stream]),
    SUMX(
        FILTER('DOWNSTREAM', 'DOWNSTREAM'[Waste stream] = EARLIER('DOWNSTREAM'[Waste stream])),
        'DOWNSTREAM'[Weight]
    ) *
    LOOKUPVALUE('WasteSteam_Rladder'[Recover - grey], 'WasteSteam_Rladder'[Waste stream], 'DOWNSTREAM'[Waste stream])
)
```

Discarded - green

```
    Downstream part discarded =
SUMX(
    VALUES('DOWNSTREAM'[Waste stream]),
    SUMX(
        FILTER('DOWNSTREAM', 'DOWNSTREAM'[Waste stream] = EARLIER('DOWNSTREAM'[Waste stream])),
        'DOWNSTREAM'[Weight]
    ) *
    LOOKUPVALUE('WasteSteam_Rladder'[Discarded], 'WasteSteam_Rladder'[Waste stream], 'DOWNSTREAM'[Waste stream])
)
```

D

Results from the model

D.1. Results from downstream

Table D.1: Results of total weight of downstream by building in 2022

Building	Sum of Weight	Percentage
3mE	154196	6,41%
Aula	82818	3,44%
BK	139869	5,81%
Bouwcampus	39970	1,66%
Campus and Real Estate	9221	0,38%
CiTG	293041	12,18%
Echo	9093	0,38%
Education Building 35	12307	0,51%
ESP Lab	738	0,03%
EWI	183379	7,62%
Greenvillage	15132	0,63%
HollandPTC	18163	0,75%
Hortus Botanicus	293021	12,18%
Industrial Catalysis Lab	3918	0,16%
Informatica	21411	0,89%
IO	104068	4,32%
Kramers Laboratory	3890	0,16%
Logistics and Environment	379713	15,78%
LR	58526	2,43%
P&E Laboratory	17180	0,71%
Reactor Institute	40201	1,67%
STUD	2098	0,09%
TBM	35856	1,49%
The Fellowship	24364	1,01%
TNO	5690	0,24%
TNW	186330	7,74%
TNW-Zuid	78324	3,26%
TU Delft Library	52281	2,17%
Vliegtuighal	19435	0,81%

Windtunnel HS	11447	0,48%
Windtunnel LS	18121	0,75%
WKT	4682	0,19%
X	87761	3,65%
Total	2406244	

Table D.2: Results of weight-to-area ratio

Building	**weight-to-area ratio**
Logistics and Environment	0.1795518896977496
Hortus Botanicus	0.15862837321650805
STUD	0.11865695635975756
Industrial Catalysis Lab	0.05951529932859567
Greenvillage	0.045564316851967164
The Fellowship	0.0285306963167563
Windtunnel LS	0.023749742681042726
X	0.022922987251908195
WKT	0.02025603840836486
Kramers Laboratory	0.01689448365493962
IO	0.015915316186935494
Bouwcampus	0.01543581565680445
Aula	0.01474016971806
Windtunnel HS	0.014065140597271394
Vliegtuighal	0.013413219672935846
Education Building 35	0.013341144639188285
TNO	0.01329299753668424
CiTG	0.012902351264276591
TU Delft Library	0.012230419396848583
BK	0.011473501238948006
TBM	0.010825119450718726
Informatica	0.010239001787369537
Echo	0.010173515215005008
TNW-Zuid	0.009416784510316073
Reactor Institute	0.008889017031667511
TNW	0.00707117378374006
3mE	0.006566570480249931
LR	0.006084031920319679
EWI	0.004296047328725286
ESP Lab	0.0007855127876572375

Table D.3: Results of total weight by waste stream

Waste stream	**Sum of Weight**
Residual	698997
Paper/cardboard	279297
Wood	59300
Hazardous	50167
GFT	46200

Coffee cups	21064
Glass	19326
Electronic	16389
PMD	14181
Confidential paper	12888
Swill	4513

Table D.4: Results of waste throughout a year, Architect

Month	**2022**	2021
January	9052	731
February	8971	778
March	6976	1296
April	7515	1730
May	4867	2028
June	4563	3132
July	11748	14255
August	3339	4892
September	6933	3790
October	8878	6610
November	5976	8415
December	7596	5798

Table D.5: Weight of waste streams, ME

Waste stream	**Sum of Weight**
Residual	47358
Paper/cardboard	45219
Wood	9240
Glass	645

D.2. Data from vending

Table D.6: Weight of vending by building, 2022

Building	Weight [kg]
TU Delft Library	1524.3
BK	1460.6
IO	662.1
CiTG	635.7
3mE	553.4
EWI	548.3
Pulse	493.8
Echo	481.0
TNW	416.3
TNW Zuid	393.8
LR	382.2
TBM	288.0
Aula	214.0
Education Building 35	198.4
Reactor Institute	57.9
Informatica	56.2
Windtunnel HS	36.3
Bouwcampus	34.8
Science Center	10.9
Flux	7.3
Lijm & Cultuur	6.1

Table D.7: Weight by vending product, 2022

Product	Weight [kg]
Chaudfontaine Still PET 50cl	1754.0
Aquarius Blue Berry 0.5 L	498.6
Coca-Cola 0.33L SC	462.9
Coca-Cola Zero 0.5 L PET	460.7
Chaudfontaine Rood PET 50cl	447.7
Twix Xtra	439.9
Snickers 2-pack	437.4
Kinder Bueno	405.8
Coca-Cola 33 cl	301.8
Coca-Cola Zero 0.33L SC	295.7
Chaudfontaine Fusion Citroen PET 0.5L	268.7
Kitkat	233.3
De Lekkerste Gevulde Koek	195.1
Coca-Cola Zero 33 cl	191.7
Fuze tea Green Tea 0.33L SC	181.4
Monster Energy ULra 355ml	174.1
Kanjers Stroopwafels	126.4
Fanta Lemon No Sugar 0.33L SC	94.7
Fuze tea Sparkling Tea 0.33L sleek	94.3
Coca-Cola Light 0.5 L PET	90.0

Lipton Clear GreenTea 0.5L	87.9
Fanta Zero Orange 0.33L SC	82.7
Propercorn Lightly sea salted	80.5
Coca-Cola Light 0.33L SC	68.3
Fuze tea green tea blik 0.25L	61.7
Fuze tea Sparkl.Tea Lem. 0.33L slk	60.6
Snelle Jelle Zero	56.4
Fanta lemon 33 cl	52.6
Sprite Refresh 0.33L SC	50.3
Monster Energy 355ml	46.9
Fuze tea sparkling blik 0.25L	44.0
Popchips Barbecue	42.5
Sprite 33 cl	39.3
Propercorn sweet&salty	35.3
Boom Gevulde koeken	34.3
Bolletje brosse eierkoek melk	33.2
Smint mint single	29.0
Coca-Cola Cherry 33 cl	26.9
Doritos Nacho Cheese	25.5
Red bull energy drink 0.25cl	25.2
Fanta Orange Zero 33 cl	25.2
Lipton Ice Tea Sparkling Zero Blik	24.9
Chaudfontaine Still PET 33cl	23.4
Coca-Cola Light 33 cl	22.5
Sprite Zero Sugar 0.33L SC	20.5
Zonnatura Rijstwafel duo	19.9
Red bull drink SF 0.25cl	18.3
Space Stroopwafels	18.1
Kinder Bueno White	17.7
Cheetos Nibb-it Sticks	15.7
Tic-tac mint T100	13.3
Sourcy Vitaminwater Mango Guave 0.5 L	13.2
Pop'd Potatoes Barbecue	11.9
Sourcy Vitaminwater Framb. Gran.appel	11.3
Peijnenburg Tussendoor Fruit	8.4
Popchips Original Potato	8.2
Coca-Cola Cherry 0.33L SC	8.1
Spa Reine 0.5 L PET	7.9
Cola Zero Cherry 33 cl	5.7
Hero B'tween Hazelnoot	4.9
Sultana Naturel	3.8
Rocky Rice ChoColate	3.5
Crystal Clear Cranberry 0.5L	2.7
Lay's Hamka's Mini	1.8
Pop'd Potatoes Sea SaL	1.6
Crystal Clear Lemon Light 0.5L	1.5
Propercorn sour cream&black pepper	1.3
Spa Intense 0.5 L PET	1.3
Fisherman fr salmiak SF	1.2

Peijnenburg Zero mini	1.1
Chaudfontaine Fusion Lime/Mint PET 0.5L	1.1
Spa Touch of Lemon	1.0
Fisherman fr Original SV	0.7
Spa Touch Of Blackcurrant 0.5L	0.7
Spa Touch of Mint	0.6
Tic-tac orange T1	0.5
Spa Touch of Grapefruit	0.5

E

Interviews

Interview: Lokale Duurzaamheidscoördinatoren

Gebouw:
Datum:

Introductie

- Persoonlijke introductie
- Introductie over het onderzoek
- Introduceer de doelen van het onderzoek

Deel I: Algemene vragen met betrekking tot circulariteit

1. Hoe beïnvloedt jouw rol als LSC de algehele circulariteit van …[faculteit/gebouw]?
2. Wat betekent het begrip circulariteit voor jou?
3. Hoe zou je de besluitvormingsprocessen met betrekking tot circulariteit en duurzaamheid willen vormgeven?
4. Wat zijn de obstakels die gepaard gaan met het implementeren van circulariteitsstrategieën binnen jouw verantwoordelijkheidsgebied?
5. Welke specifieke informatie, middelen of ondersteuning zouden je helpen bij het vervullen van je rol als Lokale Duurzaamheidscoördinator?
6. Hoe kan het verstrekken of verkrijgen van informatie en data bijdragen aan het implementeren van circulariteitsstrategieën?

Deel II: Het model testen

Deze sectie wordt op een ongestructureerde manier gepresenteerd, met echte cijfers en feiten afgestemd op jouw specifieke rol. Ik wil graag jouw gedachten verzamelen over het volgende:

7. Vind je de verstrekte informatie relevant voor jouw rol, en zo ja, waarom? Als je het niet relevant vindt, zou je dan jouw perspectief willen delen?
8. Welke aanvullende elementen of functies zouden kunnen worden opgenomen in het model die bijdragen aan het implementeren van circulariteitsstrategieën?
9. Hoe zou je dit model willen inzetten om je te ondersteunen in je rol als Lokale Duurzaamheidscoördinator?

10. Gezien de beschikbaarheid aan informatie, hoe geef je de voorkeur aan het visualiseren van deze gegevens?
11. Zijn er specifieke grafieken of visualisaties die je overzichtelijk vindt? Waarom?
12. Zijn er specifieke grafieken of visualisaties die niet overzichtelijk vindt? Waarom?

Afsluiting

- Heb je nog laatste opmerkingen, inzichten of opmerkingen die je zou willen delen?
- Bedank de geïnterviewde voor diens tijd en zichten.
- Herinner ze aan hun consent rechten.
- Herinner ze aan het feit dat ze de onderzoeker kunnen contacteren voor vragen of opmerkingen.

F

Calculations Circular Campus by 2030

F.1. Weight of total waste per capita per year

To calculate the average weight of residual waste per capita, first, the change in weight from 2022 to 2023 must be found:

$$\text{Change} = \text{2023 value} - \text{2022 value} = 36.66429165 - 36.23209891 = 0.43219274$$

Next, the average change is added to the 2023 value to predict the weight of the waste per capita in 2030:

$$\begin{aligned}\text{Predicted value for 2030} &= \text{2023 value} + (\text{Average change per year} \times \text{Number of years}) \\ &= 36.66429165 + (0.43219274 \times 7) \quad \text{(since 2023 to 2030 is 7 years)} \\ &= 36.66429165 + 3.02534918 \\ &= 39.68964083\end{aligned}$$

This results in the following value for 2030: **39.69 kg of waste per capita per year**

F.2. Weight of residual waste per capita per year

To calculate the average weight of residual waste, the change in weight from 2022 to 2023 must be calculated:

$$\text{Change} = \text{2023 value} - \text{2022 value} = 20.39543997 - 20.72523497 = -0.329795$$

This change is added to the 2023 value to predict the weight of total waste in 2030:

$$\begin{aligned}\text{Predicted value for 2030} &= \text{2023 value} + (\text{Average change per year} \times \text{Number of years}) \\ &= 20.39543997 + (-0.329795 \times 7) \quad \text{(since 2023 to 2030 is 7 years)} \\ &= 20.39543997 - 2.308565 \\ &= 18.08687497\end{aligned}$$

This results in the following value for 2030: **18.09 kg of residual waste per capita per year**.

G

Standardised Data Collection

G.1. For Suppliers

Table G.1 exemplifies a standardised data sheet encompassing all pertinent information required for modelling purposes. As explained in Chapter 5, precision demands that alongside the product description, the data should encompass precise details of the purchase, the postal code of the building, precise mass, material composition, and other relevant parameters. If each supplier adheres to furnishing these details, it guarantees a more comprehensive dataset, thereby enhancing the efficacy of modelling efforts.

Product Description	**Product Code**	**Product Category**	**Product Group**	**Postal Code**	**Building**	**Date (dd/mm/yy)**	**Mass (kg)**	**Material Composition**
Desk Type ABC1	#012345	Furniture	Desks	2629 HC	Logistics and Environment	01/01/2024	10	Mixed
Snickers snack	#09876	Vending	Food snack	2628 XE	Echo	02/02/2024	0.001	PP

Material A	**Mass A (kg)**	**Material B**	**Mass B (kg)**	**Price (€)**	**Environmental Impact (CO2 kg eq.)**
Aluminium	3	Wood	7	150	70
				0.70	0.5

Table G.1: Product Information

G.2. Building Table

Table G.2 presents an example of a unified Building table that CREFM can utilise for modelling purposes. It is imperative that suppliers accurately input the postal code to enable seamless linkage between Building data and supplier products. Additional fields can be incorporated as deemed necessary.

Building Name	Building Number	Postal Code	Faculty	Type
Aula	20	2628 CC	-	Other
BK	8	2628 BL	BK	Faculty
Bouwcampus	26	2629 HZ	-	Other
Campus and Real Estate	30b	2628 CE	-	Other
Chemical Engineering	12	2628 BA	TNW	Faculty
CiTG	23	2628 CN	CiTG	Faculty
Coffee & Bikes	33b	2628 CE	-	Other
Echo	29	2628 XE	-	Generic education
Education Building 35	35	2628 CT	-	Generic education
ESP Lab	36	2629 JH	EWI	Research
EWI	36	2628 CD	EWI	Faculty
Greenvillage	25	2628 CM	-	Research
HollandPTC	153	2628 BX	-	Other
Hortus Botanicus	6	2628 BM	TNW	Research
Industrial Catalysis Lab	67	2629 HT	TNW	Research
Informatica	28	2628 EX	EWI	Faculty
InHolland University	42	2628 CB	-	Other
IO	32	2629 CE	IO	Faculty
Kramers Laboratory	15	2628 BW	TNW	Research
LR	62	2629 HS	LR	Research
P&E Laboratory	34b	2628 CB	3mE	Research
Prometheus Manege	Other	2629 HD	-	Other
Proteus-Eretes	Other	2628 AT	-	Other
Pulse	33	2628 CE	-	Generic education
Reactor Institute	50	2628 CD	TNW	Research
Science Center	3	2628 RX	-	Research
STUD	19	2628 CC	-	Other
The Fellowship	66	2629 HS	EWI	Generic education
TNW	22	2628 CJ	TNW	Faculty
TNW-Zuid	58	2629 HZ	TNW	Faculty
TNO	46	2628 CA	-	Research
TU Delft Library	21	2628 ZC	-	Generic education
Vliegtuighal	61	2629 HS	LR	Research
WKT	43	2628 CA	-	Other
Windtunnel HS	64	2629 HS	LR	Research
Windtunnel LS	45	2628 CA	LR	Research
X	37	2628 CD	-	Other

Table G.2: Building Information