Comparative Sustainability Assessment of End-of-Life Resource Recovery Strategies for Water Meters

A Focus on Current Industry Approaches

By

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Comparative Sustainability Assessment of End-of-Life Resource Recovery Strategies for Water Meters: A Focus on Current Industry Approaches

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Preface

This thesis marks the end of my studies at Delft University of Technology, a journey that has been both humbling and transformative. I am deeply grateful for the opportunity to contribute to the scientific community, particularly in the field of sustainability sciences—an area that has long been my passion. I hope my findings will make a meaningful contribution to this field.

Writing this thesis has been a valuable experience, one filled with moments of learning, growth, and challenges. I am truly grateful to everyone who supported me throughout this process. This could not have been possible without you.

First and foremost, I want to thank my graduation committee for their support, patience, and guidance. Especially during moments when I felt stuck or doubted myself, our meetings always brought relief, renewed motivation and valuable insights.

I am deeply grateful to my family and partner for their support through the highs and lows. This achievement is dedicated to them, as their encouragement, occasional teasing (my dear sister), and constant motivation inspired me to strive for my best. I am also thankful to my friends, who supported me throughout my academic journey at TU Delft. Thank you!

Abstract

Water meters are crucial parts of the world's water supply systems, enabling households and industries to measure water consumption. These everyday items have developed in design, material composition, functional capabilities, and durability. The meters within the Dutch industry are primarily made from brass bodies with plastic internals and top parts, but this has changed in recent years due to regulations and industry trends. Water meters have an End of Life (EOL) of around 20 years. Once they reach the end of their operational life, they are replaced by new water meters.

From a sustainability perspective, old water meters require a sustainable recovery strategy. From the academic literature and the drinking water utility (DW) point of view, little is known about what happens with the water meters once they leave the warehouses, where they are piled up until they are picked up by the resource recovery (RR) facilities. The EoL resource recovery strategies of these meters remain unexplored. This absence of information leads to incomplete knowledge of the impacts of the meter's sustainability after decommissioning. Addressing this gap is essential for developing sustainable future strategies for water meters.

Through exploratory field research, this research aimed to first map out the current water meter assets, the ongoing trends and the EoL RR strategies of water meters and consequently assess and evaluate the sustainability of these current strategies given the different water meters used for this study to provide a broader perspective on how future proof these strategies are given the trends in the water meter industry.

A Life Cycle Sustainability Assessment (LCSA) is used with varying boundaries for the sustainability pillars to assess the sustainability of the different resource recovery strategies. It follows an attributional, comparative assessment, where the EoL RR strategies of manual disassembly (MD) and mechanical shredding (MS) for the selected water meters: brass-bodied meters (representing currently decommissioned models), plastic-bodied meters (reflecting current industry trends), and smart meters (aligning with future industry goals) are assessed and evaluated from a weak sustainability interpretation.

From an environmental perspective, the study's findings suggest that differences in EoL RR strategies have the strongest impact on brass-bodied water meters. Smart meters also display relatively high environmental sensitivity due to their incorporated electronics, while plastic-bodied meters show only minor variations. The study's findings also highlight the contribution of the different materials used in these meters, considering their life cycle.

Economically, the potential fluctuations in material yield outcomes make the choice of strategy for brass-bodied meters especially important. Minor amounts of content loss can have a significant financial impact on the potential scrap revenue. While MD remains stable and beneficial for brass-bodied meters, it becomes less attractive for plastic and smart meters due to lower scrap values and comparatively higher operational costs than MS.

Socially, the assessment remains open to interpretation: MD promotes greater inclusivity and job opportunities yet involves more physical exertion and potential fatigue. MS streamlines the process, reducing labour time and ergonomic strain but offering fewer inclusive employment possibilities.

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List of abbreviations

BW	Brabant Water
DWU	Drinking Water Utility
EoL	End-of-Life
FU	Functional Unit
IDEMAT	Industrial Design & Engineering Materials
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCSA	Life Cycle Sustainability Assessment
LCT	Life Cycle Thinking
LME	London Metal Exchange
MD	Manual Disassembly
MS	Mechanical Shredding
OPEX	Operational Expenditure
PCB	Printed Circuit Board
RRF	Resource Recovery Facility
RR	Resource Recovery
SA	Sustainability Assessment
SP	Sector Plan
S-LCA	Social Life Cycle Assessment
WMM	Water Meter Manufacturer
WoW	Water is our World

1 Introduction

Water meters play a crucial role in water supply systems worldwide, as they enable accurate water consumption measurement for a drinking water utility (DWU) (Van Zyl, 2011). Like any other product, water meters have an operational lifespan, at which point they need to be replaced. This is either done by a new generation of meters since this field is constantly evolving, or it is replaced by the same meter depending on the DWUs' choices (Van Zyl, 2011). This provides a continuous stream of end-of-life (EoL) meters from the DWUs that must be recycled and processed sustainably.

Water meter resource recovery (RR), defined as the recovery of the materials a water meter consists of, involves a multi-stage process of collecting, transporting, disassembling, and sorting various components. These processes are done by resource recovery facilities (RRFs) that prepare the meters' materials for eventual recycling or disposal by the end-processors. These end-processors are mostly different companies than the RRFs. Little is known regarding the RR strategies used by the RRF for the water meters or the yield efficiency of the materials.

Most current-in-use water meters feature a brass body consisting primarily of copper and zinc with small amounts of lead (4MS, 2019; AWWA, 2012). Since copper has been deemed a critical metal by the EU Regulation 1252 (2024), properly recovering and recycling brass from water meters could be economically advantageous and match waste management plans that aim to minimise the environmental impact of non-ferrous metals (Ruhrberg, 2006).

While the RR of brass water meters offers clear economic benefits from a societal point of view, it is equally important to consider the broader perspective of sustainable EoL management of other meters made from different materials. Examining current EoL RR strategies and benefits for water meters is necessary to understand future pathways with the newer generation of meters and determine their sustainability. This inquiry should consider whether these strategies contribute positively to environmental preservation, economic efficiency, and societal gains.

This study focuses on water meters within the Dutch context, specifically targeting residential and small business types used for measuring drinking water. The term "water meter" will exclusively refer to these specified categories throughout this research. The concept of a product's EoL is identified as the point at which it can no longer fulfil its intended function (Rubin et al., 2014).

The following sections will clarify what water meters are, identify the knowledge gap, present the problem statement, define the research objective and questions, and outline the research approach.

1.1 Understanding water meters

Understanding water meters begins with the internationally recognised definition, which describes a water meter as an "Instrument intended to measure continuously, memorise, and display the volume of water passing through the measurement transducer at metering conditions” (ISO 4064-1, 2017). This definition highlights the main features of a water meter, including the ability to measure continuously, memory for data storage, and display the measured volume (Van Zyl, 2011).

Because of these functions, four general components can always be identified, as displayed in **Fig. 1** sensor to detect water flow, a transducer to convert the flow into a measurable signal, a counter to add up the total volume of water measured and an indicator to display this volume. These components form the core of any water meter (Van Zyl, 2011).

Although the components mentioned above are present in every type of water meter, there are a variety of water meters based on different measuring mechanisms. The following subsections discuss these mechanisms.

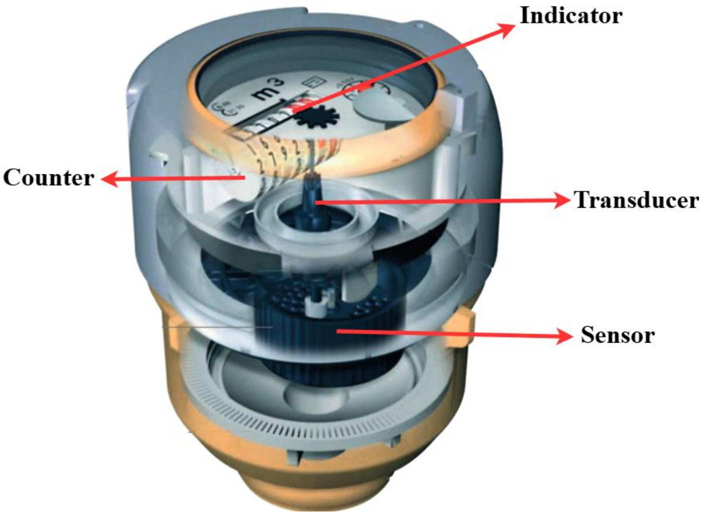

Figure 1 illustrates a water volumetric meter's interior and four fundamental components. Adapted from Honeywell (2016)

1.1.1 Water meter classification

Water meters are primarily classified by the mechanism they measure water flow with (Arregui et al., 2006; AWWA, 2012; Van Zyl, 2011). According to Van Zyl (2011) these mechanisms can be categorised into three main groups based on the measuring principle (depicted in **Fig. 2**): Mechanical, electromagnetic, and ultrasonic meters. Each type has unique features and applications, making them suitable for different settings in water distribution (Van Zyl, 2011).

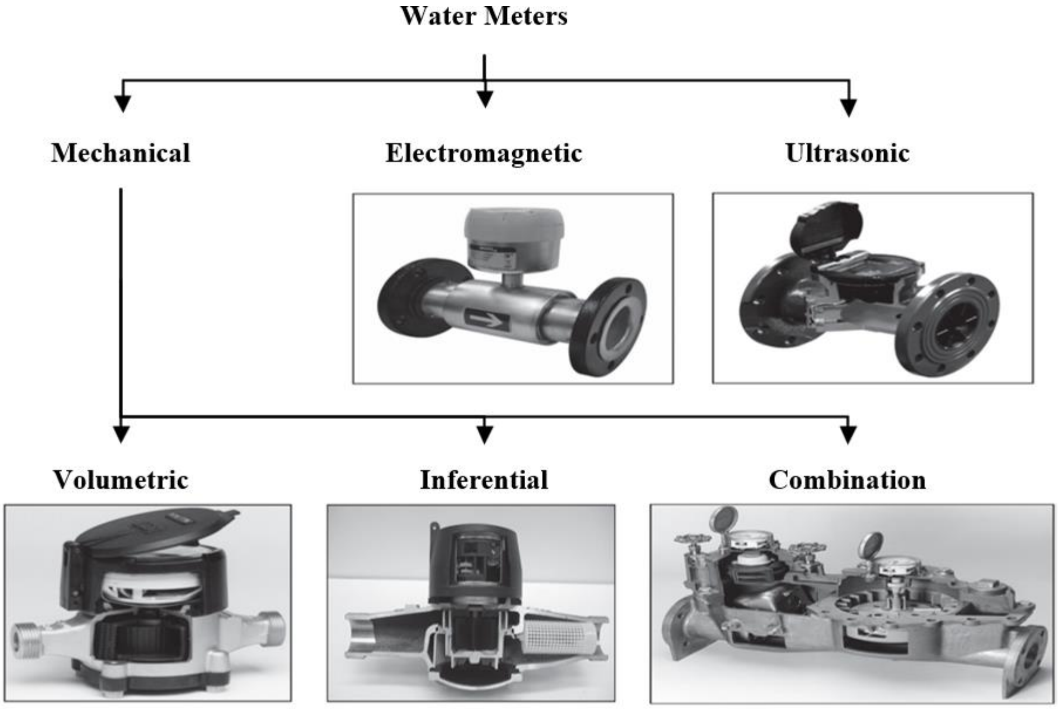

Figure 2: Overview of water meter classification according to their measuring principles. Adapted from AWWA (2012) and Van Zyl (2011)

Appendix C.1 discusses how each of these different mechanisms operates. Volumetric and inferential meters are the most used in households worldwide because they offer good performance at a reasonable cost (AWWA, 2012). Other meters have traditionally been used in large-scale industrial applications, but this is gradually changing (Charalambous & Laspidou, 2017).

1.2 Knowledge gap

To the author's knowledge, a preliminary literature review indicates a knowledge gap in EoL RR strategies for water meters. Although there are many studies on managing water meters or the accuracy levels of different water meter mechanisms, the academic work stops before covering the EoL disposal stage and the RR strategies and their potential impacts. As Arregui highlights in "Integrated Water Meter Management" (2006), "The absence of specific literature about water meters is quite striking, both from a technical and from a managerial point of view." The comment about the lack of literature is notable because it shows a mismatch between the widespread use of water meters as we know them for the last 100 years (Arregui et al, 2006), and little research has been done on these products.

This field is unexplored, contrary to the disposal and RR strategies of EoL vehicles and electrical and electronic waste, which is well represented in academic literature (Islam & Huda, 2018; Karagoz et al., 2020). This absence of research leads to incomplete knowledge of the impacts of the meters' sustainability after decommissioning. This encompasses the environmental, social, and economic aspects of water meter RR strategies for a more circular economy, which means cutting waste and reusing recovered materials or products (Wagner et al., 2019). Addressing this gap is essential for developing sustainable future strategies for water meters.

1.3 Problem statement

Given the transition from traditional meters to more advanced meters made from other materials in the future, decommissioned water meters are constantly being replaced by DWUs, leading to a steady stream of meters that must be dealt with responsibly. Although RR methods exist for water meters, their specifics, effectiveness, and sustainability remain primarily unknown—both for meters currently reaching the EoL and for newly implemented meters that will eventually require decommissioning and disposal.

This is concerning because as the industry moves towards using meters made from new materials, there are increasing demands for incorporating sustainability decisions throughout a product's life cycle; thus, it must also consider the EoL and the RR methods for these meters. These strategies cannot be improved without clearly understanding what happens now and the sustainability implications for water meters. Therefore, it is essential to assess and evaluate the current ways of RR for decommissioned water meters for more sustainable approaches in the future.

1.4 Research objective and questions

This study aims to analyse the current EoL RR strategies for water meters. The main goal is to evaluate these strategies within the context of sustainability to enable more sustainable approaches for the decommissioned water meters. The research seeks to assess and evaluate existing strategies by exploring and comparing them from a sustainability point of view that includes environmental, money-related, and social factors. Furthermore, the study intends to formulate actionable recommendations for key stakeholders—DWUs, RRFs, and water meter manufacturers (WMMs)—to promote improvements in environmental circularity based on the research findings.

Considering the defined knowledge gap, problem statement, and research objective, the main research question is translated as:

"How can the sustainability of End-of-Life (EoL) resource recovery (RR) strategies of water meters be assessed and evaluated?"

The following sub-questions further refine and clarify the main research question. They break down the main research question into smaller, more manageable components that can be explored in more detail. Furthermore, the sub-questions provide a clear direction for information collection and analysis and give the study its structure.

1. What are the water meter industry trends and the RR strategies?
2. What is sustainability, and how can EoL strategies be evaluated from a sustainability perspective?
3. How sustainable are the current EoL RR strategies for water meters?
4. What recommendations can be made for EoL water meters, considering the sustainability impact of current strategies?

1.5 Research approach

The research employs an exploratory sequential mixed methods approach to investigate an underexplored area for water meters, focusing on the EoL RR. It begins with exploratory field research, during which semi-structured interviews are conducted with key representatives of the stakeholders mentioned above to gather insights into water meters, industry trends, and current EoL RR strategies. This was followed by a literature review to define sustainability and determine how it can be evaluated. These findings informed the subsequent quantitative phase involving a sustainability assessment of the discovered strategies. The research flow diagram is found in **Fig. 3.**

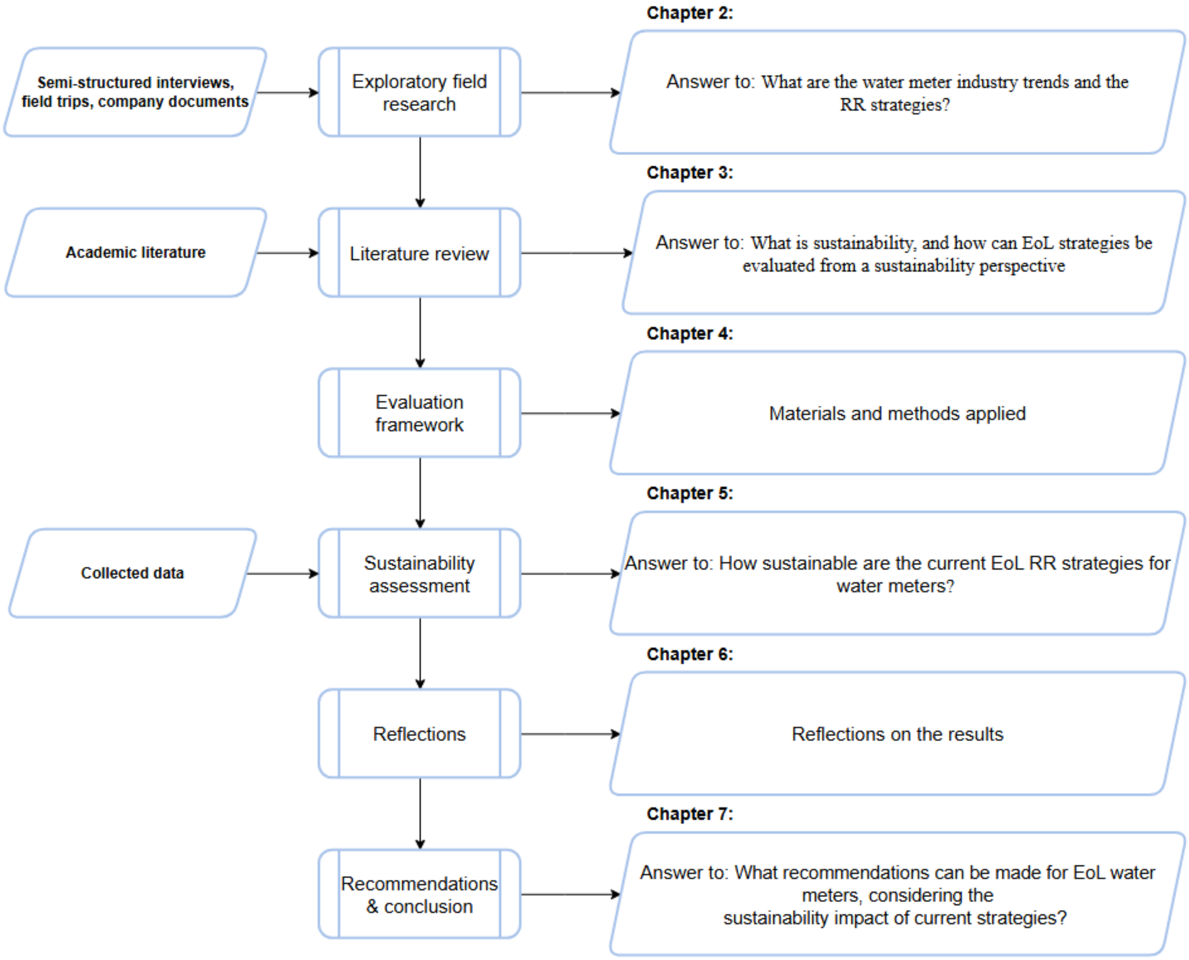

Figure 3: Research flow diagram with the inputs (left), outputs (right) and processes (middle).

1.6 Thesis Outline

Chapter 2 discusses the study's field research, highlighting current trends in water meters and associated RR strategies. Chapter 3 defines sustainability and examines how EoL RR processes can be assessed from a sustainability perspective. Chapter 4 details the methodology adopted for the assessment. Chapter 5 presents the results, while Chapter 6 discusses these findings. Finally, Chapter 7 provides conclusions and recommendations drawn from the study.

2 Exploratory Field Research

This chapter covers the study's field research, establishing the current water meter strategies. It starts with the author’s industry engagement with various parties involved, which helped map the water meter industry trends, current assets, and the RR strategies for these meters. This information gathered during this phase was subsequently used for the SA.

2.1 Industry engagement

Table 1 provides an overview of the people interviewed, with their roles, dates, methods, duration, and note-taking methods. Detailed descriptions of the interview methodology applied for this study can be found in **Appendix A.2**

For an industry-wide perspective, representatives from four out of the ten existing DWUs in the Netherlands were interviewed. The objective was to broaden our understanding of water meters, industry trends, sustainability initiatives (if any), and their selection process and assets. DWU Brabant Water (BW) is the case study; this is further covered in chapter 4.1.

Two representatives of WMMs were interviewed, focusing on the composition of the meters' materials and manufacturing processes. Although most information could not be shared due to company confidentiality, some information regarding the products was shared.

RRFs were contacted to map out all the possible RR strategies for processing water meters. This involved focusing on disassembly and sorting methods. A total of 24 RRFs were contacted, of which six responded. Three of these respondents were interviewed in person. The other two were contacted briefly through a phone call. To the best of the author's ability, this approach ensured that all strategies were represented, reaching a saturation point

Snowballing led to the association Water is our World (WoW). WoW is a volunteer foundation dedicated to providing products related to drinking water to regions lacking access to this essential resource. They gather donated and bought materials to ship to other countries for a second life. Furthermore, an Industrial Shredder Company (ISC) based in China, specialising in recovering water meters and similar products, was approached. They shared details regarding their RR operations and the machinery they use.

2.2 Industry trends for water meters

Table 1: Overview of Industry Engagement - Interviews

Company	Employee's Role	Date	Method	Duration (minutes)	Notes
DWU BW	Asset Managers	23/11/2023 06/12/2023	Online MS Teams	45 30	Recorded and transcribed
DWU II	Asset Manager	13/02/2024	Online MS Teams	60	Recorded and transcribed
DWU III	Procurement Officer	16/02/2024	Online MS Teams	30	Recorded and transcribed
DWU IV	Customer Team Leader	16/04/2024	Field Trip In-person	30	Notes taken
WMM I	Business Manager	02/02/2024	E-mail & Phone Call	15	Notes taken
WMM II	Quality Engineer	24/01/2024	MS Teams	60	Notes taken
RRF I	Commercial Director	02/02/2024	Field trip in person	60	Recorded and transcribed
RRF II	Trading Manager	24/01/2024	Field trip in person	45	Recorded and transcribed
RRF III	Purchasing Manager	29/05/2024	Online MS Teams	45	Notes taken
RRF IV	Manager	11/12/2023	Phone Call	15	Notes taken
RRF V	Purchaser	16/08/2024	Phone Call	20	Notes taken
ISC	Sales Director	02/07/2024	E-mail	-	Notes taken
WoW	Manager	27/01/2024	Field trip in person	60	Recorded and transcribed

2.2 Industry trends for water meters

The water meter industry trends for widescale household use can be categorised into two main aspects: i) the transition in measuring mechanisms and ii) advancements in material design (source: DWU II, BW). Both areas have experienced changes in the past decades, reflecting technological progress and industry adaptations (source: DWU II, BW). **Fig. 4** depicts the market trends through exploded views of the meters, which display the individual components and their assembly. Additionally, it highlights market trends observed within the Dutch industry, showing a clear shift in measuring mechanisms and the increasing use of plastic materials in meter design. These trends are explained in the following subsections.

2.2 Industry trends for water meters

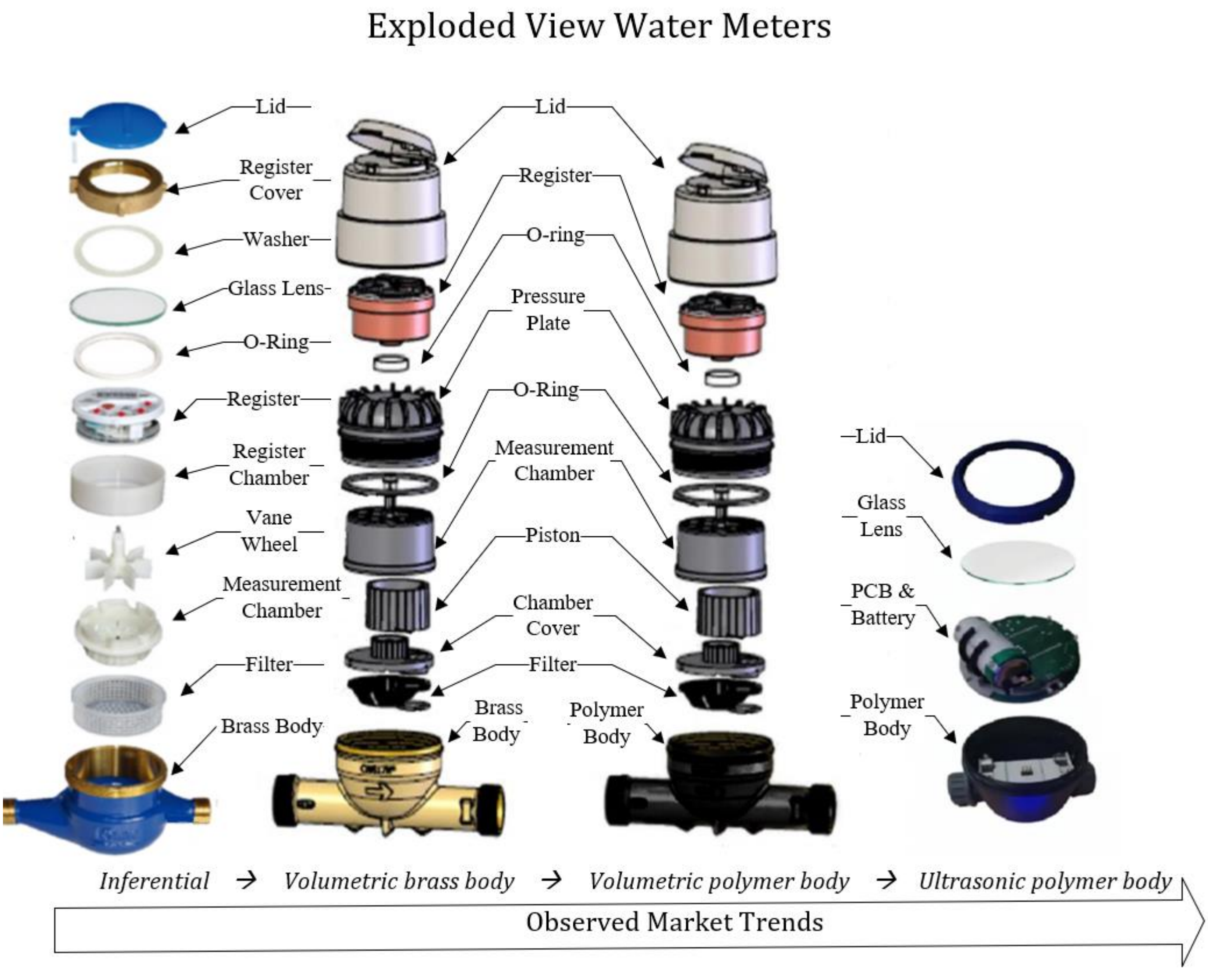

Figure 4: Exploded views of water meter designs and market trends in the Dutch DWU sector. Source: Adapted from Crainic et al. (2011), Diehl (2023a).

2.2.1.1 Transitions in measuring mechanisms

Interviews with DWU representatives indicate that the water meter sector has changed significantly over the past few decades. Initially, inferential multi-jet meters were widely used, but about 20 years ago, many DWUs began switching to volumetric water meters (source: DWU II, BW). **Fig. 5** depicts this trend. The main reasons for this shift are the better accuracy, reliability, and longer lifespan of volumetric meters (source: DWU II, BW).

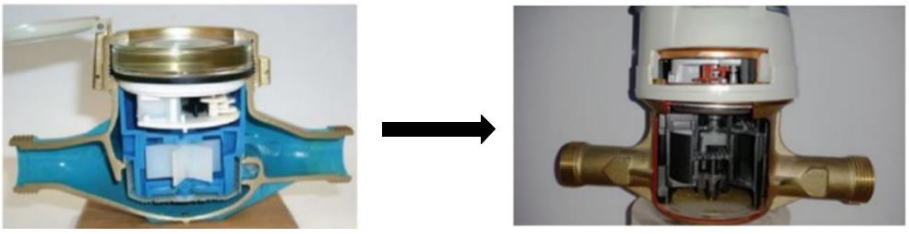

Figure 5: Transition of Measuring Mechanisms: inferential meter (Left) and a volumetric meter (Right). Source: Charalambous & Laspidou (2017)

Volumetric meters provide superior performance, particularly in areas with lower water quality, where the more sensitive inferential meters often face operational challenges (source: DWU II). The chamber design of volumetric meters helps them avoid issues caused by poor water quality in some regions. Additionally, the accuracy of volumetric meters remains consistent throughout their lifespan (source: DWU BW). Accurate billing, after all, is the main function of a water meter.

In contrast, multi-jet meters, which rely on a vane wheel design, tend to slightly overestimate water consumption, which may benefit the DWU rather than the customer (source: DWU BW). Their lifespan varies because they are more affected by the local water quality (source: DWU II, BW). The lifespan of multi-jet meters ranged from as short as seven years in some areas to as long as 17 years in others in the Netherlands (source: DWU, BW). However, a significant advantage of these meters is that they are revisable due to their simple internal design. These meters could be redeployed up to three times through refurbishment programs, extending their operational period to approximately 21-35 years (source: DWU II, BW, IV) compared to the standard 20 years of the volumetric ones (source: DWU II). Notably, refurbishing these meters resulted in 25 to 35% cost savings compared to purchasing new ones (source: DWU II, IV).

Refurbishment was once widely used by manufacturers, social development organisations, and DWUs (source: DWU II). However, it has stopped in the Netherlands except for one DWU (detailed in **Appendix C.4**), where DWU IV still refurbishes with the older inferential models. Other DWUs have moved on to models that currently cannot be refurbished.

2.2.1.1.1 The future trends in measuring mechanisms

According to all the DWU representatives, the future trend in water meter technology is shifting towards models without moving parts. Removing these components reduces wear and tear, leading to fewer operational issues over the meter's lifespan (Charalambous & Laspidou, 2017). As displayed in **Fig. 6**, these non-mechanical meters, commonly referred to as "*smart meters*", incorporate electronics, including printed circuit boards (PCBs), batteries and offer a range of functionalities (Charalambous & Laspidou, 2017). A smart meter is designed to record water consumption electronically, providing real-time or near-real-time data to both the utility company and the consumer (Sønderlund et al., 2014). Unlike traditional meters, which require manual readings at monthly or yearly intervals (Sønderlund et al., 2014). This technology improves the precision of readings, simplifies leak detection, and increases transparency for consumers (Sønderlund et al., 2014).

However, smart meters are currently three to four times more expensive than traditional mechanical ones and are still limited in number, being primarily used in pilot projects (Charalambous & Laspidou, 2017). Besides the higher costs, the accuracy benefits provided by smart meters are relatively minor when compared to the mechanical ones, which already operate under a 2% error margin under typical household water flow conditions (Arregui et al., 2020). This is discussed in the work of Arregui et al. (2020), where the accuracy of various household water meter measuring principles is tested for their accuracy under intermittent flow conditions. All the DWUs interviewed believe it is too early to use these meters widely and prefer traditional ones.

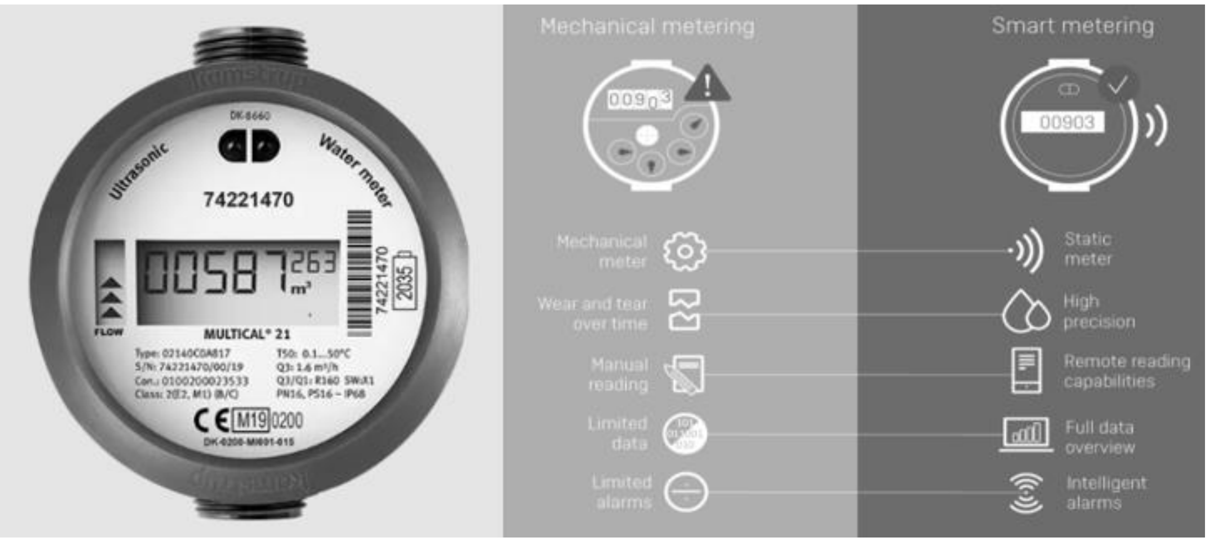

Figure 6: Shows the Multical 21 smart water meter (left) and its benefits compared to the traditional mechanical water meter (right). Source: Kampstrup (2021)

2.2.1.2 Transition to alternative materials

There has also been a notable shift in water meter manufacturing materials, as shown in **Fig. 7**, transitioning from brass bodies to specially engineered plastics and fibre-reinforced polyamide composites. This shift is mainly driven by regulatory changes and economic considerations (source: DWU II, III).

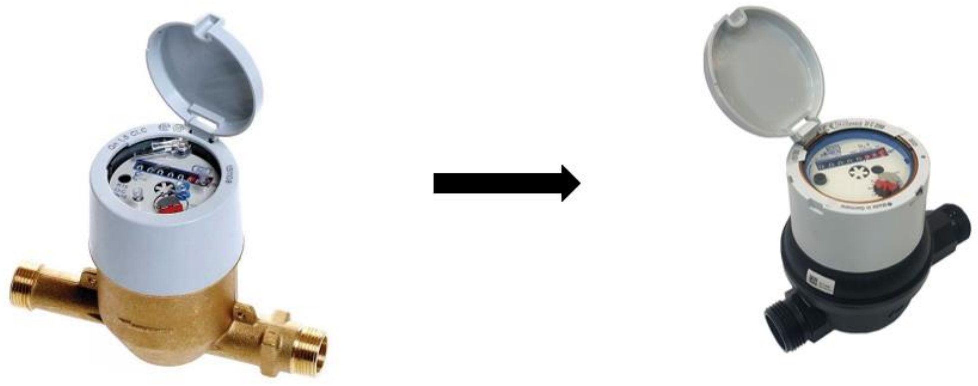

Figure 7: The transition from brass-body (left) to composite-body (right) water meters. Source: Images by Sensus model 620 & 620C

Notably, the regulatory impact of Directive 2184 (2020) which limits the lead content of drinking water from 10 µg/L to 5 µg/L. There is a 15-year phase-out period for many lead-containing materials that are still being used in drinking water, including potentially replacing water meters if lead levels exceed five µg/L (Directive 2184, 2020). Despite the relatively small contact area of water meters compared to the extensive brass piping and faucets in buildings, some DWUs are proactively phasing out all lead-containing assets (Source: DWU II). In contrast, others continue using brass bodies because they are below the thresholds (source: DWU II, III).

Economic considerations, particularly the cost of raw materials, further drive the adoption of alternative materials (source: DWU II). Since 2001, the price of copper has increased by more than 450%, and zinc by more than 350% (Trading Economics, 2024).

Considering the issues mentioned above, plastic body meters provide a solution for both problems. Although they have existed since the 1980s, they have only become a popular alternative to brass body meters in the past two decades (AWWA, 2012; Van Zyl, 2011). Since 2006, glass-reinforced polymer composite models have also been introduced, providing more durability and strength for the casing (Sensus, 2012). These composite meters, like the plastic ones, are cost-effective due to low raw material prices and energy efficiency, consuming one-third of the energy of bronze meters during production and their lighter weight during transportation (Sensus, 2012).

For the DWUs, the upfront costs of the plastic and composite versions of the same models are approximately 25% less expensive than those of brass models (source: DWU II). However, this does not consider the EoL scrap value of brass, which recovers some of the costs invested in these meters, compared to the much lower scrap value of plastic and composite meters. The scrap values of brass-body meters have increased (logically) by the abovementioned percentages during their lifespan.

2.2.1.3 Sustainability integration in selection and disposal of water meters

While sustainability is increasingly recognised as essential in the DWU sector, it has not yet been formally established as a criterion for water meters beyond the in-use stage (source: DWU II, III, BW). The selection management process of water meters mainly depends on the following factors (source: DWU II, BW):

- **Compliance with KIWA:** Only five water meter suppliers in the Netherlands are KIWA-approved. This mark is required for the certification of all water meters in the Netherlands (RIVM, 2016).
- **Economic and Performance Considerations:** Based on regional water quality, different meters may be needed, and tenders must balance cost, longevity, and performance.
- **Supplier Reputation and Experience**: A WMM's reputation, along with DWU’s past experiences with specific brands, can also influence selection decisions, helping to ensure product reliability and compatibility.

The sector is gradually evolving, with a growing awareness of sustainable strategies and new EU regulations, such as the Corporate Sustainability Reporting Directive (2022). This directive requires large companies, including DWUs, to publish regular reports on the impact of their decisions on sustainability. This could extend to a DWU's choices when selecting water meters while also considering the sustainability requirements concerning the EoL impacts for the RR and disposal impacts a meter could have. Such requirements would also encourage the WMMs and RRFs to cater to those demands.

However, for the selection of the meters, the current challenge is that the market is limited to suppliers certified by KIWA, which complicates the enforcement of DWUs' sustainability requirements for the meters. Imposing strict sustainability criteria might only leave a small number of meter options for a DWU to choose from (source: DWU II, III). These challenges are often worsened by a lack of limited oversight by meter suppliers over their subsidiaries regarding materials used in components that do not come into direct contact with water (Source: WMM II). There are also company secrets regarding certain materials used (source: WMM I, II). This often results in difficulties in declaring all materials used and their quantities for the products (source: WMM I, II).

Specific initiatives to resolve these issues are being pursued nationally and internationally, with the Blauwe Netten (Blue Nets) initiative and 4MS being prominent. These efforts, discussed in **Appendix C.7**, illustrate a steady shift towards incorporating more sustainability within the DWU sector that also tries to integrate the EoL aspects of the meters.

2.3 Resource recovery strategies

The following subsections discuss the regulations and strategies for recycling and disposing of EoL water meters. It begins by discussing the regulatory framework by which waste processing is bound, followed by an overview of manual disassembly and mechanical shredding strategies for water meters. The chapter concludes with a comparison of material yields, highlighting the efficiency and challenges of each approach.

2.3.1 Regulations for water meter waste processing

National and European regulations govern waste processing in the Netherlands. These regulations aim to promote high-quality waste recycling as much as possible. This is the process in which waste materials are recycled into raw materials of a similar or equivalent quality to the original materials (upcycling). Upcycling aims to keep materials in the cycle without degrading their value or quality (LAP3, 2017). This stands in contrast to downcycling, which refers to recycling processes where materials are converted into products of lower quality or functionality (LAP3, 2017). The focus on upcycling ensures environmental safety and enables the transition to a circular economy by 2050, as outlined in the National Waste Management Plan (LAP3, 2017).

The requirements for processing the various waste streams of different materials are broken down into 85 sector plans (SCs), each detailing the minimum recycling standards and specific handling procedures, regulations and transport (discussed in the following subsection). For water meters, an essential distinction in regulatory classification lies in the condition of the water meters and if they are considered waste, defined as “all substances, preparations or other products, which the holder thereof discards, intends to discard or must discard” in LAP3. Water meters intended for reuse may be classified as products rather than waste, exempting them from waste management regulations. EoL water meters and their resources (e.g., metals, plastics, or electronic components) are treated as waste and fall under the sector's waste management plans.

Non-biodegradable plastics, including synthetic polymers, composites and rubbers, fall under SC 11. Due to plastics' varied composition, separation is required to determine whether recycling is feasible under the minimum standards. If recycling mixed plastic fractions is technically unfeasible or prohibitively expensive, for example, exceeding €205 per ton at the processing facility's gate, then the minimum standard allows for incineration for fuel and energy recovery purposes (LAP3, 2017). Glass is covered in SC 38, and the minimum standard is recycling since it can be endlessly processed into new items.

Ferrous and non-ferrous metals, including alloys such as brass, fall under SC 12. These metals should be separated from other waste streams to maximise their potential for upcycling. Where metal separation is difficult, or residues (covered in SC 27) remain after metal recovery, they must either be incinerated if they are caloric-rich or disposed of in landfills if incineration is not viable (LAP3, 2017).

The waste electrical and electronic equipment (WEEEs) under SC 71 includes all devices that require a plug or batteries, such as smart meters. Components of WEEEs are addressed under their respective sector plans for specific processing. The handling of WEEEs is regulated under Directive 2012/19/EU (WEEE Directive) and Directive 2006/66/EC (Battery Directive). These directives mandate that plastics in devices like smart meters must be clearly labelled to identify their composition, ensuring efficient recycling. Additionally, batteries must be designed for easy removal to enable safe disposal or recycling.

2.3.1.1 Waste transport

The waste transport must follow the transport regulations established under the European Waste Shipment Regulation (WSR). These regulations aim to prevent environmental harm and promote responsible waste management. Notably, waste intended for disposal is prohibited from being transported between EU countries, a measure designed to encourage member states to manage their waste domestically (WSR, 2024). In contrast, waste intended for recycling can move freely between EU member states and, under bilateral agreements, to OECD countries that uphold EU-equivalent recycling standards. Non-OECD countries wishing to import waste from the EU must notify the European Commission of their willingness and demonstrate their ability to manage this waste, following Annexes VIII (the Green List) and IX (the Amber List) of the WSR (2024).

- **The Green List:** This list includes waste materials considered low risk to the environment, allowing their transboundary movement with minimal regulatory oversight. This can be the case for the recovery of metals (LAP3, 2017).
- **The Amber List:** This list includes wastes that pose potential environmental hazards, requiring prior notification and consent for transport for all the countries involved (exporting, importing, and transit states) (WSR, 2024). Stricter restrictions apply regarding transportation outside the EU, with many cases prohibiting exports to non-OECD countries entirely (WSR, 2024). Any waste not explicitly listed on the Green or Amber Lists is automatically treated as Amber List waste and must follow the same notification procedures (LAP3, 2017). Examples of Amber list materials can be mixed plastics or hazardous wastes like batteries and, in some cases, PCBs (LAP3, 2017).

Appendix F10 of the LAP3 (2017) report provides schematic overviews of specific kinds of waste and the rules and regulations surrounding their transport to other countries.

2.3.2 Manual strategies

Manual disassembly (MD) can be divided into two categories: (i) Disassembly and sorting, primarily done by hand with essential tools, and (ii) mechanical aids and specialised machinery. An example of the first method is shown in **Fig. 8** based on video content received from RC II. This approach is further described in **Appendix A.1** by the author's empirical study. The main challenge in disassembling these meters is rotating the registry cover, as indicated by the red arrow in the left image. This task requires significant strength, which is a major drawback of this method. RRFs that receive large volumes of these meters, such as RC II and RC V, often send them to social workplaces with people doing these tasks who are distant from the labour market because of an impairment. These meters are also sent in some cases to prisons, where RR is performed by detainees, following the Regulation on the Employment of Prisoners Act (2021) and Participation Act (2024).

Figure 8: Images from the disassembly process of the M100 meters. Red arrow indicating the registry cover. Source: RC II

For the harder-to-disassemble meters due to their complicated designs, specifically for the newer generations of volumetric meters, these facilities rely on specialised, custom-made clamps and hydraulic and pneumatic machinery like air wrenches. Electric cutting saws are often avoided due to safety concerns for the workers involved (source: RRF III). Although their processes were not directly observed, RRF III and RRF V representatives described their strategies in an interview. These strategies closely resemble those observed at WoW during the field trip to their workshop, which will be discussed in the following subsection.

2.3.2.1 Manual disassembly with mechanical aids

The observed EoL process at WoW involves manual and mechanical methods for disassembling water meter components. The WoW workshop is equipped with basic tools that enable this process. These tools include a large table, a hammer, a bench vice, various screwdrivers, multiple pliers, and a notable hydraulic machine to assist in disassembling, as depicted in **Fig. 9.**

Additionally, WoW has developed a range of custom-made clamps and tools specifically for mechanical processing to accommodate the various types of meters in their inventory. These clamps, shown at the bottom of **Fig. 9**, attach to the water meters and work in conjunction with the hydraulic machine to rotate and loosen the pieces of the meters that otherwise require significant strength. After removing the headpieces and the inner pressure plates, workers manually disassemble the remaining meter components using the previously mentioned basic tools.

Figure 9: Mechanical aids and clamps for the disassembly of various water meter designs. Source: WoW

Figure 10: Sorting of water meter materials: Brass (left), plastics (middle), stainless steel (right). Source: WoW

Using custom clamps and specialised machinery, the workshop is capable of processing meters at a much faster pace. This also solves the fatigue problem by eliminating all the physical tasking operations. The materials are separated into bags and bins, as shown in **Fig. 10**. The yield and purity for the manual methods are near 100%, except for some minor instances where some small springs or plastics are still left inside the meters or registry (source: WoW, RRF III). This is considered negligible since it is in such small quantities that it does not affect the overall purity of the stream (source: WoW, RRF III).

2.3.3 Mechanical shredding strategies

The second method used for water meter RR involves using an industrial mechanical shredder (MS), as illustrated in **Fig. 11**. The term “shredder" refers to machines designed for various functions, including crushing, shredding, and compacting (Saturn Machines, 2024). Various techniques can be used, from hammer mills and vertical crushers to rotary shear blades and granulators (Saturn Machines, 2024).

Figure 11: A typical industrial shredder and automated sorting system featuring three distinct output streams arranged from bottom left to right: brass, glass and non-ferrous metals, and plastics. Source: Metal Recycling (2014)

Following the MS, automated sorting lines can separate materials based on density, colour, magnetism, and other material characteristics (source: RRF I). This automation streamlines the disassembly and sorting processes, reducing associated costs (source: RRF I). Throughout this study, whenever MS is mentioned, it also implies automatic sorting lines being used. **Fig. 12** displays a typical hammer mill shredder and its inner mechanics, often used for metallic components (Bell et al., 2003).

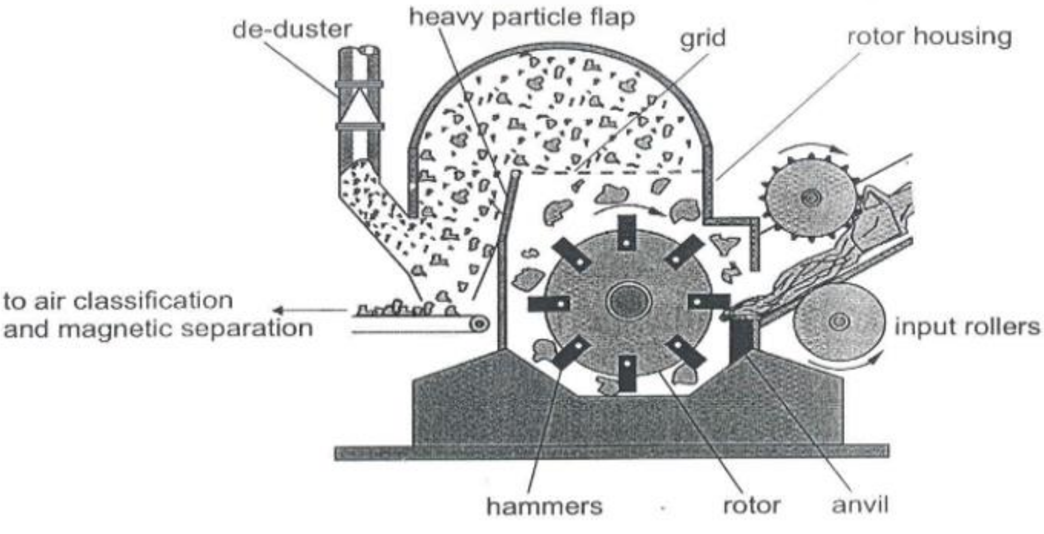

Figure 12: Illustration of a typical hammer mill. Source: Bell et al. (2003)

Water meters can be processed individually or mixed with similar products for simultaneous shredding (source: RRF I, III). Depending on the facility's capabilities and resources, multiple shredding and sorting techniques can be used sequentially with varying yields of the meter materials; unlike MD, where the recovery is 100%, mechanical shredding (MS) results in some material loss.

According to interviewees RRF I and III, the reduction in material quantities across shredder streams is attributable to several factors. These include the loss of fine particles that are challenging to recover due to their entrapment in filter dust, shredder residue, and fluff, all byproducts of MS.

The inherent limitations of MS lead to cross-contamination of materials. The percentages can differ depending on many variables, but 1 to 2% cross-contamination by weight for some of the streams is considered unavoidable (source: ISC, Bell et al., 2003). For water meters specifically, the yield can also be influenced by the type of meter and the moisture content still present within the meters, which can cause different materials to adhere to each other (source: RRF III).

During a field visit to RRF I, the plant representative detailed the water meter MS process (discussed in **Appendix D**). Although the MS process could not be directly observed, online videos and schematics of typical shredders used for water meters and WEEE, provide further insights into the operations and equipment layout. The following section discusses the RR yield for the different materials inside the meters.

2.3.4 Material yield

The material yield can be categorised into two aspects: (i) materials considered less relevant because of their recycling potential given the current industry strategies, and (ii) materials which are considered relevant because of their recycling potential or economic value.

The yield for plastics and composites is considered less significant regarding water meters for the RRFs, both from a recycling potential or economic value viewpoint (source: WoW, RRF III, IV). In the Netherlands, 38% of plastics are recycled, most of which are household packaging materials (Plastics Europe, 2022). The remaining 62% are incinerated with energy recovery, primarily in local waste incinerators (Plastics Europe, 2022). The plastics used inside meters are mainly hard, durable plastics, sometimes mixed with fibreglass, which are hard to recycle currently (WMM I, II). Most of these plastics' recovered yield, rubbers, and other small fittings are sent to the local waste facilities in a mixed plastics stream or as shredder residue and fluff to be incinerated with energy recovery (Source: RRF II, III).

The recycling potential of the metal and glass components of water meters is limitless, depending on the purity of the recovered materials. If the purity is low, they could be downcycled. For these materials, the main differences in the yield between MD and MS strategies are shown in **Table 2**, which provides the material yields obtained from typical water meters and similar products. Henceforth, when this study discusses the yield, it means the second category. This data was provided mainly (except the PCB) by RRF III for the mechanical shredder strategies that they use in many of their facilities. The data reflects estimated low and high yield ranges commonly accepted in the industry, with the average yield reflecting expected industry outcomes (source: RRF III). The estimates vary depending on the factors discussed previously.

There is limited experience with the yield of smart meters due to their relatively recent introduction to the market. However, these items can be compared to the similar processes used for WEEE. Once collected, the yield for the batteries in the smart meters is considered 100% across all RR strategies since they are all done similarly by first opening the meters and consequently removing the batteries before processing (source: RRF III, V). Lithium batteries are highly flammable when damaged, so shredding these products is avoided if retrieving the batteries is straightforward (source: III, V).

The PCB yield data relies on industry-standard estimates and literature findings. The yield and shredding processes for these components are extensively discussed in studies by Ueberschaar et al. (2017), Van Yken et al. (2021), and Bigum et al. (2012). MS of WEEE could result in material loss, with the efficiency of unit separation achieving efficiencies between 90% and 95% in WEEE products (Bigum et al., 2012; Van Yken et al., 2021).

Table 2: Water meter material yields for the MD and MS.

	MD	MS		
Material	**Yield (%)**	**High-End Yield (%)**	**Avg. Yield (%)**	**Low-End Yield (%)**
Brass	100	99	97.5	96
Ferrous Steel	100	99	98.0	97
Non-ferrous Steel	100	96	93.0	90
Glass	100	95	90	85
PCBs	100	95	92.5	90

2.4 Chapter conclusion

The industry has transitioned from the old inferential meters in the past, which have been replaced mainly by most assets of brass-bodied volumetric meters. The current trend involves shifting from traditional brass-bodied meters to polymer-bodied alternatives. In the long term, the industry will likely move towards polymer-based smart water meters with internal electronics. This shift from brass to composite and plastic materials and electronics also influences the EoL recovery of the meters, which impacts the sustainability of the current strategies.

The regulations for the minimum standards for the disposal, recycling and transport of the water meter materials are outlined in the LAP3 (2017). Two leading RR strategies were identified in the study, each with unique advantages and limitations:

- **Manual Disassembly**: This RR method for water meters is highly efficient. RRFs, in addition to using their staff for these tasks, also use social workplaces or, in some cases, prisons for the MD. Although the method can be labour-intensive, the industry has improvised with costume-made tools and hydraulic and pneumatic machinery to make the work less labour-intensive. Nearly 100% of materials are recovered due to the meters' simple designs.
- **Mechanical Shredding**: Shredding meters offer a faster, automated approach to RR, ideal for large volumes of water meters. This method reduces manual labour but has lower material yield than MD due to material cross-contamination and loss of fine particles for the metals or metal-containing items like (PCBs).

These RR strategies, regulatory frameworks, and DWUs' willingness to integrate sustainable principles into all their operations highlight the importance of sustainability-focused decision-making for the EoL. The following chapter discusses sustainability and how an EoL RR practice can be assessed and evaluated.

3 Literature Review

This literature review explores how EoL RR processes can be evaluated from a sustainability perspective, focusing on the tools and frameworks used in such assessments. It starts with the evolving concept of sustainability, focusing on its evolution, pillars, and the scientific disagreements surrounding it. It proceeds to analyse various sustainability assessment methodologies. Within this context, the focus is shifted to one prominent sustainability assessment framework and methods used in EoL waste management. The following section will explain the methodology employed for this review.

3.1 Literature methodology

A scoping review was chosen to understand the wide-ranging topic of sustainability and the various perspectives surrounding it. This type of review helps organise existing research, highlight main ideas, and give a big-picture view of what is currently known (Munn et al., 2018). It is designed to be thorough and fair, gathering all the essential information about sustainability, its methods of measuring EoL strategies, the knowledge gap and potential criticisms (Munn et al., 2018).

For this review, a detailed search was done across Scopus and Google Scholar to ensure all the essential studies were covered. Specific keywords, phrases, and combinations were used (as shown in **Table 3)** to find relevant studies. This search was conducted on October 1st, 2023.

Table 3: Search queries for literature review

Concept	Search Queries
Sustainability	"Evolution & history," "Interpretations," "Definitions," "Weak vs strong," "Triple bottom line," "Brundtland definition"
Sustainability Assessment	"Methodologies," "Frameworks," "Procedure," "Integration," "BellagioSTAMP principles," "Weak vs strong SA models"
EoL Waste Management Assessment	"EoL waste management," "Resource recovery," "System boundaries," "LCSA in waste management, "EoL science"

To ensure the relevance and quality of the included studies in the scoping review, the following inclusion criteria were applied:

- Peer-reviewed articles, conference papers, UN reports, or scholarly book chapters.
- Articles only in the English language.
- Articles from the last three decades to capture the evolution of sustainability concepts and assessment frameworks.
- Focus on the past decade for sustainability evaluations of EoL strategies in waste management

The initial search yielded a substantial number of articles. These were first screened based on titles and abstracts to eliminate irrelevant studies. The remaining articles were reviewed to ensure they met the inclusion criteria. Data extraction focused on key elements such as the interpretations of sustainability, distinctions between weak and strong sustainability, and various sustainability assessment methodologies.

3.2 Evolution and interpretations of sustainability

The concept of sustainability, initially derived from forestry to describe the practice of not harvesting more than what can naturally regrow, was termed "Nachhaltigkeit" in German (Berg, 2019; Wiersum, 1995). The modern understanding of sustainability and sustainable development are often used in modern times to mean the same thing (Meadowcroft, 2024). It was significantly shaped by the Brundtland Commission, which defined it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This definition emphasises development with environmental protection (Kuhlman & Farrington, 2010).

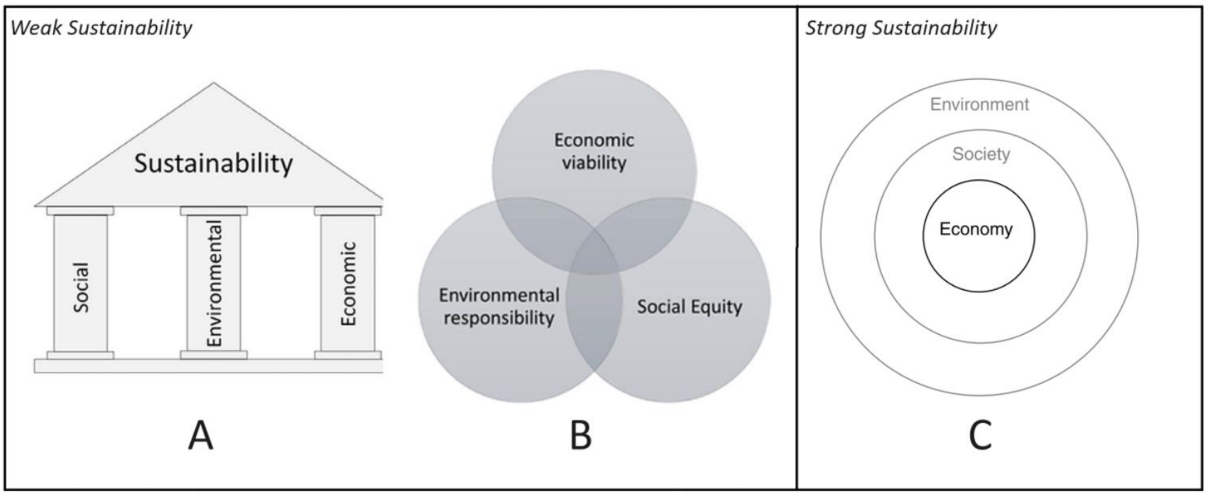

Figure 13: Different interpretations of the sustainability points of view. Adapted from Scoones (2016)

Since then, sustainability and sustainable development have been recognised as encompassing three dimensions or pillars: Social, economic, and environmental (Kuhlman & Farrington, 2010). The terms "pillar" and "dimension" are used interchangeably in the sustainability literature. For consistency, this study will only use the term pillar from now on. This tripartite point of view has existed for a long time, but it was first illustrated by Barbier (1987) in his work "The Concept of Sustainable Economic Development". This depiction of sustainability was a Venn diagram, as noted by Purvis et al. (2019). The concept gained further popularity through the triple-bottom-line approach introduced by Elkington (1999), where the concept of the 3P's—People, Planet, and Profit—originates (Kuhlman & Farrington, 2010). **Fig. 13A & B** illustrate the popular depictions of the three pillars of sustainability, featuring a Venn diagram based on the ideas of Elkington (1999) and Barbier (1987), emphasising the interdependence of these three components.

Over the years, scholarly discussions have offered various definitions of sustainability, emphasising its three pillars and their interdependence. This topic is widely debated and ranges from "broad to narrow," "dark to light green," or "strong to weak" sustainability (Scoones, 2016). With the latter being the main point of contention on how sustainability should be interpreted (Kuhlman & Farrington, 2010). These theories behind sustainability interpretations are shaped by the diverse worldviews of individuals and organisations (Giddings et al., 2002). Despite these contentions, the overarching goal of sustainability remains consistent, coined by the phrase by Pearce et al. (1994) "development that lasts"(Kuhlman & Farrington, 2010). The following subsection discusses the differences between 'strong' and 'weak' sustainability interpretation, as the choice between these two is seen as the most significant by many authors who Giddings et al. (2002) and Kuhlman & Farrington (2010).

3.2.1 Weak and strong sustainability

Sustainability involves managing resources and ensuring their availability or replacement for future generations (Giddings et al., 2002). While it is inevitable that some natural resources will be depleted, there is debate over whether human-made capital can offset or replace this loss (Kuhlman & Farrington, 2010). Some argue that human-made capital can offset the loss of specific resources, while others argue it cannot. These discussions underpin the distinctions between 'strong' and 'weak' sustainability.

Furthermore, weak sustainable development is commonly depicted, as shown in **Fig. 13A & B**, aiming to perfectly balance the three pillars (Giddings et al., 2002). However, the model usually portrays these environmental, economic and social points of view with equally sized rings and pillars, although there is no inherent reason for this representation (Giddings et al., 2002). The concept of weak sustainability suggests that the pillars of sustainability have greater independence, assuming a degree of separation and even autonomy among them (Giddings et al., 2002). In contrast, the notion of strong sustainability, as illustrated in **Fig. 13C**, is based on Giddings' interpretation. Here, the economy is visualised as nested within society, which in turn is encapsulated by the environment. On a minor note, positioning the economy at the centre does not imply it is the central hub for other sectors; instead, it is a subset dependent on them (Giddings et al., 2002). This also implies for the society being dependent on the environment. The characterise of a robust sustainability is that it advocates for a multilayered and multifaceted approach that integrates the three pillars (Giddings et al., 2002). The following subsection explores the methods for assessing sustainability.

3.3 Sustainability assessment

The sustainability's complexity and value-loaded nature drive the scientific community to find new methods to assess it (Sala et al., 2015). This has led to the emergence of sustainability science, a field dedicated to translating sustainability principles into practical solutions (Sala et al., 2015). Within this field, sustainability assessment (SA) aids decision-makers and policymakers in guiding their actions toward advancing societal sustainability (Devuyst, 2001). Preferably, these actions, whether in policies, planning, or products, must be evaluated through a SA to determine the degree of sustainability before they are enacted (Sala et al., 2015). There has been a growing concern within the scientific community and policy circles about whether the various examples of SA are appropriate assessments (Sala et al., 2015). This concern arises partly from the various interpretations and perceptions of sustainability in the scientific community. Some consider, rightly or wrongly, some SA not being an SA but merely an integrated assessment extended to the three pillars of sustainability based on their interpretations of sustainability (Sala et al., 2015).

Sala et al. (2015) address this issue by distinguishing between Integrated Assessment, which primarily focuses on environmental impacts and sometimes also encompasses economic and social ones through specific scientific and technical models. However, these efforts often fail to lead to sustainable practices. In contrast, SA integrates environmental, economic, and social aspects using multifaceted methodologies incorporating various data types and stakeholder perspectives. The following subsection shows how an SA framework can incorporate the various definitions of sustainability and work towards a recognised SA.

3.3.1 Sustainability assessment framework

In response to SA's varying perspectives and critiques, Sala et al. (2015) have developed a framework that captures and integrates sustainability's complexities and varied interpretations. This framework, illustrated in **Fig. 14**, does not seek to define the perfect SA methodology. Instead, it outlines essential steps that form the foundation of a comprehensive SA, aiming to overcome the limitations of previous methods that have often been criticised for lacking transparency, robustness, and flexibility (Sala et al., 2015).

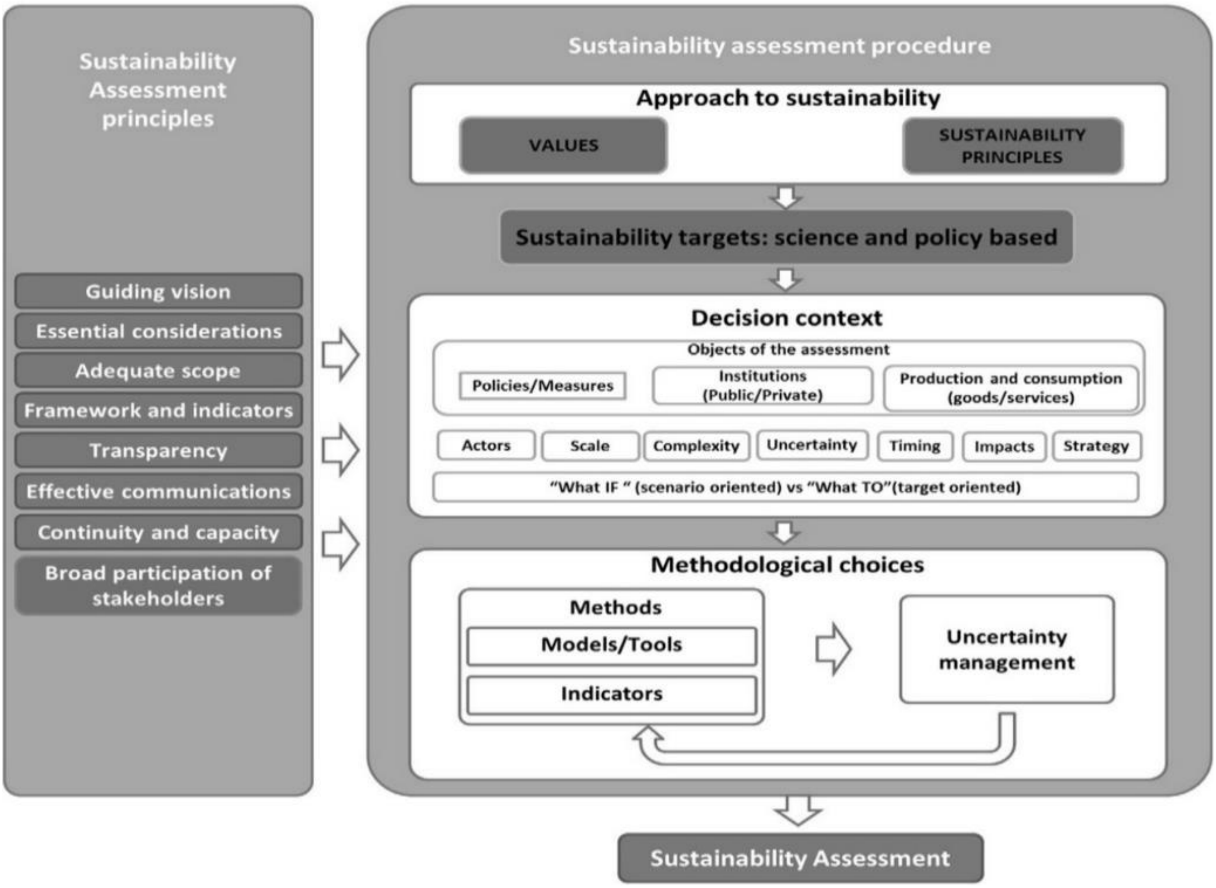

Figure 14: The sustainability assessment procedure framework (right) incorporates the BellagioStamp principles (left). Source: Sala et al. (2015)

For instance, within the framework of SA, weak sustainability interpretation, which allows for trade-offs between the pillars, the SA author should acknowledge this assumption's potential flaws or limitations. This acknowledgement reflects a commitment to transparency about the implications of their approach (Sala et al., 2015). By proactively addressing these issues, the SA procedure aims to mitigate potential criticisms of the flexibility and trade-offs allowed under the weak sustainability approach (Sala et al., 2015). Consequently, this procedural framework serves as a guide for conducting balanced sustainability assessments, ensuring adherence to established principles while acknowledging the variety and complexity of a value-loaded term as "sustainability" (Sala et al., 2015). The conceptual framework includes two main components: the SA principle and the SA procedure. The next segment will discuss these elements further.

3.3.1.1 SA principles and procedure

The SA framework incorporates the well established in scientific community BellagioSTAMP principles depicted on the left side of **Fig. 14** (Sala et al., 2015). It was developed by a global group of measurement and assessment experts in 1996 and later updated by Pinter et al. (2012) (Sala et al., 2015). These principles are designed to guide SA and have become a widely quoted reference for measuring sustainability (Pinter, 2009). The BellagioStamp, intended to be used as a complete set, includes eight principles that must be followed (Pinter et al., 2012).

Furthermore, besides BellagioStamp principles incorporated within this framework, there are SA procedures that Sala et al. (2015) proposes. These exist out of the following SA steps:

- **Approach:** This involves defining the assessment's underlying values and sustainability principles. These values determine whether a "strong" or "weak" sustainability perspective is taken. Different values and principles define different sustainability frameworks.
- **Sustainability Targets:** What is the aim of the SA, and what are the benchmarks for the evaluation? These must be clearly defined for the SA to be considered an SA. Sala et al. also recognise the challenges in setting such targets, especially in exploratory assessments or emerging areas where sustainability standards may not be established.
- **Decision Context:** This step translates the sustainability framework into practical terms relevant to an assessment. It would include stakeholders, scale, complexity of the assessment, anticipated impacts, and timeframe taken for expected or desired outcomes.
- **Methodological choices:** These are considered the core of an SA. They involve identifying the most suitable assessment methodologies (methods, models/tools), indicator selections, and sensitivity and uncertainty analysis. Methodological choices must align with the assessment goals and ensure that the approach is scientific and transparent.

3.4 Sustainability assessment methodologies

For a SA, various methodologies exist to assess and evaluate different dimensions of sustainability (Pope et al., 2004). The importance of sustainability has significantly increased in decision-making over recent decades, which has boosted the demand for such methodologies (Pope et al., 2004). Selecting the appropriate assessment methodology matters for the results you will get and the information you want to convey (Sala et al., 2015). Therefore, selecting the most appropriate methodology to make an assessment must be evaluated by a case-by-case approach (Sala et al., 2015).

Fig. 15 illustrates various popular methodologies for SA and their degree of 'integratedness', as described by Sala et al. (2015). These methodologies address either single or offer a framework for assessing multiple pillars of sustainability. This differentiation highlights the importance of carefully selecting methods based on each SA's specific requirements and objectives (Sala et al., 2015). Among those that address a single pillar, focusing on a specific compartment, such as the Water Footprint method, others like LCA provide integrated environmental assessments covering multiple compartments (Sala et al., 2015). Additionally, some methodologies specifically developed for SA offer a framework encompassing multiple sustainability pillars for an integrated assessment, such as the Life Cycle Sustainability Assessment (LCSA) covered in the sections below.

3.4 Sustainability assessment methodologies

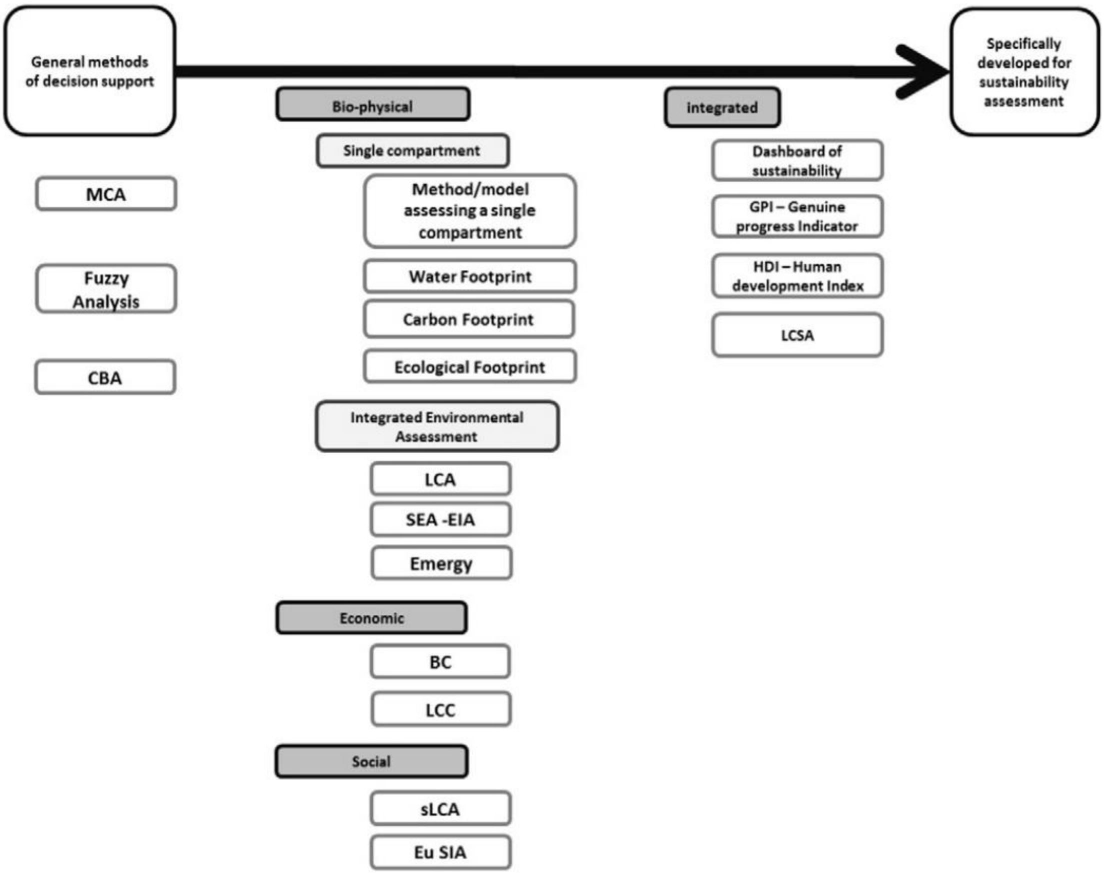

Figure 15: Methodologies for sustainability assessment, Source:Sala et al. (2015)

3.4.1 Life cycle sustainability assessment

Life Cycle Sustainability Assessment (LCSA) can be both considered as a framework and a methodology as it provides the structured, step-by-step process of a methodology while offering the flexibility and overarching structure of a framework (Zanni et al., 2020). First introduced by Kloepffer (2008), it is based on a concept called Life Cycle Thinking (LCT). LCT looks at the entire lifespan of a product or service, from creation to disposal, to understand its positive and negative impacts on the environment, economy, and society. This approach helps ensure that sustainability is considered in every stage of designing, developing, and assessing products and services (Sala et al., 2013). As illustrated in **Fig. 16**, the LCT approach incorporates the LCSA methodology to evaluate the environmental, economic, and social dimensions using components such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA).

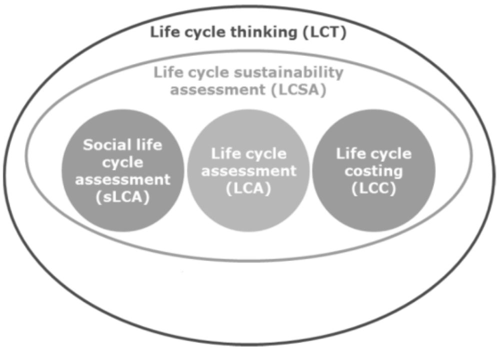

Figure 16: Life cycle thinking encompasses three methodologies: LCA, LCC, and S-LCA. Source: Sala & Garcia (2016)

There are specific guidelines developed for the use of an LCSA, which are released by UNEP/SETAC (2012), which outlines all necessary stages for the LCSA framework and the subsequent applied methodologies. Among the LCSA assessment methods, LCA is the most established and mature, complete with specific ISO guidelines. In contrast, LCC and S-LCA are less developed, especially in the impact assessment, as noted by Sala & Garcia (2016).

Progress in S-LCA includes the development of impact assessment categories (Ghisellini et al., 2023). These are outlined in the UNEP guidelines "Social Life Cycle Assessment of Products and Organizations", first developed in 2009 and later updated in 2020 (UNEP, 2020). For LCC, standardised guidelines exist for specific sectors, such as ISO 15686-5 (2017) for construction and IEC 60300-3-3 (2017) for managing the dependability of electrotechnical projects. The LCC can account for all relevant costs and cash flows within the agreed scope, from acquisition to disposal. It typically involves comparing alternatives or estimating future costs at the portfolio, project, or component level. Based on the goal of the assessment, the analysis is sometimes performed over a specific period or stage of the product life cycle or its entirety (ISO 15686-5, 2017).

Since LCSA combines the three analytical techniques, a consistent goal and scope is recommended by the UNEP/SETAC (2012) guidelines. Nonetheless, a consistent scope in LCSA does not necessarily mean that the boundaries should be identical in all three of the pillars (Martínez-Blanco et al., 2014). The next chapter will discuss this concept further, presenting examples from the literature to illustrate the nuances involved.

3.4.1.1 LCSA in End-of-Life management

The LCSA framework has become increasingly prominent in contemporary literature as an integrated SA method, particularly for waste management, as highlighted by Bhambhani et al. (2022). This framework comprehensively evaluates various processes and products' environmental, economic, and social impacts throughout their life cycle or parts of it (Zanni et al., 2020).

The system boundaries of an LCSA, depicted in **Fig. 17**, align with the commonly recognised boundaries within LCT and LCA approaches (Zanni et al., 2020). Traditional system boundaries include (JRC, 2010):

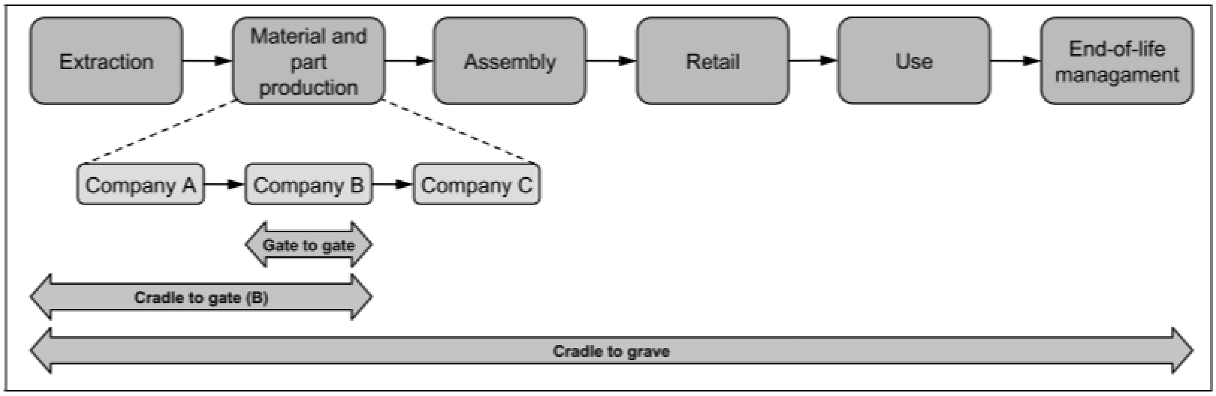

Figure 17: Cradle to grave, cradle to gate, and gate to gate system boundaries of the entire life cycle assessment. Source JRC (2010)

- **Cradle to gate**: This boundary encompasses data and information collection from the extraction of raw materials to the manufacturing and assembling of the product.
- **Cradle to grave**: This extends the entire life cycle of products, including goods and services, encompassing their supply chain, usage, and waste management

- **Gate to gate:** This refers to assessing a specific segment of the product life cycle, focusing on processes within a single facility or between two gates of a manufacturing process.

In addition to these traditional scopes, alternative boundaries such as "cradle to cradle," "gate to grave," “cradle to factory,” and "cradle to use" provide further flexibility in LCSA (Dong et al., 2023). These alternative boundaries allow researchers to tailor the assessment to their specific goals (Dong et al., 2023). The flexibility extends not only to the boundaries but also to the depth of analysis of the sustainability pillars, depending on the research objectives. **Table 4** discusses examples of SA where such flexibility is applied.

For instance, Bhambhani et al. (2022) perform a comparative cradle to cradle LCSA, comparing the RR solutions of three scenarios in the water sector. In their LCSA, they monetise the environmental impacts of the different scenarios and omit the S-LCA altogether due to the scope of their research. This raises a potential concern regarding the validity of omitting a sustainability pillar in an assessment. The author believes these studies can still be considered SA if they remain consistent with their defined scope and objectives and provide transparency for their choices.

There are also variations of assessment within the pillars themselves, for example Luthin et al. (2023) and Papo & Corona (2022) demonstrate that a complete pillar or a cradle to grave approach is not always necessary. They demonstrate that hotspot analysis within an LCSA framework can effectively target essential life cycle segments of a pillar, streamlining the identification of improvement areas.

Furthermore, Foolmaun & Ramjeawon (2013) conducted a comparative LCSA of four different disposal scenarios of an EoL product. Rather than using a conventional cradle to grave, cradle to gate, or cradle to cradle approach, they set their system boundaries from when PET bottles are disposed of until they lose their value, either through landfilling or incineration. A similar comparative assessment of different EoL scenarios is proposed by Hu et al. (2013) for the recycling of concrete. Vinyes et al. (2013) also conducted an LCSA, but they narrowed their analysis even further by mainly setting their system boundaries for the different collection methods of an EoL product. This essentially uses the LCSA framework to assess a single stage within the EoL process,

In conclusion, the LCSA framework provides a flexible approach for analysing a process or product's environmental, economic, and social impacts. Depending on the scope and targets, it enables a complete or more targeted approach to an SA.

3.4 Sustainability assessment methodologies

Table 4: Life cycle sustainability flexibility in literature for EoL processes

Article	Title of Study	Case Study of Interest	Method of Assessing
Bhambhani et al. (2022)	Life cycle sustainability assessment framework for water sector resource recovery solutions: Strengths and weaknesses	Water sector resource recovery solutions in the Netherlands	LCSA, omitting S-LCA. Giving LCA and LCC an monetary value
Luthin et al. (2023)	Demonstrating Circular Life Cycle Sustainability Assessment – A Case Study of Recycled Carbon Concrete	Recycled Carbon-Reinforced Concrete	C-LCSA applying Material Circularity Indicator alongside LCA, LCC, and social hotspot assessment
Foolmaun & Ramjeawon (2013)	Life Cycle Sustainability Assessments (LCSA) of Four Disposal Scenarios for Used Polyethylene Terephthalate (PET) Bottles in Mauritius	Disposal of used PET bottles in Mauritius	LCSA incorporates LCA, LCC, and S-LCA via an Analytical Hierarchy Process to integrate impacts across dimensions
Papo & Corona (2022)	Life Cycle Sustainability Assessment of Non-Beverage Bottles Made of Recycled High-Density Polyethylene	Non-beverage bottles made from recycled HDPE	LCSA combines an ad-hoc system expansion approach and applies weighting based on the Analytical Hierarchy Process to integrate impacts across dimensions
Hu et al. (2013)	An approach to LCSA: The case of concrete recycling	Concrete Recycling	LCSA alongside Material Flow Analysis at different system levels
Vinyes et al. (2013)	Application of LCSA to Used Cooking Oil Waste Management	Used Cooking Oil Waste Management Systems	LCSA combines LCA, LCC, and S-LCA without formal weighting. The method assigns scores based on the relative performance within each category

3.5 Chapter conclusion

In conclusion, sustainability is not a static concept but a dynamic, multifaceted one due to our changing insights and beliefs. It is shaped by historical context, scholarly debate, and practical necessities; these elements also influence its assessment. It is challenging to decide which interpretation of sustainability and its pillars is correct. While definitions of sustainability can vary, they generally share common themes of balancing environmental, social, and economic factors to safeguard the well-being of both present and future generations.

SA has developed as a tool for understanding and evaluating the impacts of the sustainability pillars. This has led to increased SA practices, which need a proper framework to overcome concerns often raised in the scientific community regarding assessment methods. The framework proposed by Sala et al. (2015) tries to bring together different interpretations of sustainability and its assessment methods while addressing potential criticism by emphasising transparency, flexibility, and robust assessment tools. The correct SA partly depends on the context, data availability, and stakeholders' perspective.

The workable definition of sustainability concerning the assessment and evaluation of RR methods for water meters is that these strategies should minimise negative environmental impacts, leading to content preservation and avoidance of primary resource materials. This should also be done with economic efficiency while supporting social welfare. A workable framework for this study would imply comparing these RR strategies with each other, given the impacts of the three pillars and chosen sustainability interpretation.

To effectively evaluate all three sustainability pillars, the assessment can integrate the LCSA framework, which includes the methodologies LCA (environmental), LCC (economic), and S-LCA (social) impact assessment. This framework allows for the flexibility needed to inform the stakeholders of the sustainability impacts concerning all three pillars regarding the RR practises with the selected meters. It can happen that in a SA applying an LCSA framework, a pillar is not included because there is too little information available about it or because quantifying the effects is difficult given the scope and goal of the study. This was also the case for quantifying the social aspects of this research, which is further explained in the next chapter. Nevertheless, all pillars were included for the SA for this study to provide a comprehensive view of the current strategies. The following chapter discusses the materials and methods used for the SA.

4 Materials & Methods

This chapter outlines the methodology used in this study, focusing on the SA of RR strategies and the water meters used for this analysis. It begins with the case study of BW and the water meter assets used for this study. The chapter then outlines the applied SA framework given the scope and goal of the study.

4.1 Introduction case study Brabant Water

BW manages a substantial portfolio of approximately 1.06 million water meter assets, primarily catering to households and small businesses. **Table 5** provides an overview of some of the BW's assets, the attributes of these assets and material compositions. These meters are typical flow capacity model Q_n 1.5 m^3/h models used for most households. The material composition of the meters was obtained from the author's empirical self-study of the meters at BW and interviews with WMM I and WMM II, discussed in **Appendix A.1.2**, together with a more detailed list of the meter materials and assumptions. It must be noted that there was no Bill of Material (BOM) for these meters, except for the Multical 21.

According to the 2023 documents provided by BW, most (roughly 90%) of the assets consist of the volumetric Elster V200 brass body water meters, which will be replaced in the coming years because they are nearing their 20-year operational lifespan. In addition to its main assets, BW has been conducting pilot projects to explore the adoption of smart water meters, which are seen as the industry's future. One such project is the Kamstrup Multical 21, which uses ultrasonic measuring mechanisms with an operational lifespan of 15 years.

Furthermore, BW is currently discussing a potential shift in the short term to composite and plastic-bodied water meters across its main population, driven by considerations of cost savings and potential environmental benefits (source: DWU BW). This is also seen as a good thing by their asset management department for diversifying their assets, which is also recommended by the VEWIN (2018) guidelines. A composite or plastic alternative of the same model exists for several of the brass-body meters available, e.g., the Elster V200 and the V200P. This transition could lower the purchase price of brass meters. This shift is not considered a priority within the company as brass body meters are regarded as more reliable in overall accuracy during the entirety of the operational lifespan than their polymer body counterparts (source: DWU BW).

This shift to polymers also introduces challenges, particularly concerning the electrical grounding of homes, which in some regions of North Brabant is connected via the water meter (source: DWU BW). BW assesses the extent of reliance on water meters for grounding and plans to notify affected homeowners if a transition to plastic meters is made (source: DWU BW).

Table 5: Overview of water meter attributes and material composition.

4.1 Introduction case study Brabant Water

Attribute	 **V200 (brass body)**	 **V200P (plastic body)**	 **Multical 21 (composite body)**
Measuring Principle	Volumetric	Volumetric	Ultrasonic
Average Lifespan (years)	20	20	15
Total Weight (g)	1,214	552	380
Material Composition (g) [%]			
Synthetic Plastics & Composites	231 (19.03%)	463 (83.88%)	210 (55.26%)
Brass (CuZnPb)	815 (67.17%)	-	-
Tombac (CuZn15)	60 (4.94%)	60 (10.79%)	-
Tempered Float Glass	22 (1.81%)	22 (3.99%)	69 (18.16%)
Non-Magnetic Steel	79 (6.48%)	-	-
Magnetic Steel	7 (0.58%)	7 (1.33%)	6 (1.58%)
Printed Circuit Board (PCB)	-	-	36 (9.47%)
Lithium Batteries	-	-	46 (12.11%)
Bentonite (Clay Mineral)	-	-	13 (3.42%)

4.2 Applied sustainability assessment

The applied sustainability assessment, depicted in **Fig. 18**, follows the LCSA framework approach defined by the general guidelines set by UNEP/SETAC (2012) for LCSA, which integrates the Life LCA methodology outlined in ISO 14040-4 (2006). The assessment comprised six key steps: (i) Defining the goal and scope; (ii) Selecting the Indicators; (iii) identifying the inventory data; (iv) performing the impact assessment; (v) Discussing the Results; (vi) formulating recommendations based on the assessment findings.

It is important to note that, for this sustainability assessment, the author chose to work with different system boundaries for the three pillars of sustainability. While the economic and social assessments are focused explicitly on the RR stage, the environmental assessment encompasses a water meter's cradle to grave life cycle. This is further detailed in the Scope Definition section.

To address gaps in the sustainability assessment, an empirical self-study of water meters in a laboratory setting was conducted. Where data remained unavailable, reasonable assumptions were made based on expert judgment, available academic literature on similar processes, or the authors' assessments. The methodology and the results of the empirical self-study can be found in **Appendix A.1**.

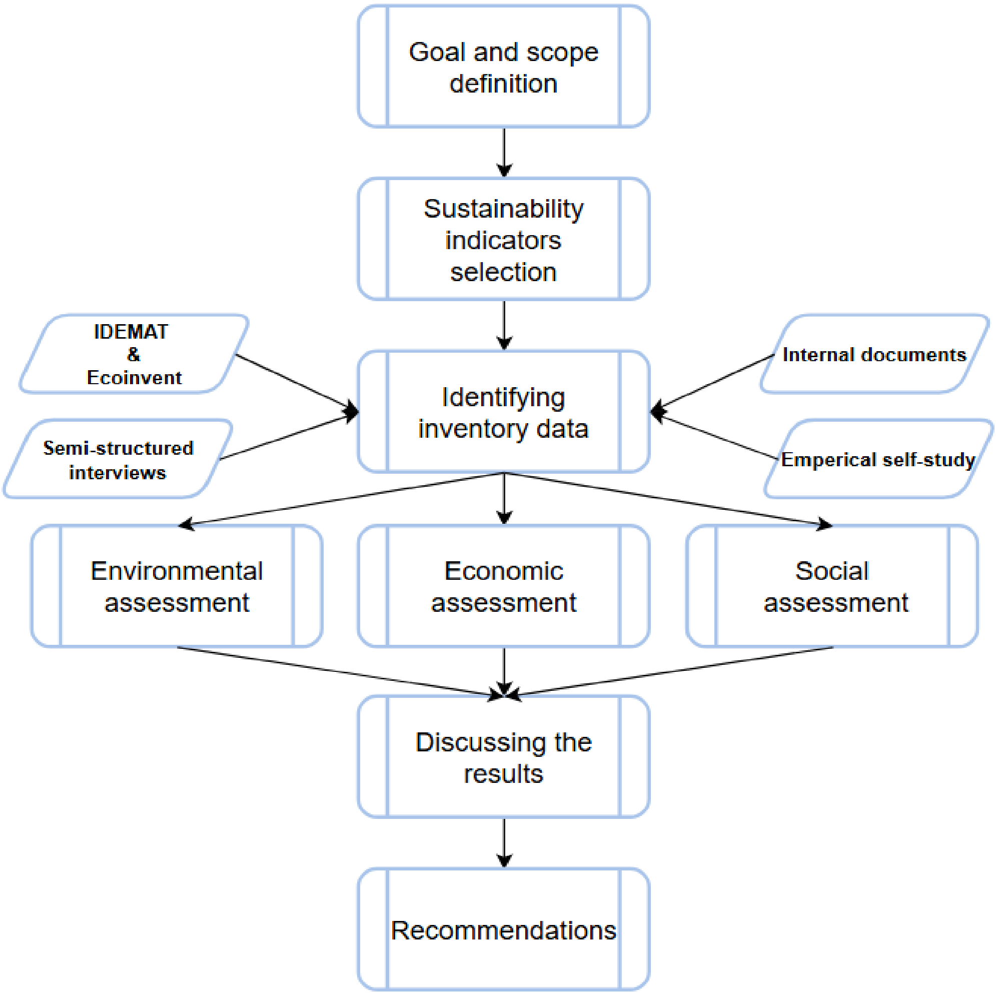

Figure 18: Methodology followed for the sustainability assessment. Adapted from: Akber et al. (2017)

4.2.1 Goal

As stated in the previous section, the main goal of the sustainability assessment is to compare the current EoL RR strategies for water meters to assess and evaluate their sustainability. The comparative assessment is done by using water meters undergoing two alternative EoL RR strategies identified as:

i. Manual disassembly (MD)
ii. Mechanical shredding (MS), which varies by yield and is defined as a range:
  - High yield (MS-H)
  - Average yield (MS-A)
  - Low yield (MS-L)

While MD yields consistent and straightforward results, MS varies depending on various factors, as discussed in Chapter 2. The functional unit (FU), as defined by ISO 14040 (2006), is the "quantified performance of a product system for use as a reference unit." In this study, the FU is "one water meter." This standardisation allows for consistent measurement and comparison of the environmental impacts of the various RR methods for the selected water meters. The water meters selected for the sustainability assessment are from the selected case study BW, **Table 5**. In the author's view, water meters accurately depict the current situation and trends within the water meter industry.

4.2.2 Scope definition

This research adopted a comparative, weak, attributional approach to the LCSA framework to analyse the EoL stage. The 'weak' LCSA approach is predicated on the assumption that the recycling process is primarily driven by the availability of secondary materials, which offsets the demand for primary production typically prompted at the production stage (Johnson et al., 2013). This allocation method aligns with the idea that natural capital can be substituted by human-made capital (Johnson et al., 2013). The initial impact of the primary material input is divided between the current and future life cycles by using the mass of reclaimed secondary material to adjust the amount of substituted primary material. The 'attributional' aspect entails detailing the environmentally relevant flows within a product system at a static point, unlike a consequential method, which requires outlining the environmental flows in response to systemic changes (Ekvall et al., 2016). The LCA for this study utilises the "Fast Track" approach (discussed in **Appendix B.1**). The coverage of the study is defined along the following aspects:

- **Geographical:** The focus is on the Netherlands, using data specific to Dutch RR strategies, energy grids, and environmental impacts.
- **Temporal:** The study covers 2023 and 2024, using recent data to reflect industry strategies without considering potential future RR technologies.
- **Technological:** The technological scope includes manual and automated RR practises, capturing a range of efficiencies and impacts relevant to the current Dutch industry. It is important to note that the effects of MS-induced cross-contamination of materials were not considered for the indicators due to data limitations.

4.2.2.1 System boundaries

The life cycle stages, as categorised according to EN 15804 (2019), as displayed in **Fig. 19** and are mainly meant for building products. Even though the standards are meant for construction works, it is common to apply these distinctions in other life cycle studies (Caruso et al., 2020; Lam et al., 2021).

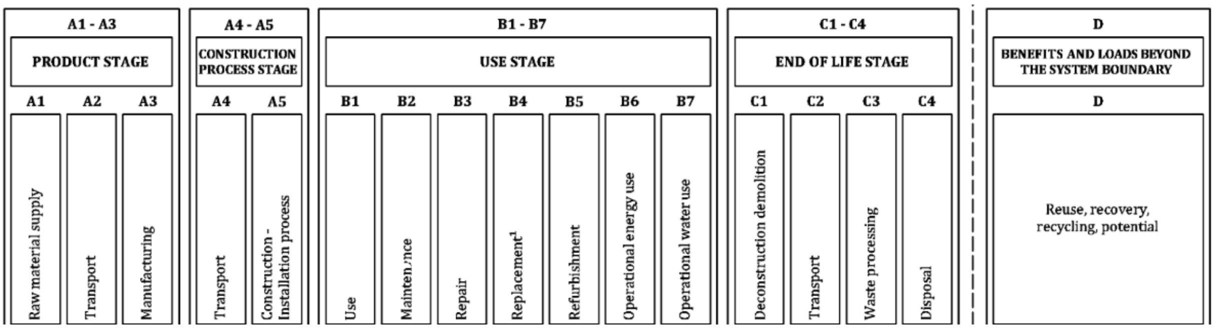

Figure 19: Life cycle stages according to EN 15804 (2019).

As mentioned, this study's environmental assessment extends beyond the RR strategies. This approach was chosen to give a more complete view of their life cycle and better understand how RR fits into the life cycle process. However, this broader approach was not applied to the economic and social aspects of the assessment due to limited data availability and time constraints. This economic and social assessment study focuses solely on the RR stage C3 (Waste Processing). The sustainability of this stage is assessed by all three of the pillars. **Fig. 20** illustrates the system boundaries of the selected stages, including their inputs and outputs, which are elaborated in the following subsection.

In the environmental assessment, stages A1-A3 (product stage), A4 (transportation), C2-C4 (End-of-Life processing), and stage D (recovery) are included. Stages A5 (installation) and C1 (de-installation) are excluded because they are similar across all meters. B1-B7 are excluded because these meters do not have any environmental impact.

Furthermore, manufacturing A3 processes like product assembly, testing and packaging processes, and treatment of waste products were excluded because these processes are universally applied to all meters and have similar impacts. Thus, they can be disregarded. These processes are also difficult to quantify and form a small percentage of a product's environmental impact, for a product like a water meter, being 1 to 2 % of the total environmental impact (Diehl, 2023b, 2023a).

Significant manufacturing activities, such as injection moulding for plastic parts and casting, deep drawing, drilling, milling, powder coating, and sheet rolling for metals, are included due to their substantial impact on manufacturing (Interview: WMM II).

4.2 Applied sustainability assessment

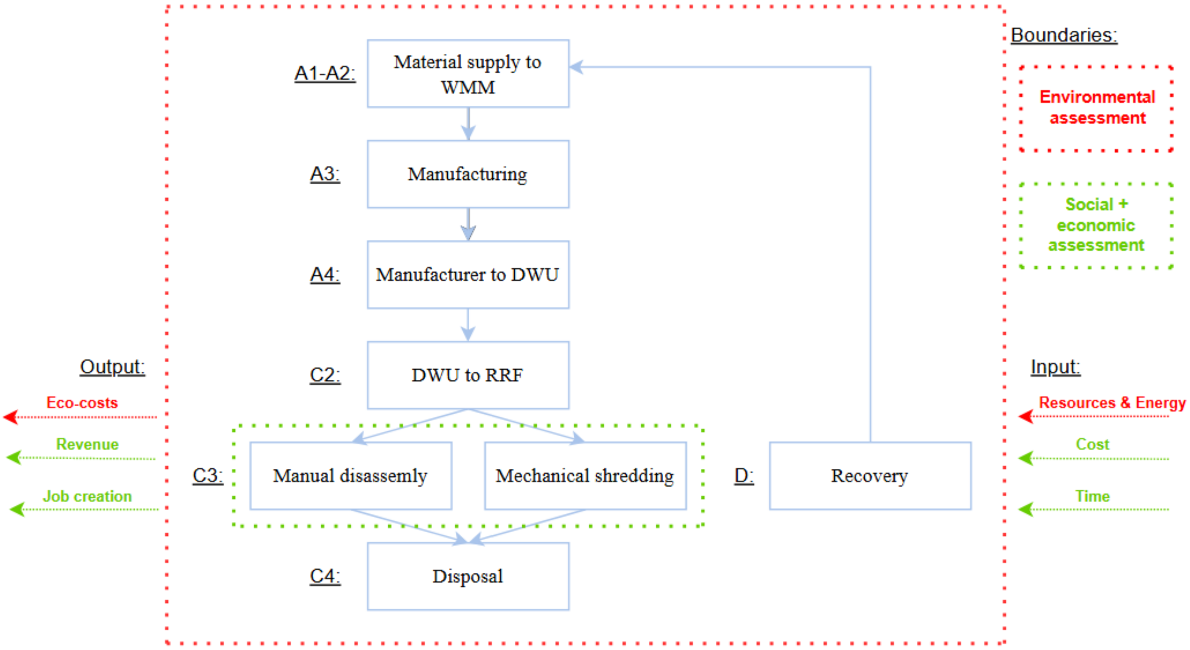

Figure 20: Overview of the water meter product system with the selected stages and boundaries for the given pillars. The system begins with the background processes of extracting and transporting the materials from the cradle to the factory (A1-A2). It ends with the eventual recovery (D) or disposal of materials (C4).

4.2.2.2 Sustainability indicator selection

Indicators evaluate products, processes, or services' environmental, economic, and social impacts (UNEP/SETAC, 2012). These indicators help assess various environmental impacts, from raw material extraction to manufacturing, use, and disposal (UNEP/SETAC, 2012). **Table 6** provides an overview of the selected indicators used in this study. The following sub-sections detail the chosen indicators for the various pillars.

Table 6: Overview of selected indicators for the SA

Stakeholder	Sustainability Pillar	Sustainability Indicator	Unit of Measurement	Life cycle Assessment
Society	Environmental	Eco-costs	[Euros (€)]	Cradle to Grave
Recycling Facilities	Economic	Revenue	[Euros (€)]	Stage C3
Workers	Social	• Job Creation • Inclusivity • Ergonomics	• [Labour Time (s)] • [N/A] • [N/A]	Stage C3

4.2.2.2.1 Environmental indicators

Life Cycle Assessments (LCAs) are typically defined by selecting indicators, which determine how the results are presented and enable benchmarking the system against alternatives. According to Vogtländer (2012), there are three main types of indicators:

- **Damage-based indicators** Examples include the ReCiPe indicator (measured in Points) and the Environmental Footprint (EF).
- **Single-issue indicators**: These focus on specific impacts, such as the carbon footprint (CF) (measured in kg CO2 equivalent) and Cumulative Energy Demand (CED).
- **Monetized indicators**: Examples include eco-costs 2022 (measured in €). These relatively new indicators convert environmental impacts into monetary terms.

Damage-based indicators measure the environmental damage of a product or process through a point system and are presented in midpoint impact categories (e.g., greenhouse gas emissions, acidification, eutrophication, fine dust, resource depletion) (Van Der Velden et al., 2014). These are mainly used in academic research (Vogtländer, 2012). Single-issue indicators like CF and CED focus on a single impact. Their advantage is that they are easy to comprehend and understand, particularly the CF, which is widely applied in the corporate world in most Environmental Product Declarations (EPD) reports (Klöpff et al., 2016). However, the disadvantage is that they do not account for toxicity and material depletion (Vogtländer et al., 2009). Both damage-based indicators and single-issue indicators can be challenging for the average reader to comprehend, as it is difficult to attach value to a point-based system or the kg CO2 equivalent of the CF indicator (Vogtländer et al., 2009). When these values are translated into monetary value, they become more manageable for the average reader to comprehend.

The author believes monetised indicators adequately address this issue using a prevention-based approach. Thus, for this research, monetised indicators are preferred for their ability to convey environmental impacts in economic terms, which appear to be easily understood ‘by instinct’ (Vogtländer et al., 2009). The Eco-costs model, for instance, calculates the marginal prevention costs throughout the life cycle of a product (from the cradle to the grave) for toxic emissions, material depletion, energy consumption, and land conversion (Vogtländer et al., 2009), see **Fig. 21**. The eco-cost model is updated every five years to represent the most accurate prevention costs based on the current technologies (Vogtländer et al., 2009). The database used for this study was the 2023 version.

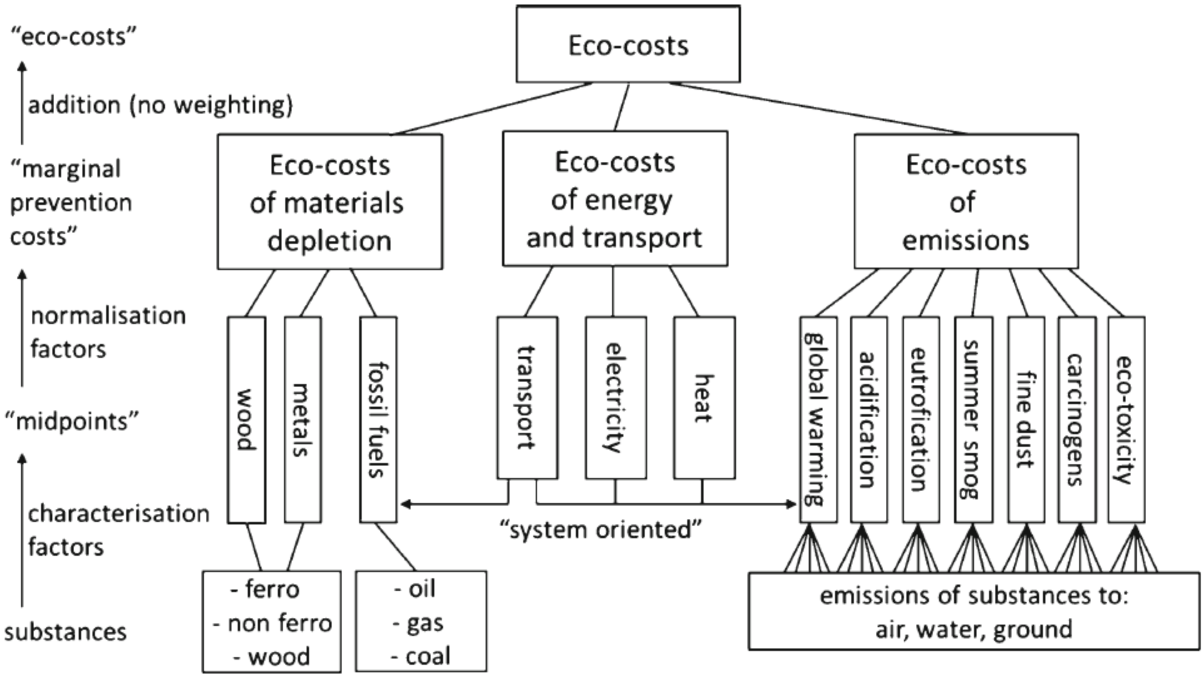

Figure 21: Eco-Costs calculation structure. Source: Vogtländer (2012)

4.2.2.2.2 Economic cost indicators

The economic assessment in this study evaluates the potential revenue from EoL water meters for the RRF, considering both MD and MS, covering from the moment of their arrival to the recovery of the materials. The following factors are considered for the assessment:

- **Scrap Value**: The monetary value derived from the recovered materials of economic value. The scrap value varies depending on the material composition of the water meter.
- **OPEX:** The costs considered include machine wear and maintenance, electricity and fuel consumption for operating MS, and labour costs associated with handpicking and operating the equipment. For MD, the costs are limited to labour and electricity expenses since there is no machine wear.
- **Content loss:** This refers to materials of economic value that are lost during RR strategies. This loss occurs when materials are sent to landfills or become unrecoverable due to mixing with other waste streams and shredder residues.

It is worth noting that although content loss is sometimes regarded as a component of OPEX, it is treated separately in this study. Additionally, the assessment excludes capital expenditure (CAPEX) costs of tools and machinery, such as shredders and hydraulic or pneumatic equipment. Since these items are used for various products and processes beyond water meters, processing meters are a small fraction of their overall use. Similarly, OPEX costs unrelated to the direct processing of water meters, such as general facility overhead (e.g., lighting and utilities), are also excluded.

4.2.2.2.3 Social Indicators

The social component of this study evaluates the social implications of different EoL scenarios for water meters from the workers' perspective. The focus is on the labour time it takes to disassemble and sort the meters, as this was the only quantifiable indicator in this study, in the author's view. This labour time can be translated to jobs created that workers from the community can fill.

Beyond the quantifiable metric of labour time, other social factors were observed regarding different recovery methods for water meters, such as the potential for inclusivity regarding each method and its ergonomics. However, these aspects could not be quantified due to limitations in the study design and lack of direct access to the relevant facilities

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4.2.3 Data collection

The following subsections explain how data is collected for the environmental, economic, and social aspects of the sustainability assessment and the broader LCA analysis.

4.2.3.1 Resource recovery cost and labour time

RR strategies' economic and labour time aspects can be divided into (i) Labour time and costs related to MS and (ii) Labour time and costs related to MD. These industry data assumptions inputs are discussed in the following two sub-chapters.

4.2.3.1.1 Economic and social aspects MS

Operational cost data for shredders in RR strategies was mainly derived from interviews with RC III and internal company documents from ISC related to the system's energy consumption. Despite the difficulty in obtaining precise data—mainly due to the limited availability of detailed information from RRFs and shredder manufacturers and the willingness to share it—industry benchmarks were obtained through the interview with RRF III for their OPEX costs for these operations, detailed in **Table 7**.

RRF III detailed that for less complex materials, such as plastic-bodied water meters with minimal metallic content, OPEX typically costs around 60 euros per metric ton. Brass-bodied water meters and similar products generally have OPEX costs of around 80 euros per ton because of the higher metallic content, which causes more wear and maintenance costs. In contrast, composite-body smart water meters (simple WEEE) with lithium batteries, which require additional manual labour for battery removal, are estimated to cost about 140 euros per ton (source: RRF III).

The labour time required for these operations is around two hours per ton (source: RRF III, ISC); one person manages the feeding belt, and another controls output streams and performs handpicking tasks as needed. This estimate is relevant for the V200 and V200P, where no pre-processing is involved.

In contrast, given the lack of specific data for processing smart meters for this task, an additional 8 hours for battery removal (10 seconds per water meter) has been estimated based on the author’s empirical experience with removing the batteries from these meters.

Table 7: OPEX costs and labour time per ton MS.

Type of Water Meter	OPEX Costs (€/ton)	Shredding (Man-Hours (h)/ton)	Additional Considerations
V200	80	2	Higher metallic content and increased wear on shredder blades or hammers.
V200P	60	2	Minimal metallic content, less complex, lower wear and maintenance costs.
Multical 21	140	10 (2 + 8)	Includes lithium batteries, which require manual labour for battery removal.

4.2.3.1.1.1 Scrap prices of metallic materials

A price list was looked up from three local middleman recyclers for the content loss calculations (Geelhoed, 2024; Janssen, 2024; KH-Metals, 2024). The locally sourced prices provide a more realistic representation of the actual scrap value of the materials. Metal scrap metal prices fluctuate based on the London Metal Exchange (LME) rates. PCBs are categorised into low, medium, and high-grade scrap depending on the quantities of valuable metals they contain, such as gold, copper, and silver. The PCBs for typical household items are generally low to medium grade (source: RRF III, V).

There are no scrap prices for lithium batteries, plastics, glass, and composites. The RRFs view these items as "cost-covering" materials because their disposal costs are offset by the fees charged to process them rather than generating direct revenue; thus, they are excluded from the assessment. **Table 8** provides an overview of the market value price list for the scrap parts; the average prices were used throughout the study.

Table 8: Market value price list for scrap material

Material	Low-End Price (€/kg)	High-End Price (€/kg)	Used avg. Price (€/kg)
Brass	3.70	4.40	4.05
Stainless Steel 316	1.55	1.75	1.65
Stainless Steel 430	1.10	1.30	1.20
PCB	2.40	4.80	3.60

4.2.3.1.2 Economic and social aspects MD

The cost associated with the MD strategies is the minimum hourly wage in the Netherlands, which is €13.27 (CBS, 2024). According to all the interviewees, these are the prices that the people who usually do these tasks get paid. The operational costs for the pneumatic and hydraulic tools, typically 500-watt machines (source: WoW), were estimated using electricity prices from EUROSTATS (2024) For non-household consumers in the Netherlands, it is 0.22 €/kwH.

According to WoW, whose workers have much experience with the RR of water meters with conventional and pneumatic/hydraulic tools, dismantling 100 meters typically takes:

- **2 hours** for water meters with two compartments, such as the V200, where the registry and body materials must be extracted.
- **1.5 hours** for easily disassembled water meters or have only one compartment, like the V200P and Multical 21

These values also highly depend on the manual tools (pneumatic air wrenches or hydraulic clamping block) (source: WoW, RRF I). The V200P model has two compartments; the lower compartment is entirely plastic. It does not require further disassembling, thus simplifying the process. According to WoW, the times mentioned above are also the standard recommendations for social workplaces that perform these tasks.

4.2.3.2 Transport of the water meters

For Transportation Stage A4, the destination chosen is BW's central warehouse in Veghel, Netherlands. The factory locations for the relevant products are as follows: the V200P and V200 meters are produced in Luton, England, 511 km away, and the Multical 21 is manufactured in Skanderborg, Denmark, 857 km from the warehouse. These distances were determined using Google Earth.

For stage C2, transport from BW to RRFs, a standard distance of 40 km is used for both MS and MD. This **Fig.** aligns with the findings of Wäger et al. (2011), who identified 40 km as the average transport distance from the collection point to processing facilities in their WEEE collection and transport study. Wager et al. (2011) also identified a truck as the typical mode of transport used for all the transport steps.

4.2.4 Impact assessment

The following subsections explain how the data were combined to quantitatively assess RR strategies for the selected meters. The impact assessment calculations are added to **Appendix B**

4.2.4.1 Environmental impact assessment

Product Stage: Material selections, production processes, transportation methods, and EOL management outcomes are entered into an Excel calculation sheet for the LCA impact assessment. This sheet integrates product data with an environmental impact indicator, specifically the eco-cost impact in our case. The structure of the sheet is based on elements adapted from the Eco-cost data sheet provided by the Eco Cost Value Website (2023).

Material and process data for the product are matched with corresponding data from the Industrial Design & Engineering Materials (IDEMAT) database, which includes impact from various life cycle stages. When specific items could not be located within the IDEMAT database Excel file, the IDEMAT Mobile Application or the Ecoinvent V3.8 database were used as an alternative. The author selected similar materials or processes if neither database contained the required information. This approach was necessary for components of the Multical 21, which utilise newly developed materials whose detailed life cycle impacts still need to be fully documented. For example, in the absence of data for lithium thionyl chloride batteries used in the Multical 21, Lithium Iron Phosphate batteries were selected as a substitute.

For the V200, the manufacturing process involves casting brass and machining operations. This is done to have precise features and threads on the brass body, with approximately 5% of the cast material removed during the machining phase and recast into new meters (source: WMM II). During the interview, WMM II indicated that other metal components within the meter, such as the registry, stainless steel pressure plate, and minor parts, are likely first sheet-rolled and then deep-drawn. An additional step for brass-bodied meters, occasionally required, depending on the preferences of the DWU, involves powder coating the bodies with blue paint. This step was observed in all V200 models examined at BW.

The plastic components of the meters, including the bodies, are primarily produced through injection moulding (source: WMM I, II). This process is widely used within the industry, not just for plastics but also composite components, because of its scalability and low costs (Crawford & Martin, 2020; Matulis, 2020)

- **Transport:** The truck + trailer weight-based transport for all the meters. The impacts of these meters were normalised from ton/km to the individual weights of the specified meters.
- **Use Stage:** Water meters are environmentally neutral during their use stage, as they emit no pollutants, require no external power, and need no repairs or maintenance. Consequently, they achieve a net environmental impact of zero.
- **End of life:** Within this study, the metals are considered from a closed-loop perspective where the waste materials are redirected back to an earlier process in the same system (Vogtländer, 2012). The same approach is taken for the glass, PCB, and batteries. The metallic elements within these products can be (not always) indefinitely recycled without degradation of their inherent properties. Recycling these materials provides a "recycling credit". These recycling credits are typically negative, reducing the total environmental costs of the product's lifecycle, which is calculated as (Vogtländer, 2012):

$$\text{Recycling Credit} = \text{Eco-costs of recycled material} - \text{Eco-costs of virgin material}$$

Materials not recovered or remaining post-incineration, like fibreglass embedded in some plastics, are classified as landfills. The energy consumption related to the RR strategies, such as that used by shredders or hydraulic machinery (500-watt machinery), is calculated and normalised based on the time required to Liberate one water meter. For MS, data provided by ISC is used, which comes down to a 147-kWh system.

4.2.4.2 Economic assessment

For the economic assessment, the OPEX and content loss costs associated with strategies were normalised to reflect the costs specific to each type of meter. The average scrap prices were used for the materials' scrap value. The revenue associated with each meter with the selected strategies was calculated using the following equation:

$$\text{Revenue} = \text{Scrap Value Water Meter} - (\text{OPEX} + \text{Content Loss Costs})$$

OPEX varies depending on the specific meter type but does not depend on yield. It is considered constant since OPEX costs are inherent to the equipment and labour used for each type of meter. The content loss can vary depending on the specific meter and yield. The meter's scrap value is a constant. For MD, the total costs include the OPEX, which, besides minimum labour wages, also consists of the cost of electricity consumption per hour of the hydraulic machine operation. All calculations were performed using a Python script executed within a Jupyter Notebook; the codes are provided in **Appendix E**.

4.2.4.3 Social impact assessment

The UNEP (2020) guidelines for the impact assessment and indicator selection are flexible due to the complex nature of the social elements attached to various products and processes (Yu & Halog, 2015). For the quantitative analysis of social impacts, each meter's labour time was normalised based on the RR strategy, whether MD or MS. This normalisation provided a quantifiable measure of labour time per meter for the given strategy, offering insights into the societal benefits of job creation.

However, while this quantitative approach provides key insights, it does not fully cover the broader social aspects. Observations during the study, mainly through interviews, highlighted significant differences in social impacts — specifically regarding inclusivity and ergonomics — between the different recovery methods. These are also discussed in the results without quantification.

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5 Results sustainability assessment

This section displays the results using the SA framework methodology detailed in the previous chapter. The research results are presented in the order of the three pillar assessments: environmental, economic and social.

5.1 Environmental assessment

The horizontal bar chart in **Fig. 22** illustrates the results for the eco-costs (€) associated with each life cycle stage of the water meters for MD & MS. Lower values indicate a reduced environmental impact. Stages A1-A2 represent the background processes of material extraction and transport to the manufacturing company. The Multical 21 and V200 meters display significantly higher eco-costs than the V200P due to the specific materials used inside these meters (further discussed in the contribution analysis).

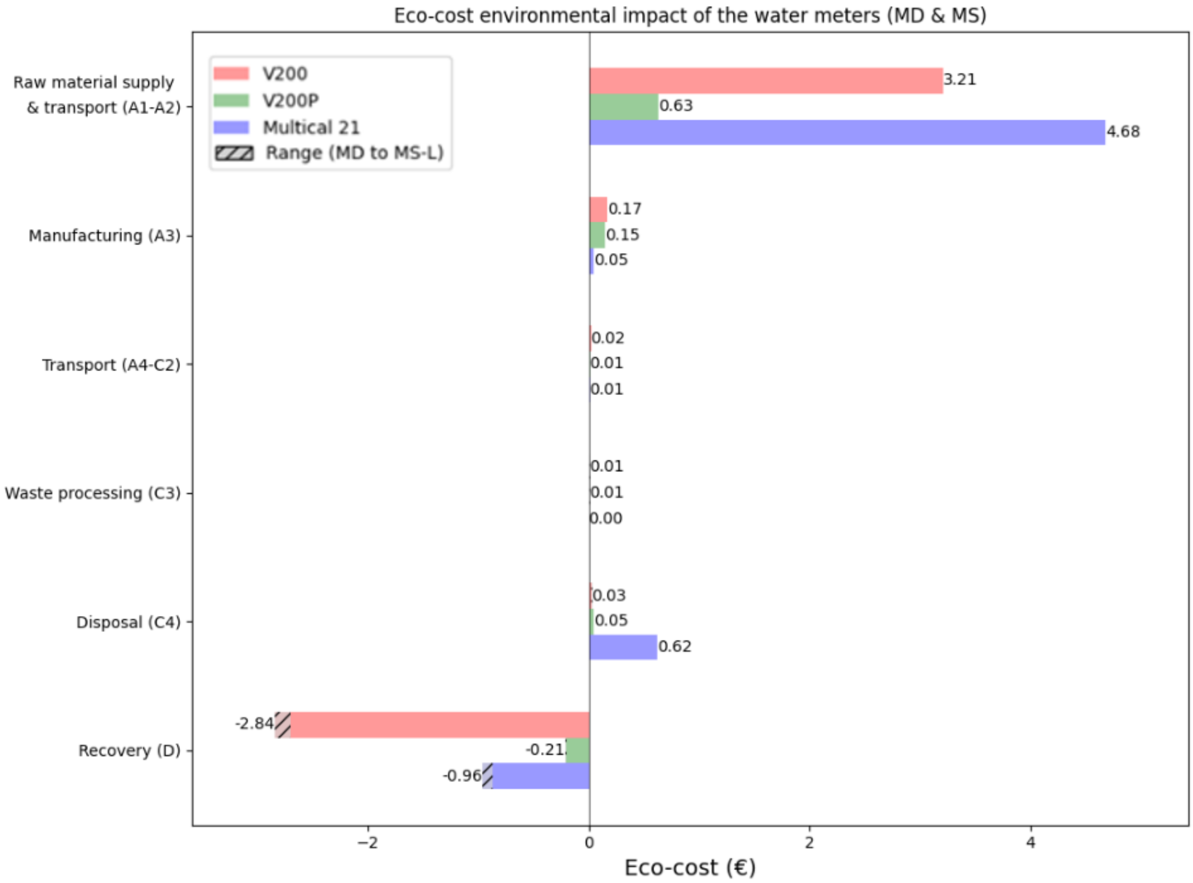

Figure 22: Eco-cost environmental impact for the given meters and strategies.

The manufacturing stage (A3) and transport stages (A4 & C2) are relatively low-impact hotspots for the water meters. The same could be said for waste processing (C3), the point from which the different EoL RR strategies (MD & MS) are considered. The impact of the tools used for waste processing, whether a shredder or hydraulic machinery, is negligibly low. Disposal (C4) of non-recycled materials also shows minimal eco-costs, with the Multical 21 as an outlier due to specific materials involved.

The recovery stage (D) displays the eco-credits and the consequences of the different strategies used for the RR, which have varying yields. The range bar compares the best practice (MD) with the least efficient (MS-L), while MS-A and MS-H fall between these values. For further clarity, **Fig. 23** provides a zoomed-in view of its eco-cost range. While similar differences exist in stages C3 and C4, their impacts are so minor that they could not be effectively represented in **Fig. 22**. For a more detailed perspective on stages C3 and C4, the author refers readers to **Appendix B**.

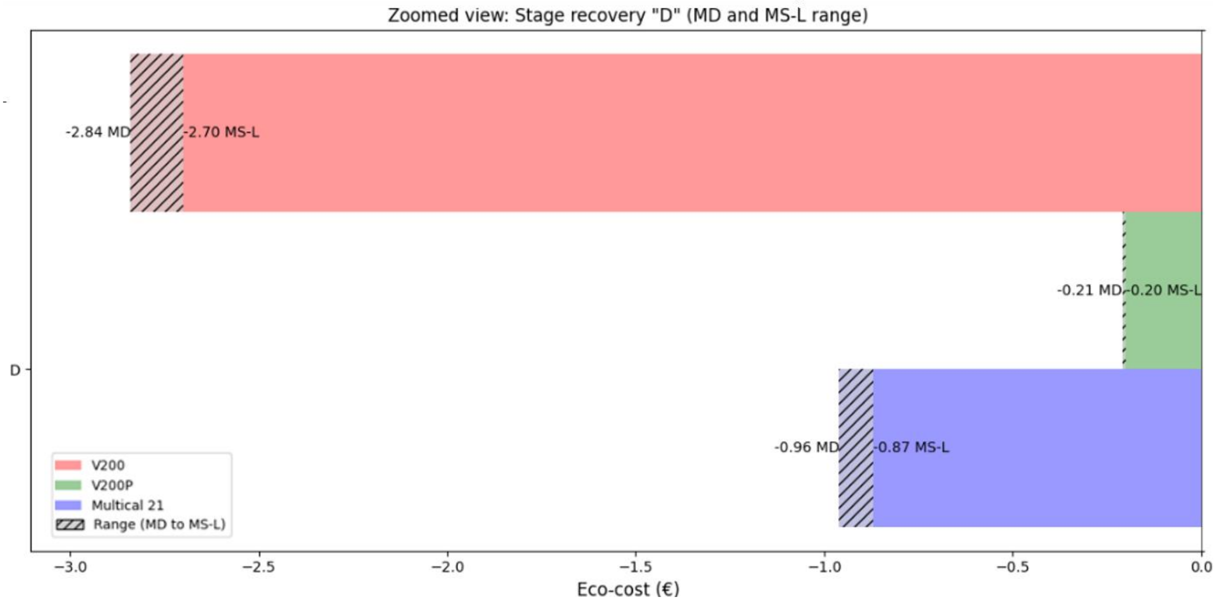

Figure 23: Zoomed-in view of the recovery stage

Table 9 summarises the net eco-costs and eco-credits for each water meter model across the entire life cycle, given the range of the MS practice. The V200 shows a significant difference in eco-costs due to the RR of recyclable materials, making it the most environmentally beneficial option when using the MD. If MS is chosen, depending on how the meters are processed, the eco-cost can get as high as €0.16 (MS-L) or as low as €0.07 (MS-H) compared to MD. In most cases, the actual value will lie between those two, around €0.12 (MS-A). This difference can also be observed for the Multical 21 where the range can be between €0.05 ≤ x ≤ €0.10 compared to MD. For the V200P, these differences are low compared to the other two meters, reaching a maximum of €0.02.

Table 9: Given the different strategies, the net eco-cost impact of the water meters.

Meter Type	MD (€)	MS-H (€)	MS-A (€)	MS-L (€)	Range Diff. (€)
V200	0.58	0.65	0.70	0.74	0.16
V200P	0.61	0.62	0.62	0.63	0.02
Multical 21	4.39	4.44	4.46	4.49	0.10

It can also be observed that the transition from a brass body to plastic material is not inherently harmful from an environmental point of view. For MD, the best environmental scenario, V200 and V200P have a €0.03 difference. In practice, a significant portion of these meters will be processed through MS with some content loss. Even though when the yield is considered high (MS-H), the V200P becomes a better alternative. This can only be said for the selected water meters; others with different materials and quantities can have differing results.

The transition to smart water meters is around x7 more harmful than the other two, with high production eco-costs and low recycling credits that could be retrieved from the recover materials to compensate for it, unlike the V200. This difference becomes even clear when considering that the eco-cost impact of a water meter can be spread out across the years it is in use before being decommissioned. For the V200 and V200P, it is 20 years; for the Multical 21, it is 15, implying that these meters are even more environmentally harmful than the mechanical meters. Still, these water meters have other benefits that could compensate for these costs beyond the production, disposal, and RR stages, which are discussed in detail in Sønderlund et al. (2014) and March et al. (2017).

5.1.1 Material contribution analysis

The segment discusses the contribution of the different materials for each of the meters for stages A1-A2, C, and D, as these were deemed the most significant due to their eco-costs. **Fig. 24** displays the eco-cost impact of the various materials in the three meters for A1-A2. Material impacts below €0.01 are not shown in the graph. These small contributions, including the weight of the materials, are further displayed in **Appendix B**.

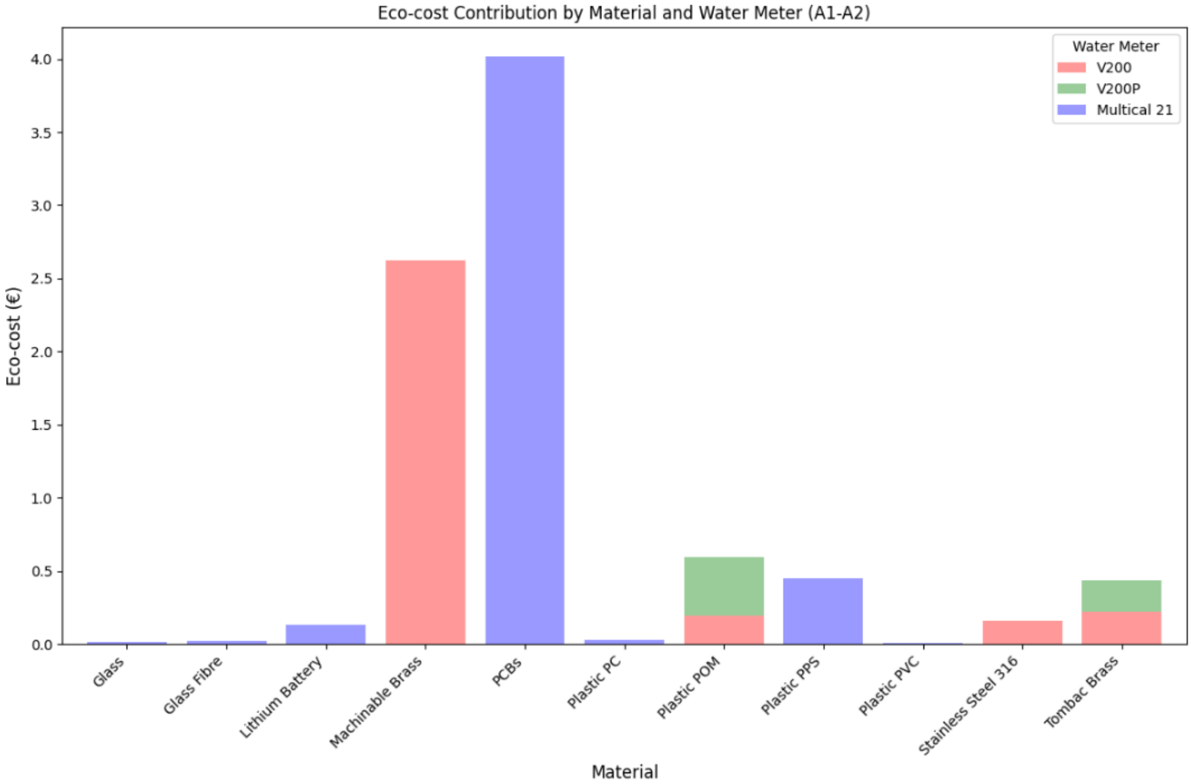

Figure 24: Eco-cost contribution by material and water meter (A1-A2)

For both the V200 and Multical 21, most of the eco-cost impact is due to brass and PCBs. As shown in **Table 5**, brass accounts for 815 grams, while the PCB weighs only 36 grams. Despite its much smaller mass, the environmental impact of PCB production is disproportionately high due to the resourceintensive materials involved. The impact of the other materials is significantly lower, mainly because of their quantities combined with the eco-cost impact (eco-intensity) these materials have.

This difference can be seen in the graph for the V200P due to its plastic-to-brass ratio. The small amounts of tombac brass (60 grams) in the meters have almost the same eco-cost impact as the plastics (463 grams). A similar observation applies to the different plastics used in these meters. The V200P utilises Polyoxymethylene (POM), whereas the Multical 21 (for the body) uses 100 grams of Polyphenylene Sulfide (PPS). However, the environmental impact of PPS per gram is five times higher than that of POM. As a result, the choice of materials for the Multical 21 significantly increases its overall eco-cost.
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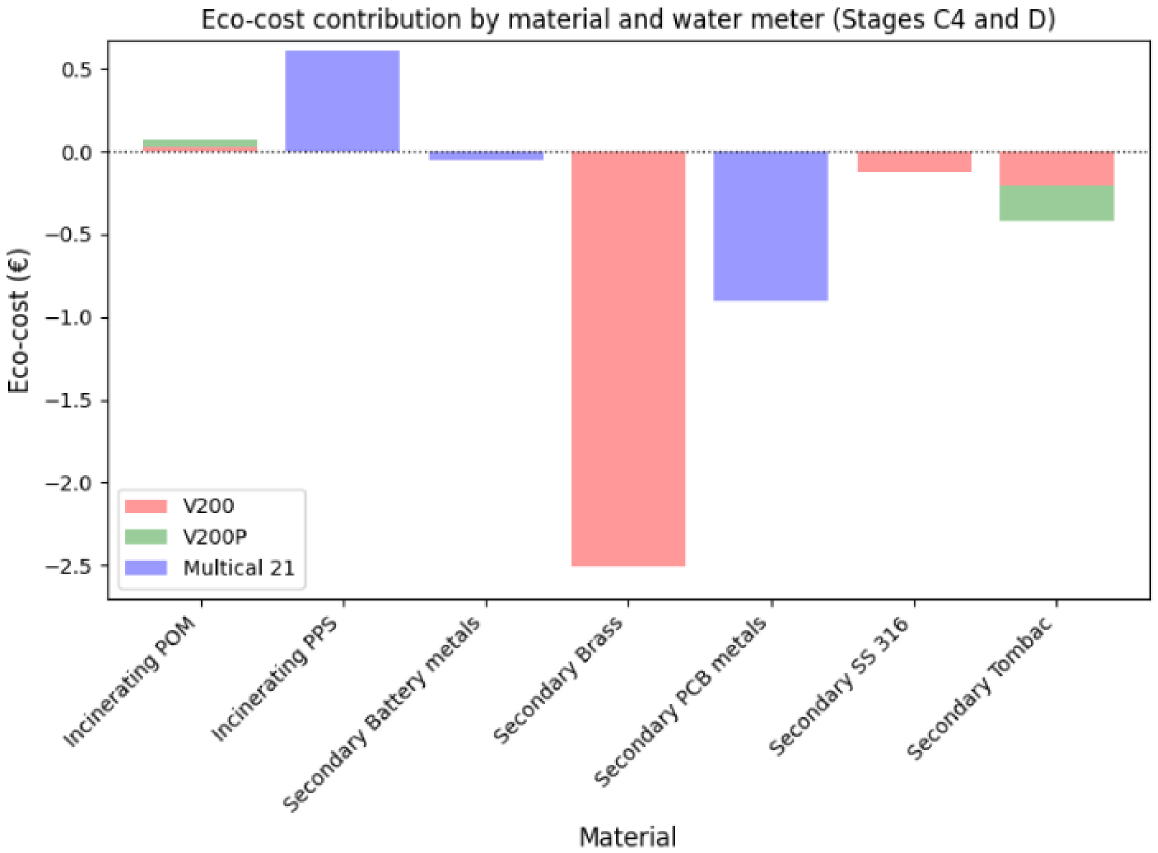

Figure 25: Eco-cost contribution by material and water meter (C4 & D)

Fig. 25 displays the eco-cost impact of stage C4 for MD, including the recycling credits for the recovered materials for D. For the V200, as expected, the impact is mainly because of the brass. Despite its high impact on A1-A2, the brass recyclability dramatically reduces its life cycle impact. The impact of the other materials (like glass) is significantly lower, mainly because of their quantities combined with the eco-cost impact (eco-intensity) these materials have. The impact of plastic production is low, while they do have (currently) minimal recycling potential.

All the plastics are incinerated at the EoL process; while this generates electricity with energy recovery at municipal disposal sites, it also releases CO_2 and other potential toxins into the environment (Vogtländer, 2012). As **Fig. 25** shows, the incineration of some plastics (PPS) is significantly more harmful to the environment than others (POM).

5.2 Economic assessment

Table 10 outlines the economic effects of various RR strategies for water meters. It presents the OPEX and content loss costs, followed by the total cost, which combines these two components. The revenue generated by each meter under the selected strategies is calculated by subtracting the total costs from the potential scrap value of the meter. It is important to note that costs associated with waste transportation and disposal have been excluded, as these details could not be obtained from the RRFs.

It is evident that the V200 has a lot of revenue potential but also coincides with a high cost. For MD, the higher cost is mainly due to the design of the meter, which makes it challenging to disassemble, resulting in a higher OPEX cost (€0.27) compared to the other meters (€0.20). Additionally, under MS, content loss plays a significant role because of the meter's high brass content, with losses reaching as high as €0.15, surpassing the OPEX cost for this method (€0.10).

In contrast, the revenues from the V200P and Multical 21 meters are significantly lower. Under MD, the V200P is barely profitable (€0.05), while the Multical 21 demonstrates a loss (-€0.06). Processing these meters through MS proves more profitable for RRFs. The variations in revenue among different MS (MS-H, MS-A, MS-L) for these meters are minimal (up to €0.01 difference). Due to their smaller size and lower weight, the OPEX costs associated with MS for these meters are lower. Furthermore, the plastic-dominant composition of these meters reduces shredder wear and maintenance costs compared to the V200.

Table 10: Breakdown of OPEX, content loss, Total Costs, and revenue for the water meters (MD & MS).

Water meter	Strategy	OPEX (€)	Content loss (€)	Total cost (€)	Revenue (€)
V200 (Scrap value € 3.68)	MD	0.27	N/A	0.27	3.41
	MS-H	0.10	0.04	0.14	3.54
	MS-A	0.10	0.10	0.19	3.49
	MS-L	0.10	0.15	0.25	3.43
V200P (Scrap value € 0.25)	MD	0.20	N/A	0.20	0.05
	MS-H	0.03	0.00	0.03	0.22
	MS-A	0.03	0.01	0.04	0.21
	MS-L	0.03	0.01	0.04	0.21
Multical 21 (Scrap value € 0.14)	MD	0.20	N/A	0.20	- 0.06
	MS-H	0.05	0.01	0.06	0.08
	MS-A	0.05	0.01	0.06	0.08
	MS-L	0.05	0.01	0.06	0.08

The data highlights the importance of selecting an appropriate RR method based on the meter type. The economic variability of RR operations is closely linked to the meters' material composition, design, and efficiency in the recovery practice employed. Besides the costs related to the RR strategies that depend on OPEX and RR yield, other external factors like the LME course of metals can also have an impact. The latter's sensitivity and contribution to the total cost are discussed in the following subsection.

5.2.1 Sensitivity and contribution of scrap price variability

This segment's sensitivity and contribution analysis focuses on the total cost element for the V200's MS because of its high metallic content and varying yield. The other water meters are less affected by the LME-course volatility. Although this volatility also affects revenue, the analysis emphasises cost dynamics, particularly the interaction between constant OPEX and variable content loss driven by yield and scrap price fluctuations. The assessment used scrap price factors ranging from 0.8 to 1.2, representing a ±20% change from the baseline. **Fig. 26** displays the total cost of the, and **Fig. 27** shows the contribution of the OPEX and content loss to the total cost.

At a baseline scrap price factor of 1.0, the MS-H scenario results indicate a total cost per piece of approximately €0.14, composed of €0.10 OPEX and €0.04 content loss. This leads to an OPEX contribution of about 70% and a content loss contribution of about 30%. Increasing the scrap price factor to 1.2 for this scenario raises the total cost to about €0.15, with content loss now contributing around 34%.

In contrast, the MS-L scenario displays higher sensitivity to scrap price fluctuations due to a lower yield. At a factor of 1.0, the total cost is approximately **€**0.25. Content loss accounts for roughly 62%, more than double the relative share observed in the MS-H scenario. When the scrap price factor increases to 1.2, the total cost rises to €0.28, of which about 66% is content loss.

The MS-A, the intermediate between the two, has a total cost of about 0.2. At a factor of 1.0, the OPEX and content loss prices are about the same. As the scrap price increases to 1.2, the total cost rises to €0.21, with the content loss share increasing to about 54.7%.

These results underpin the influence of yield and scrap price fluctuations on RR costs for high-brass-content water meters. When yield is low, the proportion of cost from lost content grows, representing inefficiencies that can be mitigated through improved RR strategies. By monitoring scrap price changes and improving the yield of the recovery process, it is possible to reduce these losses and increase overall profitability as an RRF.

Figure 26: Total cost vs scrap price factor for the meter V200 (MS).

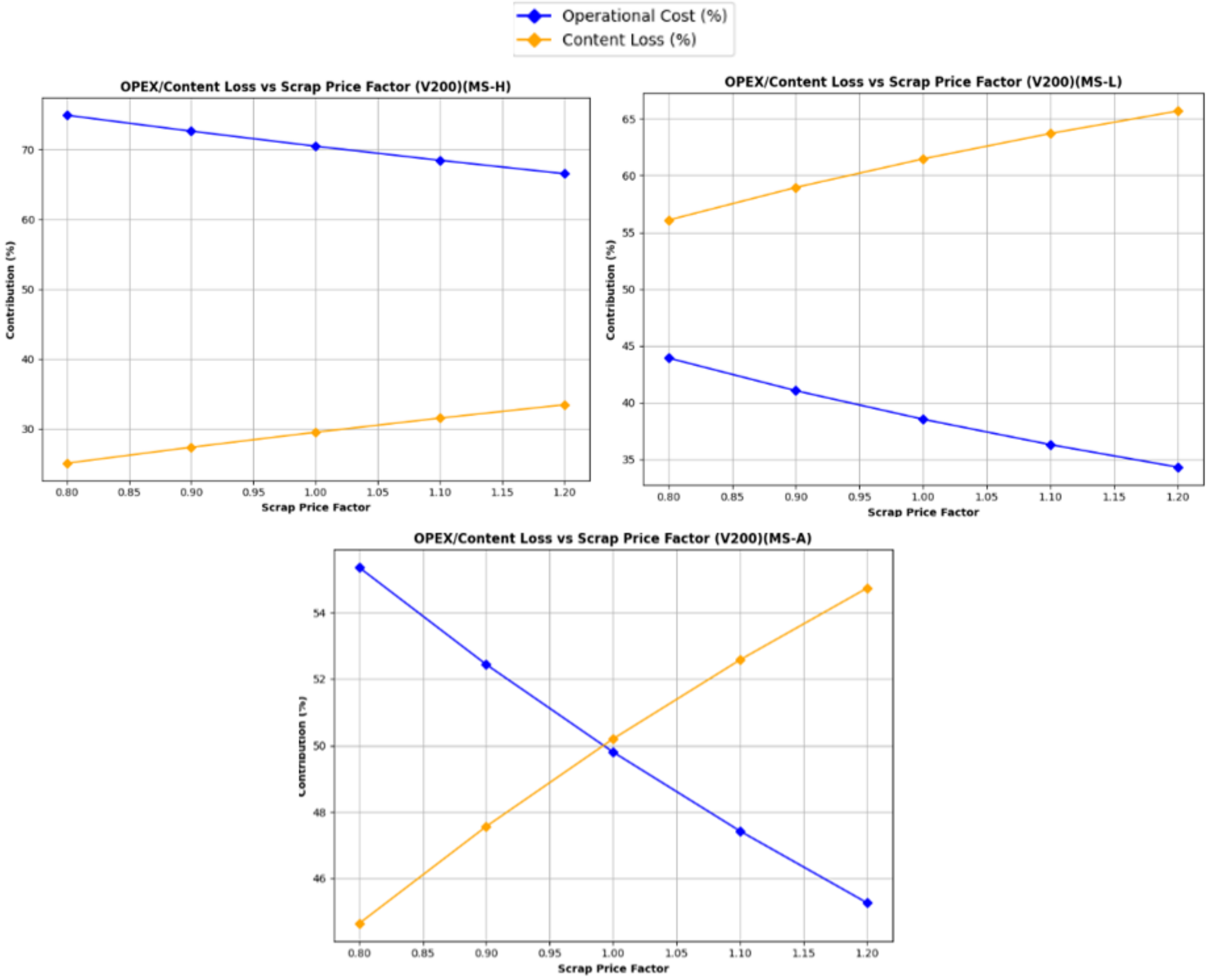

Figure 27: OPEX/Content loss contribution with the scrap price factor variability for the meter V200.

5.3 Social assessment

This section presents the results of the study's social assessment, divided into two parts: (i) the quantified job creation and (ii) the qualitative evaluation of strategies. For the first part, quantified labour times are provided in **Table 11**. It is important to note that, for the MS, the reported time does not represent the actual processing speed per water meter. However, the combined labour time generated by the shredder operation is expressed in seconds, as the shredder typically requires a team of two. In contrast, the MD time values reflect the processing speed and the labour time generated.

Table 11: Labour time (s) generated with the dismantling of the meters

Meter Type	V200	V200P	Multical 21
MD (s)	72.0	54.0	54.0
MS (s)	8.8	4.0	13.7

The MD method generates more labour time than the MS, specifically designed to reduce labour time and costs. While developing additional labour time may benefit society by creating employment, it also increases RRF costs. However, financial considerations alone do not fully capture the trade-offs between these methods, as each method offers unique benefits and challenges related to social impact and operational feasibility.

The second part of the assessment addresses the qualitative evaluation, focusing on the social indicators of inclusivity and ergonomics. These social impact categories can be possible hotspots concerning social impact for workers.

- **Inclusivity:** MD strategies are often done in collaboration with social workplaces where individuals distanced from the labour market have opportunities to participate and contribute. In contrast, the MS method requires a certain level of expertise to operate the machinery (source: RRF I, III), making it unsuitable for individuals with physical or mental impairments. The RRFs are also unsuited for these people due to noise levels and accessibility barriers (source: RRF I). That is why RRFs collaborate with centrally located social workplaces, bringing in materials for processing and then transferring them to end-processors (source: RC II, III).

- **Ergonomics**: Ergonomics is another important social indicator. For the MS method, work is relatively straightforward and less labour-intensive, even when handpicking is involved (source: RRF I). However, the MD method can be physically demanding, especially after several hours, as observed during the empirical analysis of this study. This is particularly true for meters with top-sealed registers and bottom-sealed casings (often volumetric meters) requiring more effort to disassemble. Thus, the water meter design significantly influences the physical effort needed for disassembly; water meters designed for easier disassembly, such as the V200P and Multical 21, streamline the process and reduce physical strain on the body.

Contrary to the other two assessments, deciding which strategies are suited for the selected water meters is much more challenging. While the MD strategy has the potential to generate more labour hours for the community, it must be financially feasible and physically less straining. What is clear is that the WMMs also have a role to play, especially in the ergonomics of the water meters. This gives the meters more EoL RR versatility.

6 Discussion

This chapter discusses and contextualises the study's findings. It first interprets the results and highlights how they contribute to broader research objectives. The discussion then places these results within the existing literature, assessing the methods used, their limitations, and the implications for future research

6.1 Results interpretation

This section interprets the results obtained for the SA and puts them into context. The interpretation of the results is discussed within their pillar segment.

6.1.1 Environmental pillar

Because of the use of a single-issue indicator, interpreting the environmental results of the RR part is relatively straightforward. Nonetheless, there is an important point to mention: The outcome of the assessment with the eco-costs cannot be regarded as the actual environmental impact of the water meters, considering the different RR strategies. Many other factors could influence these impacts, and single-issue indicators are known for oversimplifying complex issues (Vogtländer, 2012). Thus, the outcomes should be regarded as estimations. The oversimplification and potential errors are spread out evenly for the strategies and water meters, providing a good comparison model for different RR strategies for assessment and evaluation purposes, which was the study's goal.

The author saw no need to do an additional sensitivity assessment. The reason is that the sensitivity is already built into the strategies involved, such as MD and the varying yield of MS strategies (MS-H, MS-A, and MS-L). The current method also shows the yield effects of less or more brass in a meter compared to its weight ratio in the selected meters (V200/V200P).

A contribution analysis was needed to display the effects of recycling credits and the disposal impacts of the different materials. For example, there is a clear difference between PPS and POM usage for the main body of water meters. Various water meter models use other kinds of plastics and composites, and a contribution analysis of the materials displays the impacts of these choices from an EoL and RR perspective. The same applies to the use of PCBs and brass.

6.1.2 Economic pillar

The results in this stage were influenced by minimum wages for MD, material content loss based on scrap prices, and industry-provided OPEX for the MS method. Except for minimum wages, generally stable for MD, the other factors can vary significantly depending on multiple variables. For example, extra cost factors tied to high and low yield, such as using extra sorting machinery to improve stream purity, can impact overall costs. Li et al. (2011) highlighted this in his study on costs associated with sorting technologies for various aluminium yields. While industry benchmarks used in this study provide a foundation for an assessment, it is essential to consider that these costs can vary greatly depending on the specific facility and the machinery used.

A sensitivity and contribution assessment were conducted to better understand cost volatility by focusing on the influence of scrap price fluctuations. For the V200, these fluctuations are primarily driven by its brass body. Copper, the base element of brass, was added to the European Union's critical metals list with Regulation 1252 (2024) due to supply constraints and growing demand. Geopolitical events further amplify these fluctuations for metals in general. For example, recent export restrictions imposed by China on gallium illustrate the potential for similar disruptions in copper exports (Reuters, 2024). This will increase the revenue from the recovered material and the cost associated with the varying yield.

6.1.3 Social pillar

For the social pillar, while the two different methods display apparent differences for the given water meters and practice in job creation, as explained in the results segment, one cannot easily say that one method is better than the other because there are nonquantifiable factors that make the assessment and evaluation of this pillar challenging for the given study.

While these aspects could theoretically be quantified through binary values (e.g., assigning a "1" or "0" to indicate whether one method is superior to the other), such a simplistic representation would fail to reflect these social indicators. Therefore, the author chose to qualitatively describe the observed social differences instead of reducing them to binary quantification

The author deemed conducting a sensitivity or contribution analysis for this section unnecessary. The quantitative labour time that could be seen as a chance to employ extra workers and associated costs, as outlined in the economic assessment, combined with the qualitative differences discussed, provide sufficient context to inform the strategies for the various water meter types.

6.2 Comparison to literature

There are currently no studies on EoL or RR strategies for water meters. This work is unique to the author's best knowledge. Existing literature primarily focuses on management aspects, excluding EoL considerations. Studies also exist regarding the accuracy of different measuring mechanisms. With the advent of smart water meters, new research has also emerged regarding their benefits for water conservation and improved data coverage. However, the EoL and RR strategies have not been explored until now. By examining the EoL RR strategies for water meters, this study aligns with other sustainability assessments of EoL processes in waste management. It contributes comparable results, filling a gap in the current body of knowledge.

This work diverges from most EoL RR studies concerning the recovery of plastics; for example, in the waste management studies concerning EoL vehicles and WEEE covered in the studies of Islam & Huda (2018) and Karagoz et al. (2020), plastics also have recovery and upcycling potential. Due to the current majority of RRF methods regarding the plastics inside the water meter, the EoL incinerator option for the plastic was chosen.

Furthermore, this work diverges from other LCSA studies because it does not apply a multi-criteria assessment or other weighing factors for the selected indicators to arrive at a sustainability score for the given methods, which is the case for most LCSA studies covered in the literature review. According to the UNEP/SETAC (2012) guidelines, this step is not a necessity, given the study's objectives and the available information. In the author’s opinion, a sustainability score would not have added value to the assessment because it is difficult to say that a particular sustainability pillar or indicator weighs more than the other.

6.3 Effectiveness of the methods

The LCSA framework in this study allowed for a structured and flexible SA of EoL RR strategies for water meters, given all three pillars. On the environmental side, using a monetised single-issue indicator simplified complex datasets and made the impacts more relatable. In this research, focusing more comprehensively on environmental impacts (from cradle to grave) while limiting the economic and social solely to stage C3 was a deliberate choice driven by data constraints and the study's aims. This flexibility ensured that the analysis was both actionable and feasible with the available information. The same applies to the fast-track LCA method with the IDEMAT and Ecoinvent databases.

However, the selective boundary settings and reliance on the fast-track method introduced some trade-offs. While fast-track methods may lack the rigour of detailed LCA approaches, their accuracy often compares favourably in many cases, depending on the context of the study, specifically for a comparison study (Vogtländer, 2012). The choices for the given system boundaries gave some pillars a less comprehensive view of the entire life cycle. For instance, the study did not account for specific cost implications in the EoL process, such as transportation of the meters from the DWU or waste disposal costs.

6.4 Completeness check

The comparison of different water meters undergoing alternative EoL RR strategies is incomplete and does need future recalculation and reassessment. When comparing the two RR methods, an essential aspect of the flaws of one RR practice, which has both environmental and economic consequences, was not considered due to data unavailability. This aspect is the cross-contamination of materials, particularly metals, for the method MS. While some contamination is accepted within the industry when it comes to these metals (4MS, 2019), if the levels reach a certain point, additional virgin or market mix material must be added to the recovered materials to improve the purity. For example, as discussed by Johansson & Björklund (2010), in their study of copper recovery from dishwashers, they focus on the environmental aspects of the different yields and material purity.

Cross-contamination and content loss also have a social aspect, which is not covered in this study concerning virgin material production, which is avoided when the materials are recovered. While the recovery deprives workers of the generated job creation in countries where the virgin material is produced, it also avoids child labour, violation of human rights, pollution and health problems and many other negative social factors coupled with the production of virgin material (Ghisellini et al., 2023). These social impacts on the production of virgin material in the mining sector are discussed by Mancini & Sala (2018).

The inclusion of these aspects would make the MS, specifically for the V200, an even less sustainable method than it already is, given the study results. Nonetheless, the author wants to emphasise that the LCSA remains an iterative approach for an SA, where new insights and ideas can always lead to re-evaluations and new results (UNEP/SETAC, 2012).

6.5 Consistency check

Consistent system boundaries, FU, allocation rules, and impact assessment have been applied for this SA. However, transparency is needed regarding the study's inconsistent aspects:

- **Data quality:** Although the Netherlands was the geographical location for the environmental assessment, the author had to use EU or, in some cases, global average LCI impacts due to data availability. The author has labelled all the sources of the LCI data in the Excel files added in **Appendix B**. The author believes these impacts to be minimal on the results due to the similarities of some processes worldwide.

- **Environmental:** While the study is a cradle to grave assessment, it has omitted life cycle stages installation (A5) and de-installation (C1) for the water meters because of the lack of data and these processes being similar for all meters for all the DWUs. Nonetheless, these stages have an impact since the water meters must be driven to their destination (households) and returned to the warehouses when decommissioned. Even though the transport stage has minor impact on the life cycle for water meters due to their size and bulk transport, this is mainly the case for truck transport, not company vehicles that transport less and have a higher environmental impact. Nonetheless, the author believes that the transport impacts of this stage are still negligible and minor, even with the higher impact of company vehicles.

- **Social**: While the S-LCA is a quantitative tool, the author has also included qualitative results for the assessment. This is unusual, but the author deemed it necessary to provide a better understanding of the pillar. Furthermore, while labour hours/work hours are consistently used in the S-LCA, these are used to assess working conditions. Only a few selected studies, like Hu et al. (2013) and Lu et al. (2014) have used it as labour time generated for society as applied in this study.

6.6 Limitations

The study’s reliance on interviews with industry experts provided valuable insights not readily available in the scientific literature but also introduced potential bias due to the subjective nature of expert opinions. Contributions from industry insiders, including interviews and internal documents, may contain inherent biases favouring their organisation’s sustainability image, mainly for RRFs who want to keep their customer-supplier base happy. Additionally, efforts to conduct direct observations of social workplaces involved in MD were unsuccessful (except WoW). Facilities denied requests for visits, offering only descriptions. This limitation affects the objectivity and comprehensiveness of the study’s conclusions, mainly for the social aspects of the assessment.

Furthermore, the relatively recent development of the IDEMAT and Ecoinvent databases means some materials and processes are not yet included. This necessitated proxy materials, which introduces uncertainty in the environmental impact assessment, as proxies may only partially reflect actual environmental impacts

6.7 Major assumptions

This study identifies several major assumptions that may impact the results' accuracy. These give rise to uncertainties in the sustainability assessment of RR strategies. For transparency reasons these assumptions are discussed in more detail:

- **Closed and open-loop:** All metals were assumed to have a closed-loop perspective, implying upcycling within the industry. Plastics and composites take an open-loop approach, with incineration and energy recovery as the EoL pathway. While incineration was suggested by all the interviewed representatives due to the nature of the plastics in the meters, this may not represent the overall situation, where some plastics and composites might be upcycled with the take-back programs of some WMMs. This would make the plastic body water meter an even better option, given the selected boundaries of the study.

- **Plastics for the V200 & V200P:** It was assumed that the plastics inside the meters and surrounding the registry chamber were also made of POM, like the body material of the V200P. Unlike the Multical 21, BOM was unavailable for these meters. Consequently, if the actual plastics used differ from POM, the environmental impact of these components could significantly influence the results only when comparing the meters and their total life cycle impact.
- **Use stage:** Zero environmental impacts are assumed during the in-use stage, with no emissions, maintenance, or energy consumption. This simplifies the analysis but overlooks the potential indirect impacts of smart meters and the required transmission infrastructure, which could add to the environmental footprint. Nonetheless, the author does not believe that this impact would be significant.
- **Battery removal time:** Assumptions regarding the preprocessing of these meters, differences in worker skill and alternative tool availability could affect removal times and subsequent labour cost calculations for this assumption for the given meter. Directly shredding this kind of WEEE also happens within the industry in some facilities with the correct line-up, bringing the cost significantly down (source: RRF III), but this is not considered for this study due to data restrictions.

6.8 Future research directions and recommendations

Considering the findings and limitations of this study, several future research topics could further improve the understanding and practice of EoL RR for water meters or other products. The following recommendations aim to address the identified knowledge gaps, improve SA, and guide industry stakeholders towards better approaches:

- **Direct observation of recycling processes:** Future research should focus on securing access to recycling facilities to observe MS and MD strategies directly at multiple locations. This will ensure more accurate data collection, thereby improving the objectivity of the findings.

- **Emerging RR strategies:** Compare the current RR strategies to new practices developed to tackle content preservation. The efficiency rates regarding both RR and material purity could be assessed and evaluated

- **Inclusion of cross-contamination analysis:** Research should incorporate the study of cross-contamination during shredding processes. Understanding these rates is crucial for accurately assessing environmental and economic efficiency of different recycling methods. Again, this would require collaboration with recycling companies to obtain precise data.

- **Expansion of material Scope:** Future studies should analyse a broader range of water meters to capture the full spectrum of environmental and economic impacts. This would improve the generalisability and relevance of the findings across different types of water meters, including their design for disassembling potential.

- **Rigorous LCA:** A rigorous LCA could be chosen to evaluate the environmental impacts. This would provide more accurate results for the different life cycle stages instead of estimates. The results of these two methods can be compared to assess the precision of a fast-track method.

7 Conclusion

The main goal of this study was to compare the current EoL RR strategies for water meters to assess and evaluate their sustainability. As we came back to our main research question:

"How can the sustainability of an End-of-Life (EoL) resource recovery (RR) strategies of water meters be assessed and evaluated?"

We find that the answer to that question is by applying a comparative environmental, economic, and social assessment of the three pillars of sustainability for the RR strategies. By doing this, the study compares the pillar impacts of the strategies involved so one can determine how each of them scores against each other, using specific indicators to quantify their impacts.

The following sections address the research sub-questions and their role in answering the main research question. It begins by mapping current strategies and water meter trends, followed by the development of a sustainability evaluation framework, the study's results given the selected framework, and recommendations for stakeholders.

R.Q. 1: What are the water meter industry trends and the RR strategies?

The industry is transitioning from brass to plastic and composite-body meters and increasingly towards smart meters. Sustainability is increasingly recognised in the DWU sector, yet it has not been formally integrated into water meter selection beyond the in-use stage. Due to design and material composition variations, these trends directly influence EoL RR strategies.

How the EoL water meters are processed is regulated by the minimum standards set by the LAP3 and the given SC plans, which set rules and regulations for the recycling, transport and disposal of the materials. The plastics used in these meters are challenging to recycle and are mostly incinerated with energy recovery meters through the local waste management facilities. The metals and metal-containing items like PCBs inside these water meters are valuable and are recovered for recycling by RRFs. Although not considered valuable, the glass is recovered and recycled following the LAP3 regulations.

Of all the observed RRFs, the study identified two leading RR strategies. MD can be labour-intensive; the industry has improvised with costume-made tools and hydraulic and pneumatic machinery to make the work less labour-intensive. Nearly 100% of materials are recovered due to the simple designs of the meters. MS offers a faster, automated approach to RR, ideal for large volumes of water meters. This method reduces manual labour but yields lower than MD due to content loss and material cross-contamination.

R.Q. 2: What is sustainability, and how can EoL strategies be evaluated from a sustainability perspective?

Sustainability is a dynamic, value-laden concept that has been reinterpreted as having three pillars: environmental, economic, and social. How interdependent these pillars are or their degree of interaction is currently the centre of the scientific debate, centring around whether human-made capital can replace natural resources and to what extent. No "correct" definition of sustainability exists, and the interpretation can vary per person or institution. Nonetheless, they all generally share common themes of balancing environmental, social, and economic factors to safeguard the well-being of both present and future generations.

SA should be flexible and transparent and employ tools that suit the context, data availability, and stakeholders' perspectives. For EoL strategies, this can be achieved through specialised frameworks and methodologies developed in sustainability science to evaluate policies, products, or processes and determine their degree of sustainability. One framework that can be used for EoL strategies for an SA incorporating the three pillars is LCSA. This framework enables stakeholders to make informed decisions regarding EoL strategies, keeping the three pillars of sustainability in mind.

R.Q. 3: How sustainable are the current EoL RR strategies for water meters?

The study establishes that from an environmental point of view, the difference in the EoL RR strategies is most profound for the V200, where the eco-cost impact can reach up to €0.16 per water meter for the MS, depending on the yield. These meters will be mainly decommissioned in the coming years. The Multical 21, representing the smart meter where the industry is eventually headed, is also influenced by the RR strategies assessed in this study due to its PCB yield reaching up to €0.10. For the plastic body mechanical water meter, the current alternative for the V200, the difference in the EoL strategies is considerably less than the other two, only reaching €0.02 eco-cost impact.

From an economic perspective, the range of potential outcomes for MS can significantly affect the revenue of the V200, with impacts between approximately €0.14 and €0.25 since it has a scrap value of 3.68, mainly due to the brass body. The fluctuating scrap metal prices can also influence the MS cost and revenues, as they vary depending on the supply and demand of the metals and geopolitical reasons. These dynamics can make losing valuable materials via MS either more expensive or cheaper. In contrast, MD has more stable costs (€0.27)—since it involves no content loss.

MD is less attractive for the V200P and the Multical 21, particularly considering its more predictable OPEX cost of around €0.20 per meter. The Multical 21, for example, has a scrap revenue of about €0.14, leading to a net negative return if dismantled manually. The V200P still yields a modest profit (€0.05) thanks to its brass registry casing. Nevertheless, given the limited scrap value of these meters and the substantially lower costs associated with MS (€0.03 to €0.06), processing them through mechanical shredding remains the more economically sensible option.

The social implications of the SA are open to interpretation because both MD and MS have benefits and drawbacks for all meters involved. While the MD generates more labour time and includes more inclusivity, having experienced the fatigue and labour load involved with the disassembly of water meters, one cannot easily say that one method for the given meter is better from a social point of view. The MS method, which has less generated labour time for the meters involved and is not as inclusive as MD involving workers distant from the labour market but significantly reduces the ergonomic-related issues, is a significant factor to consider.

R.Q. 4: What recommendations can be made for EoL water meters, considering the sustainability impact of current strategies?

Under current EoL RR and disposal methods, choosing polymer-based water meters is not necessarily environmentally harmful. For example, given the best current environmental strategies (MD), both meters have a similar overall eco-cost impact (roughly €0.60). The practical situation is worse for the V200 because, with minor amounts of content loss, which is inevitable with MS, the V200P becomes a better option

For the plastic meters, the environmental impact depends significantly on the type of polymer used. For instance, PPS, used in the body of the Multical 21 smart meter, adds roughly five times POM's (used for V200P) environmental impact during production and incineration. Smart meters also bring added complexity due to the presence of electronics such as PCBs, which increases their eco-cost. However, these devices also offer "smart" benefits—such as improved functionality and data capabilities—that are hard to measure in purely environmental or economic terms. These electronics also limit the transport options for the eventual recycling of these products because they fall under the Amber list.

Within the existing regulatory framework (e.g., KIWA and ISO standards) and client demands (DWUs), WMMs can make improvements that increase the environmental sustainability of their water meter not just during the product and in-use stage but also considering the current EoL RR and disposal strategies. The same applies to the DWUs when selecting the meters and the EoL RR practice, where they could also have a say.

MD should be encouraged for the V200, given the eco-cost impacts and potential revenue losses that could occur with MS, even with a high yield (MS-H). Depending on the RRF's working methods and connections with the social workplaces, this option could also employ workers distant from the labour market due to impairments. Because of the complicated design of some of these meters, the RRF would require specialised tools to dismantle these meters.

Given the environmental impact and cost associated with the other two water meters, it is difficult to recommend one or the other method. While there are some environmental impacts, MS is significantly cost-effective compared to the V200. It also lowers the strain on the involved worker, making it suitable for low-value materials with little market return. This practice does come with less labour inclusivity and labour time generated.

To improve the social pillar while also providing EoL RR versatility for the meters, WMMs should incorporate design features that enable easier disassembly with minimal exertion and basic tools. For instance, models like the V200P and Multical 21 display this feature better than the V200.

Bibliography

4MS. (2019). Umwelt Bundesamt: Approval and Harmonization – 4MS Initiative. German Environment Agency. www.umweltbundesamt.de

Akber, M. Z., Thaheem, M. J., & Arshad, H. (2017). Life cycle sustainability assessment of electricity generation in Pakistan: Policy regime for a sustainable energy mix. Energy Policy, 111, 111–126. https://doi.org/10.1016/j.enpol.2017.09.022

Arregui, Enrique Cabrera Jr, & R. Cobacho. (2006). Integrated Water Meter Management . https://books.google.nl/books?id=2onbCwAAQBAJ&printsec=frontcover&hl=nl#v=onepage&q&f=false

Arregui, F. J., Pastor-Jabaloyes, L., Mercedes, A. V., & Gavara, F. J. (2020). Accuracy of solid-state residential water meters under intermittent flow conditions. Sensors (Switzerland), 20(18), 1–28. https://doi.org/10.3390/s20185339

AWWA. (2012). M6 Water Meters - Selection, Installation, Testing and Maintenance, Fifth Edition. American Water Works Association. https://doi.org/10.5942/jawwa.2013.105.0130

Barbier, E. B. (1987). The Concept of Sustainable Economic Development. Environmental Conservation, 14(2), 101–110. https://doi.org/10.1017/S0376892900011449

Bell, S., Davis, B., Javaid, A., & Essadiqi, E. (2003). Final Report on Scrap Management, Sorting and Classification of Aluminum Enhanced Recycling. https://natural-resources.canada.ca/sites/www.nrcan.gc.ca/files/mineralsmetals/pdf/mms-smm/busi-indu/rad-rad/pdf/2003-22(cf)cc-eng.pdf

Berg, C. (2019). Sustainable action: Overcoming the barriers. Sustainable Action: Overcoming the Barriers, 1–318. https://doi.org/10.4324/9780429060786/SUSTAINABLE-ACTION-CHRISTIAN-BERG

Bhambhani, A., van der Hoek, J. P., & Kapelan, Z. (2022). Life cycle sustainability assessment framework for water sector resource recovery solutions: Strengths and weaknesses. In Resources, Conservation and Recycling (Vol. 180). Elsevier B.V. https://doi.org/10.1016/j.resconrec.2021.106151

Bigum, M., Brogaard, L., & Christensen, T. H. (2012). Metal recovery from high-grade WEEE: A life cycle assessment. Journal of Hazardous Materials, 207–208, 8–14. https://doi.org/10.1016/j.jhazmat.2011.10.001

BRL-K618 [A1]. (2020). Guideline for the Kiwa Product Certificate for Water Meters. www.kiwa.nl

Caruso, M., Luchini, M., Montomoli, S., Camacho, E., Nteze, E., Gastaldo, E., & Tretjakov, A. (2020). Rethinking coastal defence and Green-energy Service infrastructures through enHancEd-durAbiLity high-performance cement-based materials D7.1-Life Cycle Sustainability Assessment: LCA, LCC and SLCA. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5d770a7e8&appId=PPGMS

CBS. (2024). Minimumloon | Centraal Bureau voor de statistiek. https://www.cbs.nl/nl-nl/visualisaties/dashboard-arbeidsmarkt/ontwikkeling-cao-lonen/minimumloon

Charalambous, B., & Laspidou, C. (2017). Dealing with the Complex Interrelation of Intermittent Supply and Water Losses. Water Intelligence Online, 16, 9781780407074. https://doi.org/10.2166/9781780407074

Crainic, M., Monica, P., & Crainic, S. (2011). OVERVIEW OF THE CURRENT STATE OF THE ART IN THE DOMAIN OF DOMESTIC WATER METERS. https://www.researchgate.net/publication/283045954

Crawford, R. J., & Martin, P. J. (2020). Processing of plastics. In Plastics Engineering (pp. 279–409). Elsevier. https://doi.org/10.1016/b978-0-08-100709-9.00004-2

De Zorg Voor de Kwaliteit van Drinkwater (BWBR0026338) (2024). https://wetten.overheid.nl/BWBR0026338/2024-01-01

De Zorg Voor de Kwaliteit van Drinkwater (BWBR0030111) (2024). https://wetten.overheid.nl/BWBR0030111/2024-01-01

Devuyst, D. (2001). Introduction to Sustainability Assessment at the Local Level. In D. Devuyst, L. Hens, & W. De Lannoy (Eds.), Sustainability Assessment and the Management of Urban Environments (pp. 1–36). Columbia University Press. https://doi.org/doi:10.7312/devu11802-intro

Diehl. (2023a). ALTAIR V5 20/190 Brass Environmental Product Declaration.

Diehl. (2023b). ALTAIR V5 Concentric Composite Environmental Product Declaration.

Directive 98/83. (1998). COUNCIL DIRECTIVE 98/83/EC: On the quality of water intended for human consumption. Official Journal of the European Communities, L 330, 32-54. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31998L0083

Directive 2184. (2020). DIRECTIVE (EU) 2020/2184 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL: on the quality of water intended for human consumption. Official Journal of the European Union, L 435, 1-62. https://eur-lex.europa.eu/legal-content/NL/TXT/?uri=CELEX:32020L2184

Dong, Y., Ng, S. T., & Liu, P. (2023). Towards the principles of life cycle sustainability assessment: An integrative review for the construction and building industry. Sustainable Cities and Society, 95. https://doi.org/10.1016/j.scs.2023.104604

Eco Cost Value. (2023). Sustainability Impact Metrics. https://www.ecocostsvalue.com/EVR/img/info-of-the-day/Volvo_case_2023.xlsx

Ekvall, T., Azapagic, A., Finnveden, G., Rydberg, T., Weidema, B. P., & Zamagni, A. (2016). Attributional and consequential LCA in the ILCD handbook. International Journal of Life Cycle Assessment, 21(3), 293–296. https://doi.org/10.1007/s11367-015-1026-0

Elkington, J. (1999). Cannibals with Forks: The Triple Bottom Line of 21st Century Business. https://doi.org/https://doi.org/10.1002/tqem.3310080106

EN 15804. (2019). Duurzaamheid van bouwwerken - Milieuverklaringen van producten - Basisregels voor de productgroep bouwproducten. In Nederlands Normalisatie-instituut. https://www.nen.nl/en/nen-en-15804-2012-a2-2019-en-265036

European Commission. (2022). Corporate Sustainability Reporting Directive. https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en

EUROSTATS. (2024, August 12). Energy prices visualisation tool. https://ec.europa.eu/eurostat/cache/infographs/energy_prices/enprices.html

Foolmaun, R. K., & Ramjeawon, T. (2013). Life cycle sustainability assessments (LCSA) of four disposal scenarios for used polyethylene terephthalate (PET) bottles in Mauritius. Environment, Development and Sustainability, 15(3), 783–806. https://doi.org/10.1007/s10668-012-9406-0

Geelhoed. (2024). Prijslijst met alle oud ijzer en metaalsoorten | Geelhoed Oud Metaalhandel. https://oudmetaalhandel.nl/prijslijst/

Ghisellini, P., Passaro, R., & Ulgiati, S. (2023). Environmental and Social Life Cycle Assessment of Waste Electrical and Electronic Equipment Management in Italy According to EU Directives. Environments - MDPI, 10(7). https://doi.org/10.3390/environments10070106

Giddings, B., Hopwood, B., & O'Brien, G. (2002). Environment, economy and society: Fitting them together into sustainable development. Sustainable Development, 10(4), 187–196. https://doi.org/10.1002/sd.199

Hu, M., Kleijn, R., Bozhilova-Kisheva, K. P., & Di Maio, F. (2013). An approach to LCSA: The case of concrete recycling. International Journal of Life Cycle Assessment, 18(9), 1793–1803. https://doi.org/10.1007/s11367-013-0599-8

IEC 60300-3-3. (2017). Dependability management - Part 3-3: Application guide - Life cycle costing. Nederlands Normalisatie-Instituut.

Islam, M. T., & Huda, N. (2018). Reverse logistics and closed-loop supply chain of Waste Electrical and Electronic Equipment (WEEE)/E-waste: A comprehensive literature review. In Resources, Conservation and Recycling (Vol. 137, pp. 48–75). Elsevier B.V. https://doi.org/10.1016/j.resconrec.2018.05.026

ISO 4064-1. (2017). Water meters for cold potable water and hot water Part 1: Metrological and technical requirements. https://www.nen.nl/nen-en-iso-4064-1-2017-en-234435#:~:text=NEN%2DEN%2DISO%204064%2D1%20applies%20to%20water%20meters,which%20indicate%20the%20integrated%20volume.

ISO 14040. (2006). Environmental management — Life cycle assessment — Principles and framework. Nederlands Normalisatie-Instituut. https://www.nen.nl/en/nen-en-iso-14040-2006-en-109085

ISO 15686-5. (2017). Buildings and constructed assets - Service life planning - Part 5: Life-cycle costing (ISO 15686-5:2017,IDT). Nederlands Normalisatie-Instituut.

ISO Statutes (2018). https://www.iso.org/files/live/sites/isoorg/files/archive/pdf/en/statutes.pdf

Janssen. (2024, August 19). Prijzen - Janssen Metaalrecycling Sittard B.V. https://janssen-metaal.nl/prijzen/

Johansson, J. G., & Björklund, A. E. (2010). Reducing life cycle environmental impacts of waste electrical and electronic equipment recycling. Journal of Industrial Ecology, 14(2), 258–269. https://doi.org/10.1111/j.1530-9290.2009.00191.x

Johnson, J. X., Mcmillan, C. A., & Keoleian, G. A. (2013). Evaluation of Life Cycle Assessment Recycling Allocation Methods. Journal of Industrial Ecology, 17(5), 700–711. https://doi.org/10.1111/JIEC.12050

JRC. (2010). International Reference Life Cycle Data System (ILCD) Handbook general guide for life cycle assessment : detailed guidance. Publications Office.

Karagoz, S., Aydin, N., & Simic, V. (2020). End-of-life vehicle management: a comprehensive review. In Journal of Material Cycles and Waste Management (Vol. 22, Issue 2, pp. 416–442). Springer. https://doi.org/10.1007/s10163-019-00945-y

KH-Metals. (2024, August 19). Oud RVS prijs - Krommenhoek Metals. https://www.kh-metals.nl/nl/oude-metalen/oud-rvs-prijs/

Kloepffer, W. (2008). Life cycle sustainability assessment of products (with Comments by Helias A. Udo de Haes, p. 95). International Journal of Life Cycle Assessment, 13(2), 89–95. https://doi.org/10.1065/lca2008.02.376

Klöpff, W., Mary, ·, Curran, A., & Finkbeiner, M. (2016). LCA Compendium-The Complete World of Life Cycle Assessment Series Editors: Special Types of Life Cycle Assessment. http://www.springer.com/series/11776

Kuhlman, T., & Farrington, J. (2010). What is sustainability? In Sustainability (Vol. 2, Issue 11, pp. 3436–3448). MDPI. https://doi.org/10.3390/su2113436

Lam, W. C., de Regel, S., Peeters, K., & Spirinckx, C. (2021). Applying life cycle sustainability assessment to maximise the innovation potential of new technologies for critical components in wind turbines. Journal of Physics: Conference Series, 2042(1). https://doi.org/10.1088/1742-6596/2042/1/012103

LAP3. (2017). Landelijk afvalbeheerplan 2017-2029. https://lap3.nl/beleidskader/beleidskader-geheel/

Li, P., Dahmus, J., Guldberg, S., Riddervold, H. O., & Kirchain, R. (2011). How much sorting is enough: Identifying economic and scrap-reuse benefits of sorting technologies. Journal of Industrial Ecology, 15(5), 743–759. https://doi.org/10.1111/j.1530-9290.2011.00365.x

Lu, B., Li, B., Wang, L., Yang, J., Liu, J., & Wang, X. V. (2014). Reusability based on life cycle sustainability assessment: Case study on WEEE. Procedia CIRP, 15, 473–478. https://doi.org/10.1016/j.procir.2014.06.046

Luthin, A., Crawford, R. H., & Traverso, M. (2023). Demonstrating circular life cycle sustainability assessment – a case study of recycled carbon concrete. Journal of Cleaner Production, 433. https://doi.org/10.1016/j.jclepro.2023.139853

Mancini, L., & Sala, S. (2018). Social impact assessment in the mining sector: Review and comparison of indicators frameworks. Resources Policy, 57, 98–111. https://doi.org/10.1016/j.resourpol.2018.02.002

March, H., Morote, Á. F., Rico, A. M., & Saurí, D. (2017). Household smart water metering in Spain: Insights from the experience of remote meter reading in alicante. Sustainability (Switzerland), 9(4). https://doi.org/10.3390/su9040582

Martínez-Blanco, J., Lehmann, A., Muñoz, P., Antón, A., Traverso, M., Rieradevall, J., & Finkbeiner, M. (2014). Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment. Journal of Cleaner Production, 69, 34–48. https://doi.org/10.1016/j.jclepro.2014.01.044

Matulis, D. (2020). The Development of Testing Solutions for Plastic Injection Moulded Water Meter Housing Master's Final Degree Project.

Meadowcroft, J. (2024). Sustainability | Description, Theories, & Practices | Britannica. https://www.britannica.com/science/sustainability

Metal Recycling. (2014). Recycling watermeters van Vitens door Genius Metalrecycling BV - YouTube. https://www.youtube.com/watch?v=R8kBUy8Kccs&t=1s

Munn, Z., Peters, M. D. J., Stern, C., Tufanaru, C., McArthur, A., & Aromataris, E. (2018). Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. BMC Medical Research Methodology, 18(1). https://doi.org/10.1186/s12874-018-0611-x

MVO. (2022). Aan de slag met het materialenpaspoort | Enhanced Reader. Maatschappelijke Verantwoord Ondernemen - Nederland. https://madaster.com/app/uploads/sites/2/2022/10/Aan-de-slag-met-het-materialenpaspoort.pdf

Papo, M., & Corona, B. (2022). Life cycle sustainability assessment of non-beverage bottles made of recycled High Density Polyethylene. Journal of Cleaner Production, 378. https://doi.org/10.1016/j.jclepro.2022.134442

Participation Act. (2024). wetten.nl - Regeling - Participatiewet - BWBR0015703. Ministerie van Sociale Zaken en Werkgelegenheid. https://wetten.overheid.nl/BWBR0015703/2024-07-01

Pearce, D. W., Atkinson, G. D., & Dubourg, W. R. (1994). The Economics of Sustainable Development. Annual Review of Environment and Resources, 19(Volume 19,), 457–474. https://doi.org/10.1146/ANNUREV.EG.19.110194.002325

Pinter, L. (2009, August 7). BellagioSTAMP: SusTainability Assessment and Measurement Principles brochure | International Institute for Sustainable Development. https://www.iisd.org/publications/bellagiostamp-sustainability-assessment-measurement-principles-brochure

Pinter, L., Hardi, P., Martinuzzi, A., & Hall, J. (2012). Bellagio STAMP: Principles for sustainability assessment and measurement. Ecological Indicators, 17, 20–28. https://doi.org/10.1016/j.ecolind.2011.07.001

Plastics Europe. (2022). THE CIRCULAR ECONOMY FOR PLASTICS. https://plasticseurope.org/

Pope, J., Annandale, D., & Morrison-Saunders, A. (2004). Conceptualising sustainability assessment. Environmental Impact Assessment Review, 24(6), 595–616. https://doi.org/10.1016/j.eiar.2004.03.001

Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. Sustainability Science, 14, 681–695. https://doi.org/10.1017/S0376892900011449

Regulation 1252. (2024). Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020Text with EEA relevance. http://data.europa.eu/eli/reg/2024/1252/oj

Regulation on the Employment of Prisoners Act. (2021). wetten.nl - Regeling - Regeling arbeid gedetineerden - BWBR0010172. Ministerie van Sociale Zaken en Werkgelegenheid. https://wetten.overheid.nl/BWBR0010172/2021-12-01

Reuters. (2024). China bans export of critical minerals to US as trade tensions escalate | Reuters. https://www.reuters.com/markets/commodities/china-bans-exports-gallium-germanium-antimony-us-2024-12-03/

Rijksoverheid. (2010). Ministerie van Binnenlandse Zaken. https://www.rijksoverheid.nl/onderwerpen/certificaten-keurmerken-en-meetinstrumenten/normen-voor-producten-diensten-of-processen

RIVM. (2016). Materialen en chemicaliën in contact met drinkwater. https://www.rivm.nl/drinkwater/drinkwaterkwaliteit/materialen-chemicalien-drinkwater

Rubin, R. S., Castro, M. A. S. De, Brandão, D., Schalch, V., & Ometto, A. R. (2014). Utilization of Life Cycle Assessment methodology to compare two strategies for recovery of copper from printed circuit board scrap. Journal of Cleaner Production, 64, 297–305. https://doi.org/10.1016/j.jclepro.2013.07.051

Ruhrberg, M. (2006). Assessing the recycling efficiency of copper from end-of-life products in Western Europe. Resources, Conservation and Recycling, 48(2), 141–165. https://doi.org/10.1016/j.resconrec.2006.01.003

Sala, S., Ciuffo, B., & Nijkamp, P. (2015). A systemic framework for sustainability assessment. Ecological Economics, 119, 314–325. https://doi.org/10.1016/j.ecolecon.2015.09.015

Sala, S., Farioli, F., & Zamagni, A. (2013). Progress in sustainability science: Lessons learnt from current methodologies for sustainability assessment: Part 1. International Journal of Life Cycle Assessment, 18(9), 1653–1672. https://doi.org/10.1007/s11367-012-0508-6

Sala, S., & Garcia, J. C. (2016). Life cycle assessment for the impact assessment of policies. https://doi.org/10.2788/318544

Saturn Machines. (2024). Guide to different types of industrial blades — Saturn Machine Knives. https://saturnmachineknives.co.uk/blogs/news/guide-to-different-types-of-industrial-blades

Scoones, I. (2016). The Politics of Sustainability and Development. In Annual Review of Environment and Resources (Vol. 41, pp. 293–319). Annual Reviews Inc. https://doi.org/10.1146/annurev-environ-110615-090039

Sensus. (2012). White Paper Composite Meters Have History. https://cdn2.webdamdb.com/md_xjHwDmzwEV1l.jpg.pdf?v=1

Sønderlund, A. L., Smith, J. R., Hutton, C., & Kapelan, Z. (2014). Using smart meters for household water consumption feedback: Knowns and unknowns. Procedia Engineering, 89, 990–997. https://doi.org/10.1016/j.proeng.2014.11.216

THValve. (2020). The difference and application of stainless steel 430, 304, 316. Tanghai Valve. https://www.tanghaivalve.com/the-difference-and-application-of-stainless-steel-430-304-316/

Trading Economics. (2024). Copper & Zinc - Price - Chart - Historical Data. https://tradingeconomics.com/commodity/zinc

Ueberschaar, M., Geiping, J., Zamzow, M., Flamme, S., & Rotter, V. S. (2017). Assessment of element-specific recycling efficiency in WEEE pre-processing. Resources, Conservation and Recycling, 124, 25–41. https://doi.org/10.1016/j.resconrec.2017.04.006

UNEP. (2020). Guidelines for SOCIAL LIFE CYCLE ASSESSMENT OF PRODUCTS AND ORGANIZATIONS 2020. https://www.lifecycleinitiative.org/wp-content/uploads/2021/01/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-22.1.21sml.pdf

UNEP/SETAC. (2012). Towards a life cycle sustainability assessment. Making informed choices on products. https://wedocs.unep.org/bitstream/handle/20.500.11822/8001/UNEP_LifecycleInit_Dec_FINAL.pdf?sequence=3&amp%3BisAllowed=

Van Der Velden, N. M., Patel, M. K., & Vogtländer, J. G. (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. International Journal of Life Cycle Assessment, 19(2), 331–356. https://doi.org/10.1007/s11367-013-0626-9

Van Yken, J., Boxall, N. J., Cheng, K. Y., Nikoloski, A. N., Moheimani, N. R., & Kaksonen, A. H. (2021). E-waste recycling and resource recovery: A review on technologies, barriers and enablers with a focus on oceania. In Metals (Vol. 11, Issue 8). MDPI AG. https://doi.org/10.3390/met11081313

Van Zyl, J. E. (2011). Introduction to integrated water meter management. Water Research Commission. https://www.esi-africa.com/wp-content/uploads/Kobus_vanZyl.pdf

VEWIN. (2018). Handboek RKW voor de Vewin - Regeling Kwaliteitsborging Watermeters (RKW). www.kiwa.nl

Vinyes, E., Oliver-Solà, J., Ugaya, C., Rieradevall, J., & Gasol, C. M. (2013). Application of LCSA to used cooking oil waste management. International Journal of Life Cycle Assessment, 18(2), 445–455. https://doi.org/10.1007/s11367-012-0482-z

Vogtländer, J. (2012). Lca: a practical guide for students, designers and business managers. https://www.researchgate.net/publication/258220969_Lca_a_practical_guide_for_students_designers_and_business_managers

Vogtländer, J., Vogtländer, J. G., & Mestre, A. C. (2009). The Eco-costs/Value Ratio for quantitative, LCA based, assessment of sustainability. https://www.researchgate.net/publication/258220975_LCA-based_assessment_of_sustainability_the_Eco-costsValue_Ratio_EVR#:~:text=The%20ratio%20of%20eco%2Dcost,for%20pollution%20and%20materials%20depletion.

Wäger, P. A., Hischier, R., & Eugster, M. (2011). Environmental impacts of the Swiss collection and recovery systems for Waste Electrical and Electronic Equipment (WEEE): A follow-up. Science of the Total Environment, 409(10), 1746–1756. https://doi.org/10.1016/j.scitotenv.2011.01.050

Wagner, F., Peeters, J. R., De Keyzer, J., Janssens, K., Duflou, J. R., & Dewulf, W. (2019). Towards a more circular economy for WEEE plastics – Part A: Development of innovative recycling strategies. Waste Management, 100, 269–277. https://doi.org/10.1016/j.wasman.2019.09.026

WEEE Directive. (2012). Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0038:0071:EN:PDF

Wiersum, K. F. (1995). 200 Years of Sustainability in Forestry: Lessons from History. Environmental Management , 19, 321–329. https://doi.org/https://doi.org/10.1007/BF02471975

WSR. (2024). Waste shipments - European Commission. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-shipments_en

Yu, M., & Halog, A. (2015). Solar photovoltaic development in Australia-a life cycle sustainability assessment study. Sustainability (Switzerland), 7(2), 1213–1247. https://doi.org/10.3390/su7021213

Zanni, S., Awere, E., & Bonoli, A. (2020). Life cycle sustainability assessment: An ongoing journey. In Life Cycle Sustainability Assessment for Decision-Making: Methodologies and Case Studies (pp. 57–93). Elsevier. https://doi.org/10.1016/B978-0-12-818355-7.00004-X

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Appendix

A.1 Section: Empirical self-study

A controlled laboratory environment was set up to familiarise with the design and disassembly process of the meters. This simulation was informed by data gathered during the field research research.

The empirical study was done with conventional tools suggested by the RRFs. The study identified the best tool combination for dismantling various types of water meters, which included hammers, screwdrivers, multiple types of pliers, and crucially, a vise (see **Fig. 28**). Subsequently, adding a chisel was found to improve the efficiency of the process for specific water meter models. Pneumatic and hydraulic machinery were not used because of a lack of access to these machines.

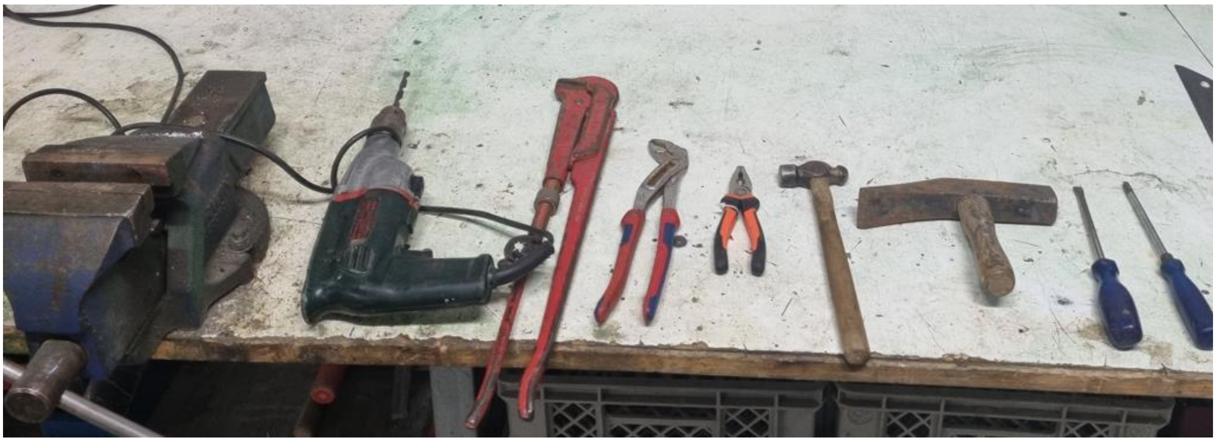


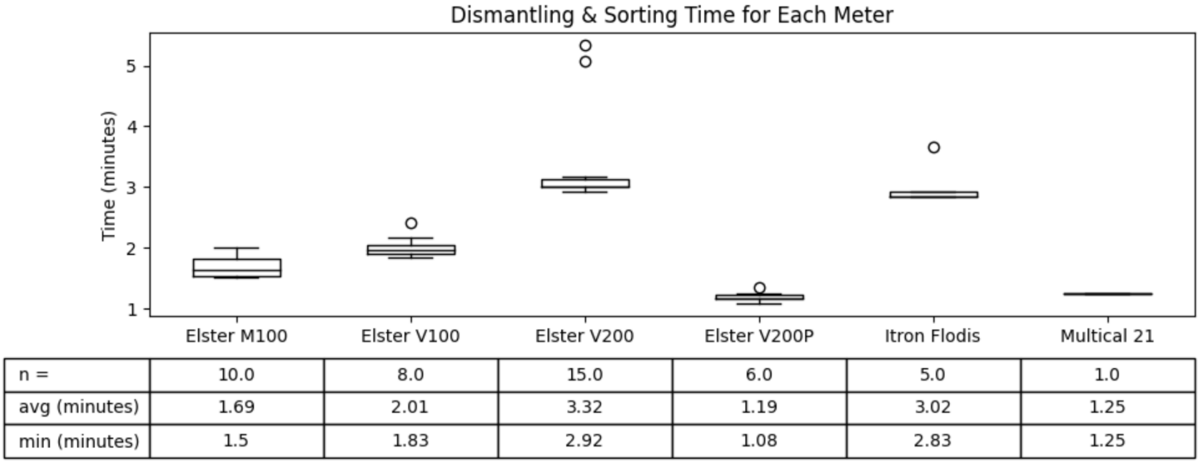
Figure 28: Tools used for the disassembly method. From left to right: Vise clamp, electric drill, multiple pliers, two sets of hammers and a flat and Philips head screwdriver.

The empirical study was divided into two primary components:

1. **Disassembly time analysis**: This component aimed to quantify the time required to Liberate and sort the different water meters manually. The time required for disassembly, including sorting into different streams, was tracked and standardised to the nearest 5-second increment.
2. **Material composition analysis**: This analysis aimed to identify the composition of a typical water meter by measuring the weight of the different materials within different water meters.

During the material composition analysis, materials weighing less than 3 grams, such as small springs and magnets, were excluded from further consideration. The following chapters show the results of the empirical study.

A.1.1 Disassembly & sorting time analysis



	Elster M100	Elster V100	Elster V200	Elster V200P	Itron Flodis	Multical 21
n =	10.0	8.0	15.0	6.0	5.0	1.0
avg (minutes)	1.69	2.01	3.32	1.19	3.02	1.25
min (minutes)	1.5	1.83	2.92	1.08	2.83	1.25

Figure 29: Boxplot illustrating various meter models' disassembly and sorting times. The boxplot provides a detailed account of the number of meters processed ("n") and the corresponding time required.

Two samples were analysed for the Multical 21 meters; however, one was partially disassembled before the study. The remaining models had enough samples available.

The outliers observed in the data, particularly for the V200 model, reflect the initial attempts to navigate its complex design rather than standard disassembly efforts. Notably, the pace of work across all meters was deliberately casual, with no emphasis on speed. This approach ensured the data reflected the disassembly process under typical working conditions.

The meters have been categorised into two groups based on the ease with which the meters can be dismantled and the materials sorted, as displayed in **Fig. 30**:

- **S1: Easy dismantling**—This category includes models V200P, V100, M100 and Multical 21, noted for their straightforward disassembly and effortless sorting of material streams. The main difficulty was primarily opening the chambers; beyond that, the sorting and disassembly of the parts posed no challenge.
- **S2: Moderate Difficulty in Material Separation**—As represented by model V200 and Itron Flodis, these meters pose more challenges in disassembly and material separation than S1. This is due to the complex two-compartment designs of the Tombac registry can on top and the sealed brass body with a pressure plate bottom.

Figure 30: Dismantled meters. Left to right S1: Elster V200P, V100, M100, Kamstrup Multical 21. S2: Elster V200, Itron Flodis

It is important to acknowledge that increased experience with disassembling a particular meter type correlated with improved time efficiency. Workers who do this regularly will improve until a certain point. While the S1 meters were relatively straightforward to disassemble and sort, the S2 meters presented more complexity. The differences in the ease of disassembly across these meter designs are displayed in the boxplot graph. The yield of the disassembly process was 100%.

Fig. 31 presents images from the various stages of the disassembly process alongside the recovered materials. Despite the high yield, the disassembly processes, mainly for S2 volumetric meters, were not easily performed. Removing the black O-ring (7) atop the pressure plate (8) proved highly difficult, requiring a considerable amount of strength. The efficiency of this step could have been significantly improved with the use of specialised machinery and custom clamps, as employed in professional RRFs.

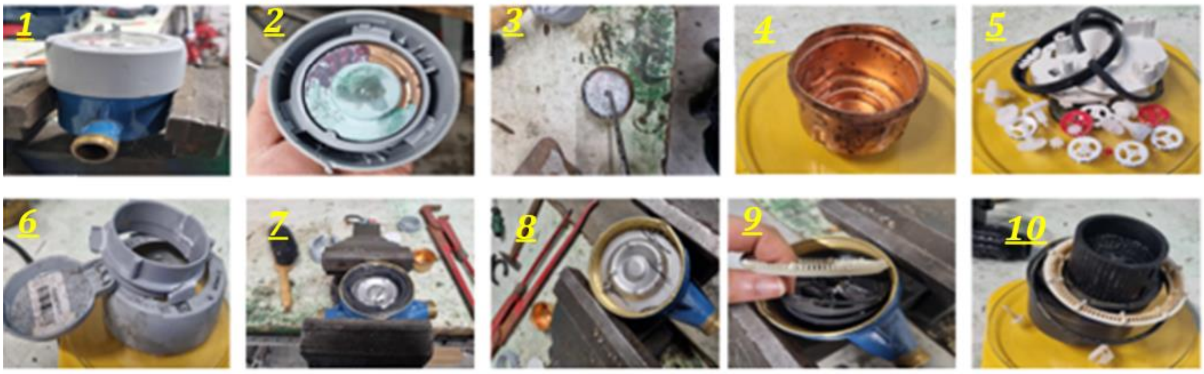


Figure 31: Images of the disassembly process for the Elster V200 Water Meter

A.1.2 Water meter material composition

The following subsections discuss the different materials used in the water meters for the SA. All the models for the V200P and Multical 21 examined shared the same weight, with minor differences below 5 grams. However, significant weight variations exist among V200 models produced throughout the years. The model representing most BW assets was selected for the assessment.

A.1.2.1 Polymers

The internal components of the V200P and V200 meters were mainly composed of plastics. The main distinction between these two models lies in the material of the main body. The plastic body of the Elster V200P was identified as Polyoxymethylene (POM), a high-performance engineering thermoplastic known for its stiffness and creep resistance (source: WMM II).

The specific types of plastics used in the internal components of the V200 and V200P meters could not be identified due to confidentiality and variations in materials over time. Additionally, the components of these meters are sourced from different suppliers, sometimes located in different countries, leading to minor differences in weight and plastic types (source: WMM II). For this study, the author assumed that the unidentified plastics were also POM.

The Multical 21 meter is primarily composed of polymer composites, with the types of plastics and materials clearly labelled following the WEEE Directive (2012). These polymers are reinforced with glass fibres to achieve high strength and durability. The main body is made of PPS GF40, while other plastic parts are a combination of PVC and PC GF10.

A.1.2.2 Metals

Both V200 and V200P meters contain a registry case comprising 85% copper and 15% zinc, known in the industry as Tombac (source: RCI). Tombac is favoured for its magnetic and water-resistant properties and is used in brass and plastic-bodied water meters observed during this study. The brass body of the V200 meter is made from CW617N, a machinable brass composed of at least 57% copper (CuZn40Pb), with the remainder primarily zinc and a small amount of lead to improve corrosion resistance and machinability (4MS, 2019; AWWA, 2012). This type of brass is commonly used in materials that come into contact with potable water and is often recycled within the industry (Ruhrberg, 2006).

The non-magnetic steel in the V200 was confirmed as Stainless Steel 316 (source: WMM II). This material is used as a tightly fitting pressure plate to separate the bottom compartment of the meter from the top. Stainless Steel 316 is well-known for its corrosion resistance, particularly in moist environments, and its non-magnetic properties (THValve, 2020). The other magnetic steels, in small amounts within all the models, were assumed to be Stainless Steel 430, a commonly used material in the industry (THValve, 2020).

A.1.2.3 Glass

The tombac casing in the V200 and V200P and the lid of the Multical 21 all contain tempered float glass (source: RRF I & WMM I). This type of glass is prevalent within the industry for its durability and resistance to temperature fluctuations. It is primarily composed of silica and lime. When breaking, the glass shatters into small pieces instead of large, sharp fragments (source RRF III).

A.1.2.4 Other materials

The Multical 21 meter includes a PCB with internal circuits and lithium batteries. The lithium battery used in this meter is a clearly labelled thionyl chloride lithium battery. Additionally, bentonite clay is a minor component in the Multical 21. Bentonite is a type of absorbent clay often used for its swelling and moisture-absorbing properties and contributes to the meter's electronics durability.

A.2 Section: Methods interview approach

The semi-structured interviews were conducted in person, via Microsoft Teams, or through email or phone to ensure data collection where further insights were needed. Participant selection was based on the author's judgment, targeting individuals with knowledge relevant to the subject matter. This strategy sometimes led to a snowball sampling effect, where participants recommended other potential candidates.

A.2.1 Interview execution

Before the interviews started, interviewees were presented with an informed consent document. The researcher explained the document's contents, the research objectives, and the safeguards to related to the recordings. The consent form sought permission for recording and transcribing the interviews. Upon completion of the project, audio files are scheduled for deletion to protect interviewees' privacy, as names and other personal details have been omitted from this thesis except for the case study company BW and Water is our World (WoW). The latter insisted on being mentioned. The consent form is available in the following section.

If the interviewee was comfortable being recorded, the conversation was captured using a laptop or a cellular device and later transcribed word for word. If not, keynotes were taken in Microsoft Word, and the questions and responses were transcribed as accurately as possible during the interview.

A.2.2 Data extraction

Data extraction from the interviews used Atlas.ti, a licensed tool designed for qualitative data analysis. The transcribed interviews were examined through thematic analysis to identify, assess, and interpret patterns within the data, thereby deriving meaningful themes and codes. This was done following the framework provided by Castleberry et al. (2009) in their work "Thematic Analysis of Qualitative Research Data". The analysis was carried out in three main stages:

- **Compiling**: The data was organised into a manageable format. The interviews were formatted with only the information relevant to the study, preparing for the subsequent analysis phase.
- **Disassembling**: Interviews were revisited to familiarise with the content, aiding later grouping. The disassembly step involves deconstructing the data by creating themes of similar topics. This process was done through coding, facilitating the identification of common themes, concepts, and similarities.
- **Reassembling**: Identified codes and phrases were categorised under broader themes showcasing significant similarities. This hierarchical arrangement allowed for a comprehensive understanding of overarching concepts and themes, simplifying data extraction through various levels of detail.

A.2.3 Informed consent

Project informatieblad

Project Information	
Project Titel	Recovery of Resources from Watermeters
Project duur	7 month from October 25, 2023
Hoofdonderzoeker	Name Illias Timori Email i.timori@student.tudelft.nl

Deelname aan dit onderzoek

Door deel te nemen aan dit onderzoek draag je bij aan het vergroten van ons begrip van het recyclen van watermeters en de milieugevolgen daarvan. Houd er rekening mee dat er geen financiële vergoeding is voor je deelname aan dit onderzoek. Voordat je besluit deel te nemen, willen we benadrukken dat je deelname volledig vrijwillig is en moedigen we je aan om de verstrekte informatie over dit onderzoek en de onderzoeksdoelstellingen zorgvuldig te lezen.

Je wordt aangemoedigd om de tijd te nemen om je deelname te overwegen en om vragen te stellen of verduidelijking te vragen over alle aspecten van het onderzoek. Je hebt het recht om vragen te stellen over eventuele zorgen voordat je het toestemmingsformulier ondertekent, en je hebt het recht om duidelijke en begrijpelijke antwoorden te ontvangen op elk moment, of het nu voor, tijdens of na je deelname aan dit onderzoek is.

Mocht je vragen hebben of aanvullende informatie nodig hebben, aarzel dan niet om vragen te stellen of contact op te nemen met de hoofdonderzoeker, Illias Timori, op i.timori@student.tudelft.nl of +31681822418 voordat je besluit deel te nemen aan dit onderzoek.

Doel van het onderzoek

Het Resource Recovery from Watermeters project beoogt de implementatie van de principes van de Circulaire Economie in de waterleveringssector te faciliteren door het ontwikkelen van de nodige concepten, technologische oplossingen voor materialen die uit watermeters worden teruggewonnen. Dit project richt zich op het bevorderen van het recyclingproces van watermeters door de terugwinning van waardevolle hulpbronnen zoals metalen en kunststoffen te optimaliseren.

Een belangrijk onderdeel van het project is de samenwerking met Brabant Water N.V. en de Technische Universiteit Delft, gericht op het ontwikkelen van efficiënte demontage- en sorteermethoden voor watermeters. Uw deelname aan deze studie omvat het geïnterviewd worden over uw ideeën en verwachtingen met betrekking tot de efficiënte recycling en terugwinning van hulpbronnen uit watermeters.

Toestemmingsformulier

Net als bij elke onderzoeksactiviteit is het risico op een schending van de vertrouwelijkheid altijd mogelijk. Naar ons beste vermogen zullen uw reacties vertrouwelijk blijven. We zullen eventuele risico's minimaliseren door ervoor te zorgen dat persoonlijke identificatiegegevens niet gekoppeld worden aan interviewreacties. Als directe citaten worden gebruikt, zullen deze geanonimiseerd worden, tenzij expliciete toestemming wordt gegeven.

Dit onderzoek ondersteunt de principes van open data; persoonlijke informatie en gevoelige gegevens zullen echter vertrouwelijk blijven en zullen niet worden opgenomen in publiekelijk beschikbare datasets.

Voordat u toestemming geeft om deel te nemen aan het onderzoek, verzoeken wij u het informatieblad voor deelnemers te lezen en elke box hieronder te markeren met uw initialen als u akkoord gaat. Uw deelname aan deze studie is volledig vrijwillig, en u kunt op elk moment zonder enige straf terugtrekken. U bent vrij om vragen of onderwerpen die u niet wilt bespreken weg te laten. Mocht u willen dat uw gegevens uit de studie verwijderd worden, informeer ons dan binnen een maand na het interview.

Voor vragen of verdere informatie, neemt u alstublieft contact op met Illias Timori op i.timori@student.tudelft.nl of +31681822418, die de verantwoordelijke onderzoeker voor deze studie is.

Gelieve elke verklaring te markeren	
Ik bevestig dat ik het informatieblad heb gelezen en volledig begrijp wat er van mij wordt verwacht in deze studie.	
Ik bevestig dat ik de gelegenheid heb gehad om vragen te stellen en antwoorden te krijgen.	
Ik begrijp dat er aantekeningen worden gemaakt zonder enige verwijzing die kan leiden tot mijn of andermans identiteit die herkend wordt.	
Ik begrijp dat er [geen] vergoeding is voor deelname aan deze studie.	
Ik begrijp dat mijn deelname vrijwillig is en dat ik op elk moment kan stoppen zonder opgaaf van redenen, zonder dat dit mijn medische zorg of juridische rechten beïnvloedt.	
Ik begrijp dat mijn persoonlijke gegevens volledig anoniem worden gehouden en vertrouwelijk worden behandeld.	
Ik begrijp dat, zodra mijn gegevens zijn geanonimiseerd en opgenomen in thema's, het misschien niet mogelijk is om ze terug te trekken, hoewel er elke poging zal worden gedaan om mijn gegevens te verwijderen, tot het moment van publicatie.	
Ik begrijp dat de informatie uit mijn interview/observaties wordt samengevoegd met de reacties van andere deelnemers, geanonimiseerd en algemene conclusies kunnen worden gepubliceerd.	
Ik geef toestemming voor het gebruik van informatie en citaten uit mijn interview in rapporten, conferenties en trainingsbijeenkomsten.	
Ik begrijp dat alle informatie die ik geef strikt vertrouwelijk en anoniem blijft, tenzij wordt gedacht dat er een risico is op schade aan mijzelf of anderen, in welk geval de hoofdonderzoeker deze informatie met zijn/haar onderzoekssupervisor zal/moet delen.	
Ik geef toestemming aan de Technische Universiteit Delft om aantekeningen of audio-opnames van het interview voor 5 jaar na afloop van de studie te bewaren.	
Ik geef toestemming om deel te nemen aan bovengenoemde studie.	

B Section: Sustainability assessment

This appendix section includes information and calculations relevant to the sustainability assessment. Section E provides a portion of the information related to the Python calculations.

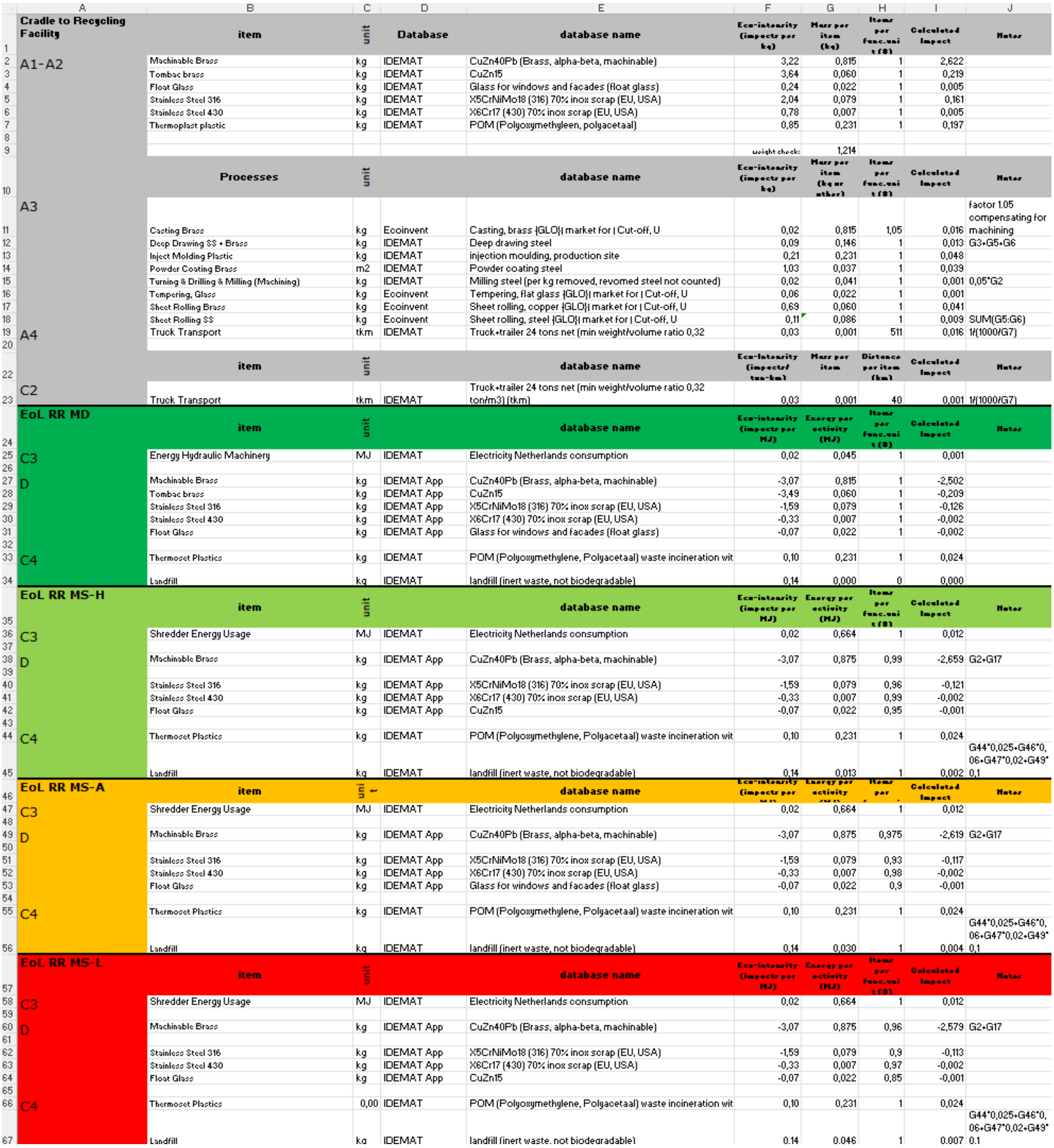
B.1 Fast-Track Life Cycle Assessment

The LCA for this study utilises the "Fast Track" LCA approach, also known as the “Phillips method,” to expedite the assessment process (Vogtländer, 2012). LCAs are broadly categorised into the classical rigorous LCA and the Fast-Track LCA (Vogtländer, 2012). The classical method involves a thorough assessment of environmental impacts from the ground up, focusing primarily on Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) (Vogtländer, 2012). In contrast, the Fast-Track method provides a quicker approach to conducting an LCA, commonly used for comparing design alternatives (Vogtländer, 2012).

The Fast-Track method utilises LCI data sourced from databases such as Ecoinvent and Industrial Design & Engineering Materials (IDEMAT), where the data is precompiled based on selected LCIs from peer-reviewed papers and scientific databases from universities (Vogtländer, 2012). This method employs Excel lookup tables to multiply inputs (materials or energy) and outputs (environmental impact) with specific factors to determine single indicators. These factors are derived using Simapro LCA software and data from the Ecoinvent database (Vogtländer, 2012). This approach streamlines the process by eliminating the need for researchers to manually perform steps involved in single indicator calculation, such as classification, characterisation, normalisation, and weighting (Vogtländer, 2012).

The databases used follow standardised rules of ISO 14040, ISO 14044, EN15804, and the LCA handbook of the ILCD (Vogtländer, 2012). This ensures that the Fast-Track LCA adheres to recognised international standards while providing a more efficient means of conducting environmental impact assessments (Vogtländer, 2012).

B.2 V200 impact calculations

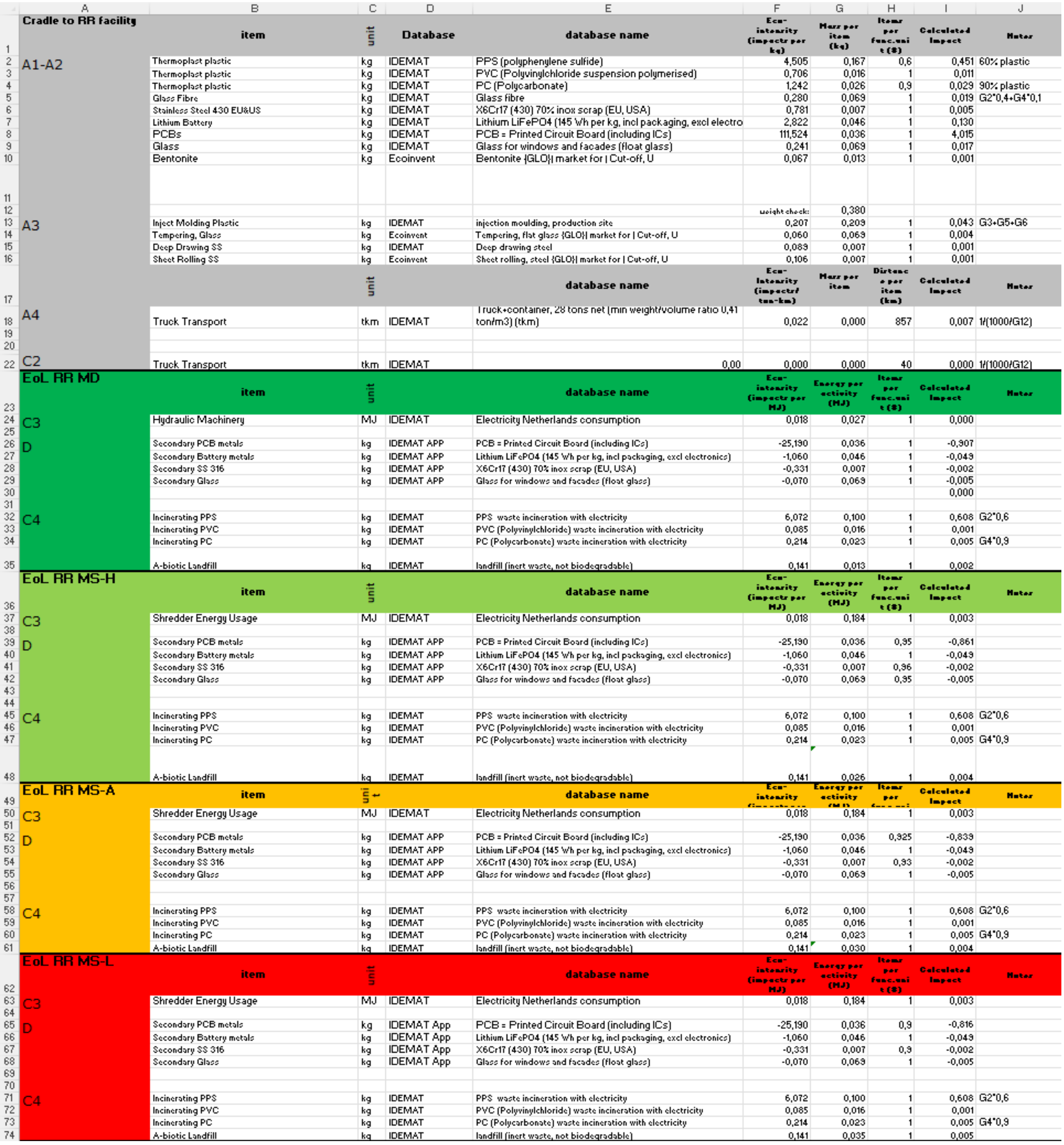


	A	B	C	D	E	F	G	H	I	J
1	**Cradle to Recycling Facility**	**item**	**unit**	**Database**	**database name**	**Eco-intensity (impacts per kg)**	**Mass per item (kg)**	**Items per func.unit (#)**	**Calculated Impact**	**Notes**
2	A1-A2	Machinable Brass	kg	IDEMAT	CuZn40Pb (Brass, alpha-beta, machinable)	3,22	0,815	1	2,622	
3		Tombac brass	kg	IDEMAT	CuZn15	3,64	0,060	1	0,219	
4		Float Glass	kg	IDEMAT	Glass for windows and facades (float glass)	0,24	0,022	1	0,005	
5		Stainless Steel 316	kg	IDEMAT	X5CrNiMo18 (316) 70% inox scrap (EU, USA)	2,04	0,079	1	0,161	
6		Stainless Steel 430	kg	IDEMAT	X6Cr17 (430) 70% inox scrap (EU, USA)	0,78	0,007	1	0,005	
7		Thermoplast plastic	kg	IDEMAT	POM (Polyoxymethyleen, polyacetaal)	0,85	0,231	1	0,197	
8										
9						weight check:	1,214			
10		**Processes**	**unit**		**database name**	**Eco-intensity (impacts per kg)**	**Mass per item (kg or other)**	**Items per func.unit (#)**	**Calculated Impact**	**Notes**
11	A3	Casting Brass	kg	Ecoinvent	Casting, brass {GLO}| market for | Cut-off, U	0,02	0,815	1,05	0,016	factor 1.05 compensating for machining
12		Deep Drawing SS + Brass	kg	IDEMAT	Deep drawing steel	0,09	0,146	1	0,013	G3+G5+G6
13		Inject Molding Plastic	kg	IDEMAT	injection moulding, production site	0,21	0,231	1	0,048	
14		Powder Coating Brass	m2	IDEMAT	Powder coating steel	1,03	0,037	1	0,039	
15		Turning & Drilling & Milling (Machining)	kg	IDEMAT	Milling steel (per kg removed, revomed steel not counted)	0,02	0,041	1	0,001	0,05*G2
16		Tempering, Glass	kg	Ecoinvent	Tempering, flat glass {GLO}| market for | Cut-off, U	0,06	0,022	1	0,001	
17		Sheet Rolling Brass	kg	Ecoinvent	Sheet rolling, copper {GLO}| market for | Cut-off, U	0,69	0,060	1	0,041	
18		Sheet Rolling SS	kg	Ecoinvent	Sheet rolling, steel {GLO}| market for | Cut-off, U	0,11	0,086	1	0,009	SUM(G5:G6)
19	A4	Truck Transport	tkm	IDEMAT	Truck+trailer 24 tons net (min weight/volume ratio 0,32	0,03	0,001	511	0,016	1/(1000/G7)
20										
22		**item**	**unit**		**database name**	**Eco-intensity (impacts/ ton-km)**	**Mass per item**	**Distance per item (km)**	**Calculated Impact**	**Notes**
23	C2	Truck Transport	tkm	IDEMAT	Truck+trailer 24 tons net (min weight/volume ratio 0,32 ton/m3) (tkm)	0,03	0,001	40	0,001	1/(1000/G7)
24	**EoL RR MD**	**item**	**unit**		**database name**	**Eco-intensity (impacts per MJ)**	**Energy per activity (MJ)**	**Items per func.unit (#)**	**Calculated Impact**	**Notes**
25	C3	Energy Hydraulic Machinery	MJ	IDEMAT	Electricity Netherlands consumption	0,02	0,045	1	0,001	
26										
27	D	Machinable Brass	kg	IDEMAT App	CuZn40Pb (Brass, alpha-beta, machinable)	-3,07	0,815	1	-2,502	
28		Tombac brass	kg	IDEMAT App	CuZn15	-3,49	0,060	1	-0,209	
29		Stainless Steel 316	kg	IDEMAT App	X5CrNiMo18 (316) 70% inox scrap (EU, USA)	-1,59	0,079	1	-0,126	
30		Stainless Steel 430	kg	IDEMAT App	X6Cr17 (430) 70% inox scrap (EU, USA)	-0,33	0,007	1	-0,002	
31		Float Glass	kg	IDEMAT App	Glass for windows and facades (float glass)	-0,07	0,022	1	-0,002	
32										
33	C4	Thermoset Plastics	kg	IDEMAT	POM (Polyoxymethylene, Polyacetaal) waste incineration wit	0,10	0,231	1	0,024	
34		Landfill	kg	IDEMAT	landfill (inert waste, not biodegradable)	0,14	0,000	0	0,000	
35	**EoL RR MS-H**	**item**	**unit**		**database name**	**Eco-intensity (impacts per MJ)**	**Energy per activity (MJ)**	**Items per func.unit (#)**	**Calculated Impact**	**Notes**
36	C3	Shredder Energy Usage	MJ	IDEMAT	Electricity Netherlands consumption	0,02	0,664	1	0,012	
37										
38	D	Machinable Brass	kg	IDEMAT App	CuZn40Pb (Brass, alpha-beta, machinable)	-3,07	0,875	0,99	-2,659	G2+G17
39										
40		Stainless Steel 316	kg	IDEMAT App	X5CrNiMo18 (316) 70% inox scrap (EU, USA)	-1,59	0,079	0,96	-0,121	
41		Stainless Steel 430	kg	IDEMAT App	X6Cr17 (430) 70% inox scrap (EU, USA)	-0,33	0,007	0,99	-0,002	
42		Float Glass	kg	IDEMAT App	CuZn15	-0,07	0,022	0,95	-0,001	
43										
44	C4	Thermoset Plastics	kg	IDEMAT	POM (Polyoxymethylene, Polyacetaal) waste incineration wit	0,10	0,231	1	0,024	
45		Landfill	kg	IDEMAT	landfill (inert waste, not biodegradable)	0,14	0,013	1	0,002	G44*0,025+G46*0,06+G47*0,02+G49*0,1
46	**EoL RR MS-A**	**item**	**unit**		**database name**	**Eco-intensity (impacts per**	**Energy per activity**	**Items per**	**Calculated Impact**	**Notes**
47	C3	Shredder Energy Usage	MJ	IDEMAT	Electricity Netherlands consumption	0,02	0,664	1	0,012	
48										
49	D	Machinable Brass	kg	IDEMAT App	CuZn40Pb (Brass, alpha-beta, machinable)	-3,07	0,875	0,975	-2,619	G2+G17
50										
51		Stainless Steel 316	kg	IDEMAT App	X5CrNiMo18 (316) 70% inox scrap (EU, USA)	-1,59	0,079	0,93	-0,117	
52		Stainless Steel 430	kg	IDEMAT App	X6Cr17 (430) 70% inox scrap (EU, USA)	-0,33	0,007	0,98	-0,002	
53		Float Glass	kg	IDEMAT App	Glass for windows and facades (float glass)	-0,07	0,022	0,9	-0,001	
54										
55	C4	Thermoset Plastics	kg	IDEMAT	POM (Polyoxymethylene, Polyacetaal) waste incineration wit	0,10	0,231	1	0,024	
56		Landfill	kg	IDEMAT	landfill (inert waste, not biodegradable)	0,14	0,030	1	0,004	G44*0,025+G46*0,06+G47*0,02+G49*0,1
57	**EoL RR MS-L**	**item**	**unit**		**database name**	**Eco-intensity (impacts per MJ)**	**Energy per activity (MJ)**	**Items per func.unit (#)**	**Calculated Impact**	**Notes**
58	C3	Shredder Energy Usage	MJ	IDEMAT	Electricity Netherlands consumption	0,02	0,664	1	0,012	
59										
60	D	Machinable Brass	kg	IDEMAT App	CuZn40Pb (Brass, alpha-beta, machinable)	-3,07	0,875	0,96	-2,579	G2+G17
61										
62		Stainless Steel 316	kg	IDEMAT App	X5CrNiMo18 (316) 70% inox scrap (EU, USA)	-1,59	0,079	0,9	-0,113	
63		Stainless Steel 430	kg	IDEMAT App	X6Cr17 (430) 70% inox scrap (EU, USA)	-0,33	0,007	0,97	-0,002	
64		Float Glass	kg	IDEMAT App	CuZn15	-0,07	0,022	0,85	-0,001	
65										
66	C4	Thermoset Plastics	0,00	IDEMAT	POM (Polyoxymethylene, Polyacetaal) waste incineration wit	0,10	0,231	1	0,024	
67		Landfill	kg	IDEMAT	landfill (inert waste, not biodegradable)	0,14	0,046	1	0,007	G44*0,025+G46*0,06+G47*0,02+G49*0,1

B.3 V200P impact calculations

	A	B	C	D	E	F	G	H	I	J
1	**Cradle to Recycling Facility**	**item**	**unit**	**Database**	**database name**	**Eco-intensity (impacts per kg)**	**Mass per item (kg)**	**Items per func.unit (#)**	**Calculated Impact**	**Notes**
2	A1-A2	Thermo Plastic	kg	IDEMAT	POM (Polyoxymethyleen, polyacetaal)	0,855	0,463	1	0,396	
3		Tombac brass	kg	IDEMAT	CuZn15	3,645	0,060	1	0,219	
4		Float Glass	kg	IDEMAT	Glass for windows and facades (float glass)	0,241	0,022	1	0,005	
5		Stainless Steel 430	kg	IDEMAT	X6Cr17 (430) 70% inox scrap (EU, USA)	0,781	0,007	1	0,005	
6										
7										
8										
9						weight check:	0,552			
10		**Processes**	**unit**		**database name**	**Eco-intensity (impacts per kg)**	**Mass per item (kg or other)**	**Items per func.unit (#)**	**Calculated Impact**	**Notes**
11	A3	Deep Drawing SS + Brass	kg	IDEMAT	Deep drawing steel	0,089	0,067	1	0,006	
12		Inject Molding Plastic	kg	IDEMAT	injection moulding, production site	0,207	0,463	1	0,096	
13		Tempering, Glass	kg	Ecoinvent	Tempering, flat glass {GLO}| market for | Cut-off, U	0,060	0,022	1	0,001	
14		Sheet Rolling Brass	kg	Ecoinvent	Sheet rolling, copper {GLO}| market for | Cut-off, U	0,687	0,060	1	0,041	
15		Sheet Rolling SS	kg	Ecoinvent	Sheet rolling, steel {GLO}| market for | Cut-off, U	0,106	0,007	1	0,001	
16										
17										
18										
19			**unit**		**database name**	**Eco-Intensity (impacts/ ton-km)**	**Mass per item**	**Distance per item (km)**	**Calculated Impact**	**Notes**
20	A4	Truck Transport	tkm	IDEMAT	Truck+trailer 24 tons net (min weight/volume ratio 0,32	0,026	0,001	511	0,007	1/(1000/G7)
21										
23	C2	Truck Transport	tkm	IDEMAT	Truck+trailer 24 tons net (min weight/volume ratio 0,32 ton/m3) (tkm)	0,026	0,001	40	0,001	1/(1000/G7)
24	**EoL RR MD**	**item**	**unit**		**database name**	**Eco-intensity (impacts per MJ)**	**Energy per activity (MJ)**	**Items per func.unit (#)**	**Calculated Impact**	**Notes**
25	C3	Energy Hydraulic Machinery	MJ	IDEMAT	Electricity Netherlands consumption	0,018	0,027	1	0,000	
26										
27	D	Secondary Tombac brass	kg	IDEMAT App	CuZn15	-3,490	0,060	1	-0,209	
28		Secondary SS 430	kg	IDEMAT App	X6Cr17 (430) 70% inox scrap (EU, USA)	-0,331	0,007	1	-0,002	
29		Secondary Glass	kg	IDEMAT App	Glass for windows and facades (float glass)	-0,070	0,022	1	-0,002	
30										
31										
32										
33	C4	Incinerating POM	kg	IDEMAT	POM (Polyoxymethylene, Polyacetaal) waste incineration with electricity	0,102	0,463	1	0,047	
34										
35	**EoL RR MS-H**	**item**	**unit**		**database name**	**Eco-intensity (impacts per MJ)**	**Energy per activity (MJ)**	**Items per func.unit (#)**	**Calculated Impact**	**Notes**
36	C3	Shredder Energy Usage	MJ	IDEMAT	Electricity Netherlands consumption	0,018	0,302	1	0,006	
37										
38	D	Secondary Tombac brass	kg	IDEMAT App	CuZn15	-3,490	0,060	0,99	-0,207	
39		Secondary SS 430	kg	IDEMAT App	X6Cr17 (430) 70% inox scrap (EU, USA)	-0,331	0,007	0,99	-0,002	
40		Secondary Glass	kg	IDEMAT App	Glass for windows and facades (float glass)	-0,070	0,022	0,95	-0,001	
41										
42										
43										
44	C4	Incinerating POM	kg	IDEMAT	POM (Polyoxymethylene, Polyacetaal) waste incineration with electricity	0,102	0,463	1	0,047	
45										
46	**EoL RR MS-A**	**item**	**uni t**		**database name**	**Eco-intensity (impacts per**	**Energy per activity**	**Items per**	**Calculated Impact**	**Notes**
47	C3	Shredder Energy Usage	MJ	IDEMAT	Electricity Netherlands consumption	0,018	0,302	1	0,006	
48										
49	D	Secondary Tombac brass	kg	IDEMAT App	CuZn15	-3,490	0,060	0,975	-0,204	
50		Secondary SS 430	kg	IDEMAT App	X6Cr17 (430) 70% inox scrap (EU, USA)	-0,331	0,007	0,98	-0,002	
51		Secondary Glass	kg	IDEMAT App	Glass for windows and facades (float glass)	-0,070	0,022	0,9	-0,001	
52										
53										
54										
55	C4	Incinerating POM	kg	IDEMAT	POM (Polyoxymethylene, Polyacetaal) waste incineration with electricity	0,102	0,463	1	0,047	
56										
57	**EoL RR MS-L**	**item**	**unit**		**database name**	**Eco-intensity (impacts per MJ)**	**Energy per activity (MJ)**	**Items per func.unit (#)**	**Calculated Impact**	**Notes**
58	C3	Shredder Energy Usage	MJ	IDEMAT	Electricity Netherlands consumption	0,018	0,302	1	0,006	
59										
60	D	Secondary Tombac brass	kg	IDEMAT App	CuZn15	-3,490	0,060	0,96	-0,201	
61		Secondary SS 430	kg	IDEMAT App	X6Cr17 (430) 70% inox scrap (EU, USA)	-0,331	0,007	0,97	-0,002	
62		Secondary Glass	kg	IDEMAT App	Glass for windows and facades (float glass)	-0,070	0,022	0,85	-0,001	
63										
64										
65										
66	C4	Incinerating POM	kg	IDEMAT	POM (Polyoxymethylene, Polyacetaal) waste incineration with electricity	0,102	0,463	1	0,047	
67		Landfill	kg	IDEMAT	landfill (inert waste, not biodegradable)	0.14	0.00055	1	0.000	G36*0.025+G37*0.02

B.4 Multical 21 impact calculations



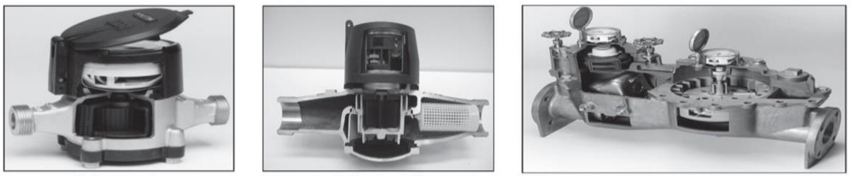
	A	B	C	D	E	F	G	H	I	J
1	Cradle to RR facility	item	unit	Database	database name	Eco-intensity (impacts per kg)	Mass per item (kg)	Items per func.unit (#)	Calculated Impact	Notes
2	A1-A2	Thermoplast plastic	kg	IDEMAT	PPS (polyphenylene sulfide)	4,505	0,167	0,6	0,451	60% plastic
3		Thermoplast plastic	kg	IDEMAT	PVC (Polyvinylchloride suspension polymerised)	0,706	0,016	1	0,011	
4		Thermoplast plastic	kg	IDEMAT	PC (Polycarbonate)	1,242	0,026	0,9	0,029	90% plastic
5		Glass Fibre	kg	IDEMAT	Glass fibre	0,280	0,069	1	0,019	G2*0,4+G4*0,1
6		Stainless Steel 430 EU&US	kg	IDEMAT	X6Cr17 (430) 70% inox scrap (EU, USA)	0,781	0,007	1	0,005	
7		Lithium Battery	kg	IDEMAT	Lithium LiFePO4 (145 Wh per kg, incl packaging, excl electro	2,822	0,046	1	0,130	
8		PCBs	kg	IDEMAT	PCB = Printed Circuit Board (including ICs)	111,524	0,036	1	4,015	
9		Glass	kg	IDEMAT	Glass for windows and facades (float glass)	0,241	0,069	1	0,017	
10		Bentonite	kg	Ecoinvent	Bentonite {GLO}| market for | Cut-off, U	0,067	0,013	1	0,001	
11										
12						weight check:	0,380			
13	A3	Inject Molding Plastic	kg	IDEMAT	injection moulding, production site	0,207	0,209	1	0,043	G3+G5+G6
14		Tempering, Glass	kg	Ecoinvent	Tempering, flat glass {GLO}| market for | Cut-off, U	0,060	0,069	1	0,004	
15		Deep Drawing SS	kg	IDEMAT	Deep drawing steel	0,089	0,007	1	0,001	
16		Sheet Rolling SS	kg	Ecoinvent	Sheet rolling, steel {GLO}| market for | Cut-off, U	0,106	0,007	1	0,001	
17			unit		database name	Eco-Intensity (impacts/ ton-km)	Mass per item	Distance per item (km)	Calculated Impact	Notes
18	A4	Truck Transport	tkm	IDEMAT	Truck+container, 28 tons net (min weight/volume ratio 0,41 ton/m3) (tkm)	0,022	0,000	857	0,007	1/(1000/G12)
19										
20										
22	C2	Truck Transport	tkm	IDEMAT	0,00	0,000	0,000	40	0,000	1/(1000/G12)
23	EoL RR MD	item	unit		database name	Eco-intensity (impacts per MJ)	Energy per activity (MJ)	Items per func.unit (#)	Calculated Impact	Notes
24	C3	Hydraulic Machinery	MJ	IDEMAT	Electricity Netherlands consumption	0,018	0,027	1	0,000	
25										
26	D	Secondary PCB metals	kg	IDEMAT APP	PCB = Printed Circuit Board (including ICs)	-25,190	0,036	1	-0,907	
27		Secondary Battery metals	kg	IDEMAT APP	Lithium LiFePO4 (145 Wh per kg, incl packaging, excl electronics)	-1,060	0,046	1	-0,049	
28		Secondary SS 316	kg	IDEMAT APP	X6Cr17 (430) 70% inox scrap (EU, USA)	-0,331	0,007	1	-0,002	
29		Secondary Glass	kg	IDEMAT APP	Glass for windows and facades (float glass)	-0,070	0,069	1	-0,005	
30									0,000	
31										
32	C4	Incinerating PPS	kg	IDEMAT	PPS waste incineration with electricity	6,072	0,100	1	0,608	G2*0,6
33		Incinerating PVC	kg	IDEMAT	PVC (Polyvinylchloride) waste incineration with electricity	0,085	0,016	1	0,001	
34		Incinerating PC	kg	IDEMAT	PC (Polycarbonate) waste incineration with electricity	0,214	0,023	1	0,005	G4*0,9
35		A-biotic Landfill	kg	IDEMAT	landfill (inert waste, not biodegradable)	0,141	0,013	1	0,002	
36	EoL RR MS-H	item	unit		database name	Eco-intensity (impacts per MJ)	Energy per activity (MJ)	Items per func.unit (#)	Calculated Impact	Notes
37	C3	Shredder Energy Usage	MJ	IDEMAT	Electricity Netherlands consumption	0,018	0,184	1	0,003	
38										
39	D	Secondary PCB metals	kg	IDEMAT APP	PCB = Printed Circuit Board (including ICs)	-25,190	0,036	0,95	-0,861	
40		Secondary Battery metals	kg	IDEMAT APP	Lithium LiFePO4 (145 Wh per kg, incl packaging, excl electronics)	-1,060	0,046	1	-0,049	
41		Secondary SS 316	kg	IDEMAT APP	X6Cr17 (430) 70% inox scrap (EU, USA)	-0,331	0,007	0,96	-0,002	
42		Secondary Glass	kg	IDEMAT APP	Glass for windows and facades (float glass)	-0,070	0,069	0,95	-0,005	
43										
44										
45	C4	Incinerating PPS	kg	IDEMAT	PPS waste incineration with electricity	6,072	0,100	1	0,608	G2*0,6
46		Incinerating PVC	kg	IDEMAT	PVC (Polyvinylchloride) waste incineration with electricity	0,085	0,016	1	0,001	
47		Incinerating PC	kg	IDEMAT	PC (Polycarbonate) waste incineration with electricity	0,214	0,023	1	0,005	G4*0,9
48		A-biotic Landfill	kg	IDEMAT	landfill (inert waste, not biodegradable)	0,141	0,026	1	0,004	
49	EoL RR MS-A	item	uni		database name	Eco-intensity	Energy per activity	Items per	Calculated Impact	Notes
50	C3	Shredder Energy Usage	MJ	IDEMAT	Electricity Netherlands consumption	0,018	0,184	1	0,003	
51										
52	D	Secondary PCB metals	kg	IDEMAT APP	PCB = Printed Circuit Board (including ICs)	-25,190	0,036	0,925	-0,839	
53		Secondary Battery metals	kg	IDEMAT APP	Lithium LiFePO4 (145 Wh per kg, incl packaging, excl electronics)	-1,060	0,046	1	-0,049	
54		Secondary SS 316	kg	IDEMAT APP	X6Cr17 (430) 70% inox scrap (EU, USA)	-0,331	0,007	0,93	-0,002	
55		Secondary Glass	kg	IDEMAT APP	Glass for windows and facades (float glass)	-0,070	0,069	1	-0,005	
56										
57										
58	C4	Incinerating PPS	kg	IDEMAT	PPS waste incineration with electricity	6,072	0,100	1	0,608	G2*0,6
59		Incinerating PVC	kg	IDEMAT	PVC (Polyvinylchloride) waste incineration with electricity	0,085	0,016	1	0,001	
60		Incinerating PC	kg	IDEMAT	PC (Polycarbonate) waste incineration with electricity	0,214	0,023	1	0,005	G4*0,9
61		A-biotic Landfill	kg	IDEMAT	landfill (inert waste, not biodegradable)	0,141	0,030	1	0,004	
62	EoL RR MS-L	item	unit		database name	Eco-intensity (impacts per MJ)	Energy per activity (MJ)	Items per func.unit (#)	Calculated Impact	Notes
63	C3	Shredder Energy Usage	MJ	IDEMAT	Electricity Netherlands consumption	0,018	0,184	1	0,003	
64										
65	D	Secondary PCB metals	kg	IDEMAT App	PCB = Printed Circuit Board (including ICs)	-25,190	0,036	0,9	-0,816	
66		Secondary Battery metals	kg	IDEMAT App	Lithium LiFePO4 (145 Wh per kg, incl packaging, excl electronics)	-1,060	0,046	1	-0,049	
67		Secondary SS 316	kg	IDEMAT App	X6Cr17 (430) 70% inox scrap (EU, USA)	-0,331	0,007	0,9	-0,002	
68		Secondary Glass	kg	IDEMAT App	Glass for windows and facades (float glass)	-0,070	0,069	1	-0,005	
69										
70										
71	C4	Incinerating PPS	kg	IDEMAT	PPS waste incineration with electricity	6,072	0,100	1	0,608	G2*0,6
72		Incinerating PVC	kg	IDEMAT	PVC (Polyvinylchloride) waste incineration with electricity	0,085	0,016	1	0,001	
73		Incinerating PC	kg	IDEMAT	PC (Polycarbonate) waste incineration with electricity	0,214	0,023	1	0,005	G4*0,9
74		A-biotic Landfill	kg	IDEMAT	landfill (inert waste, not biodegradable)	0,141	0,035	1	0,005	

C Section: Water meter management

This section covers water meter classifications, regulatory frameworks, declining refurbishment practices, replacement and installation processes, and sustainability initiatives to improve environmental impact and industry standards.

C.1 Water meter classification

The classification of water meters showcases a range of measurement principles, emphasising accuracy, durability, and adaptability to different water distribution environments. A visual representation of the water meters is given in **Fig. 32**. The visual representation is not on scale. The combination meters are generally much more prominent in size than their counterparts and are often used for industrial purposes (AWWA, 2012).



Volumetric

Inferential

Combination Meters

Electromagnetic

Ultrasonic

Figure 32: Representation of the water meters based on their water measurement mechanism. Source: (Awwa, 2012)

1. **Mechanical** meters rely on moving components, such as pistons or impellers, to measure water flow. The mechanical meters can be classified into:

    - **Volumetric meters**: Known for directly measuring water volume, these meters, like the rotary piston and disc meter, excel in accuracy, especially at low flow rates, ensuring equitable water billing. They are particularly effective in systems with high water quality as they are sensitive to suspended solids (AWWA, 2012).
    - **Inferential meters**: These meters estimate flow rate based on the velocity of water passing through them. Types include single jet and multijet meters, which are adaptable to various conditions and are known for their durability and ease of maintenance. The Woltmann meters, another subclass, are distinguished by their use in larger pipes and higher flow conditions, offering robust performance over a wide flow range (AWWA, 2012).
    - **Combination meters**: These are designed to offer a compromise between volumetric and inferential water meters. They provide the best characteristics by incorporating a primary meter for high flow rates and a secondary meter for lower flow rates. This design is applied in settings with fluctuating water consumption, ensuring consistent, accurate, and reliable water measurements (AWWA, 2012).

The following meters are known as solid-state meters or static meters, and they measure the flow of water based on static sensors (Arregui et al., 2020). An external or autonomous power source is required to operate these meters (Arregui et al., 2006).

2. **Electromagnetic meters**: Operating on the principles of electromagnetic induction, these meters offer the advantage of having no moving parts, which translates to minimal wear and tear and an extended lifespan of the water meter. Ideal for applications requiring high accuracy or large pipe diameters, electromagnetic meters are valued for their precision and minimal maintenance requirements (Van Zyl, 2011).
3. **Ultrasonic meters**: Like electromagnetic meters without moving parts, ultrasonic meters measure flow using sound waves. Their high-precision measurement method makes them suitable for various specialised applications, ranging from residential to industrial settings (Van Zyl, 2011).

C.2 Government and industry regulations

Government and self-imposed industry regulations regulate the water distribution sector in the Netherlands (VEWIN, 2018). The Association of Dutch Water Companies (VEWIN), representing all Dutch water distribution companies, is a crucial agency directing the partly self-imposed industry regulations (VEWIN, 2018). These members collectively develop and adhere to guidelines detailed in the Water Meter Quality Assurance Regulation Manual. Managed by VEWIN’s Commission Regulation Quality Assurance for Water Meters, with input from the Water Meter Quality Assurance Guidance Group. The manual aims to standardise practices across the sector (VEWIN, 2018). It includes guidelines for water meter classification, sampling for condition determination and inspection, and protocols for meter removal, transportation, and storage (VEWIN, 2018).

The Dutch government's involvement in the water sector encompasses various regulatory measures to safeguard public health, preserve environmental integrity, and maintain water quality. Central to these efforts are key regulations, such as the Drinking Water Law, the Drinking Water Decree, and the Regulation of Materials and Chemicals for Drinking and Hot Tap Water Supply (Drinkwaterbesluit, 2024; Drinkwaterwet, 2024; RIVM, 2016). These measures align with the European Drinking Water Directive 98/83/EC, which sets standards for materials and chemicals that meet water, including water meters (Directive 98/83, 1998).

C.3 Water meter certifications

The Ministry of Infrastructure and Water Management is responsible for ensuring compliance with rules and standards, working closely with Kiwa Netherlands B.V., the organisation recognised for issuing the Kiwa Water Mark (KWM). This mark is required for the certification of all water meters in the Netherlands (RIVM, 2016). Kiwa has integrated the regulatory requirements into its Assessment Guidelines, matching them with product specifications (BRL-K618 [A1], 2020).

The Dutch regulatory framework for water meters prominently incorporates ISO 4064 1-5, an international standard specifying the metrological and technical requirements for water meters used in measuring cold potable water and hot water (ISO 4064-1, 2017). Following these standards ensures that WMMs and utilities comply with international and national regulations (Rijksoverheid, 2010). Moreover, the standards play an essential role in harmonising the requirements across borders, allowing for the use of universally accepted measurement metrics (ISO Statutes, 2018).

C.4 Decline of water meter refurbishment

Revising and refurbishing meters, once common among water meter producers, social development companies, and DWUs, is now largely abandoned in the Netherlands. The gradual decline in refurbishment is attributed to rapid advancements and changes in the water meter industry (source: DWU II, IV).

Previously feasible refurbishing plans required significant time and effort to put in place (source: DWU II). With the transition to volumetric meters in the past, which offered better performance and a longer lifespan, adapting the entire refurbishment operation to accommodate this new type became economically unfeasible (source: DWU II, IV). Furthermore, the switch to volumetric meters refurbishment would have entailed a waiting period of approximately 20 years without an active replacement program for these newly installed meters, with no work being done (source: DWU II, IV). Inconsistencies in meter supply and demand and frequent changes in management and cost-saving strategies made it challenging to maintain a sustainable refurbishment cycle (source: DWU II). As a result, all but one DWU has ceased refurbishment operations.

C.5 The continued small-scale practice of refurbishment

The only remaining one that still practices refurbishing the inferential meters is DWU IV. They have tailored their entire process to specialise in this specific type of meter. An interview with the manager revealed that this specialisation is feasible due to the company's small size and focus on a single type of meter (source: DWU IV). They foresee a bright future in this niche, viewing it as sustainable and an opportunity to employ individuals distant from the labour market in their refurbishment operations. Additionally, the abandonment of the process by others allows DWU IV to purchase materials needed for revising meters at lower prices, providing an economic incentive to continue these practices. The **Fig. 33** shows their workplace, where the entire refurbishment operation occurs.

Water meters that are beyond refurbishment and revision are disassembled through a combination of manual and mechanical labour. The plastic and metal components are carefully segregated. The plastic segments are sent to a nearby waste processing facility, while the metal parts are sold to local recyclers (source: DWU IV). The same tools and machinery are being used, as observed during the field trip to WoW for their RR and dismantling process.

Figure 33: Water meter refurbishment process (inferential M100 model)

C.6 Management of replacing and installing meters

The replacement and installation of water meters involve installing new meters or replacing defective or ageing ones. The following description of this process at BW is based on interviews with the Asset Manager. The description below outlines the approach taken within their operations, and **Fig. 34** provides a flowchart representation of the water meter placement process.

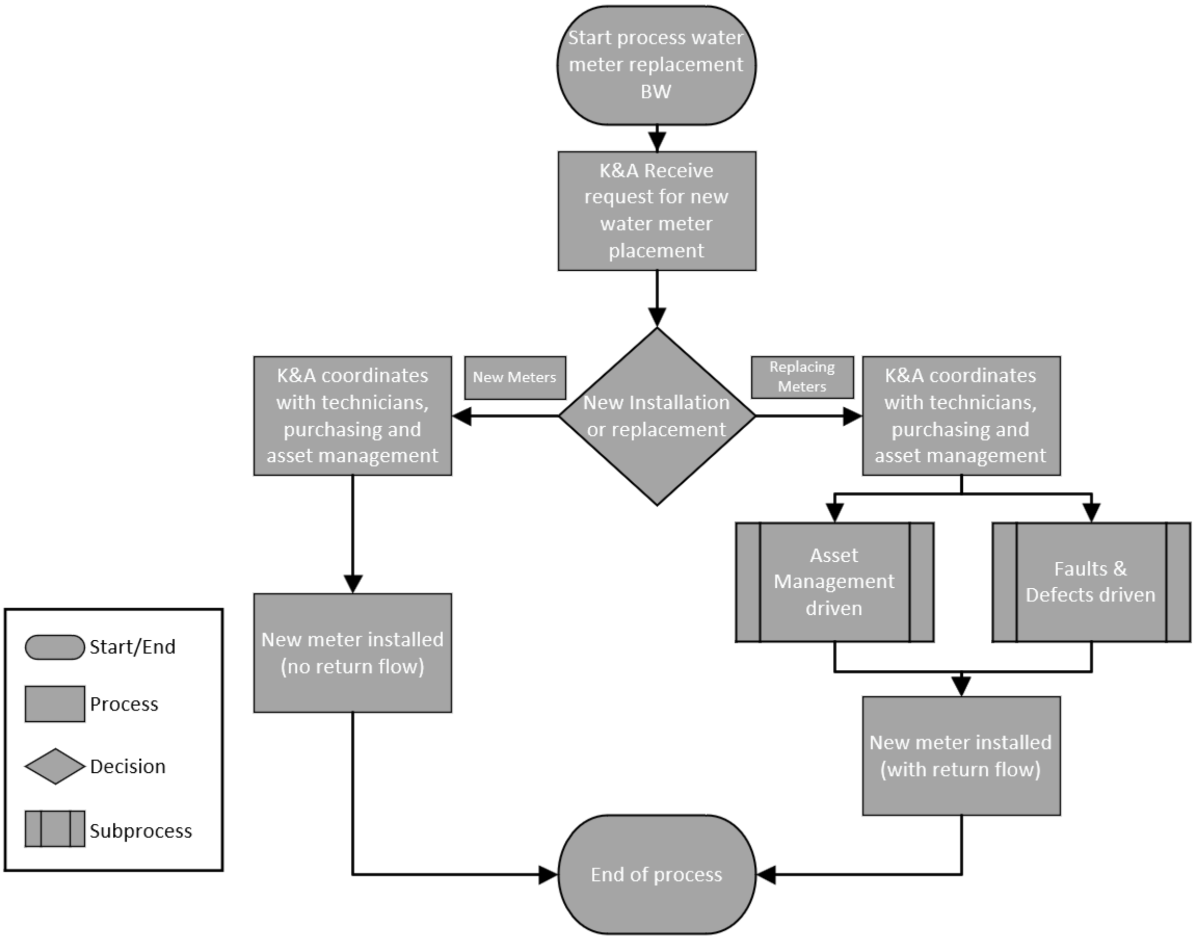


Figure 34: Flow chart diagram of installing or replacing meters at BW

C.6.1 Installing new meters

The installation of water meters in new residential and small commercial buildings begins with a formal request from developers to the Quality and Connections Department (K&A). Upon receiving the request, K&A collaborates with the purchasing and asset management divisions to review available options and determine the timing and pace of execution. Once a plan is established, technicians are assigned to install the new water meters. This process involves a singular flow of assets into the field, without the return of old assets.

C.6.2 Replacing meters

Replacing old meters and installing new meters begins again at K&A. The replacement of the old meters is driven by two subprocesses: asset management or faults and defects detection. These two processes are described here below (source: DWU BW):

- **Asset management-driven replacements:** These replacement programs are only active when assets are nearing EoL. In coordination with the asset management team, purchasing and K&A plans are made to replace certain assets during a specified period.
- **Faults and defects-driven replacements**: These are done when abnormalities in water usage are detected during meter readings, either reported by customers or discovered by BW during their sampling check-ups.

This dual approach to water meter replacement varies annually. The faults and defects-driven process remains consistently active due to ongoing routine check-ups, sampling, and customer notifications. Conversely, asset management-driven replacement may be inactive in some years if the assets do not reach their average EoL span (source: BW).

C.6.3 End-of-Life water meters

The collection of the water meters is done similarly across all the DWUs examined. Technicians collect all disposed EoL water meters in their company vehicles. When they accumulate sufficient stock, the meters are collected in large volume bins at the nearest DWU warehouse, as displayed in **Fig. 35**. The recyclers then collect the full bins and transport them to their facilities for further processing, leaving empty bins behind to initiate the collection of the next batch of disposed EOL water meters (source: DWU BW).

Figure 35: Example of bins for EoL water meter collection at DWUs

C.7 Sustainability initiatives

The following two initiatives aim to improve industry regulatory standards and increase the sector's sustainability.

C.7.1 4MS initiative

The 4MS Initiative is a collaborative effort with the countries listed in **Table 12**, aimed at harmonising national assessment systems for water contact materials across Europe (4MS, 2019).
The objectives of the 4MS Initiative include using standard or directly comparable practices for (4MS, 2019):

- Accepting the constituents used in materials that come with drinking water.
- Testing these materials.
- Utilizing standard test methods and establishing acceptance levels.
- Specifying tests to be applied to products.
- Reviewing factory production control and setting audit testing requirements.
- Assessing the capabilities of certification and testing bodies.

Using a common approach, the 4MS Initiative would enable the broader recognition of European quality certifications, like the Kiwa Water Mark. This expansion would increase the pool of available water meters certified under these unified standards (4MS, 2019).

Table 12: MS initiative members and aspiring members

EU Member State	4MSI Full Member: joining date	4MSI Candidate Member
France	2011 (Initiator)	
Germany	2011 (Initiator)	
Netherlands	2011 (Initiator)	
United Kingdom	2011 (Initiator)	
Denmark	2018	
Portugal		X

C.7.2 Blue Nets initiative

Sustainability efforts are progressing through various initiatives within the DWU sector, with the Blue Nets project as an example. This voluntary initiative, led by MVO Nederland, involves all 10 Dutch drinking water companies (MVO, 2022). Blue Nets primarily focuses on implementing a digital material passport system that transparently documents product materials. This initiative currently has three primary goals (MVO, 2022):

- To systematically record product information to enable high-quality reuse after the product's initial lifespan.
- To assess and compare the circularity and environmental impact of products.
- To improve sustainability performance through sustainable procurement practices.

Currently, the project's efforts are concentrated on the first goal, specifically targeting underground pipes (MVO, 2022). Water meters, which are installed above ground, are not yet included in the scope of this initiative but are planned to be addressed in future phases (MVO, 2022).

D Section: Water meter shredding

The following sections discuss the shredding and separation process detailed by RRF I for EoL water meters, detailing the stages involved in MS. Additional shredder details are provided through online videos and outreach to ISC.

D.1 Shredding and separation process for water meters

The following MS, illustrated in **Fig. 36**, was detailed during the field visit to RRF1. Water meters are fed into the hammer mill shredder via a conveyor, breaking them into coarse pieces in a pre-shredding phase. This stage uses a magnetic band to extract ferromagnetic metals from non-magnetic components. Additionally, hand pickers are used to separate non-magnetic stainless steel from the conveyor belt.

Following the initial shredding, the materials are shredded again in a granulator, reducing them to particles several centimetres in size. These particles are sorted on a shaking table based on their specific densities, separating plastics from non-ferrous metals. By the conclusion of the process, five distinct material streams are produced for EoL water meters: shredder residue consisting of a mix of materials, plastics, ferromagnetic metals (collected by the magnet), non-ferromagnetic metals like stainless steel (separated manually), and brass.

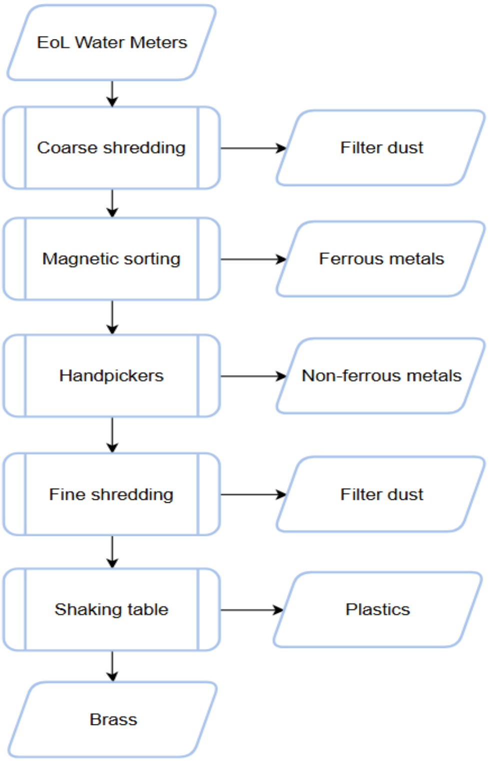


Figure 36: Flowchart representation of the water meter shredding process (Source: RC1).

D.2 Water meter mechanical shredding

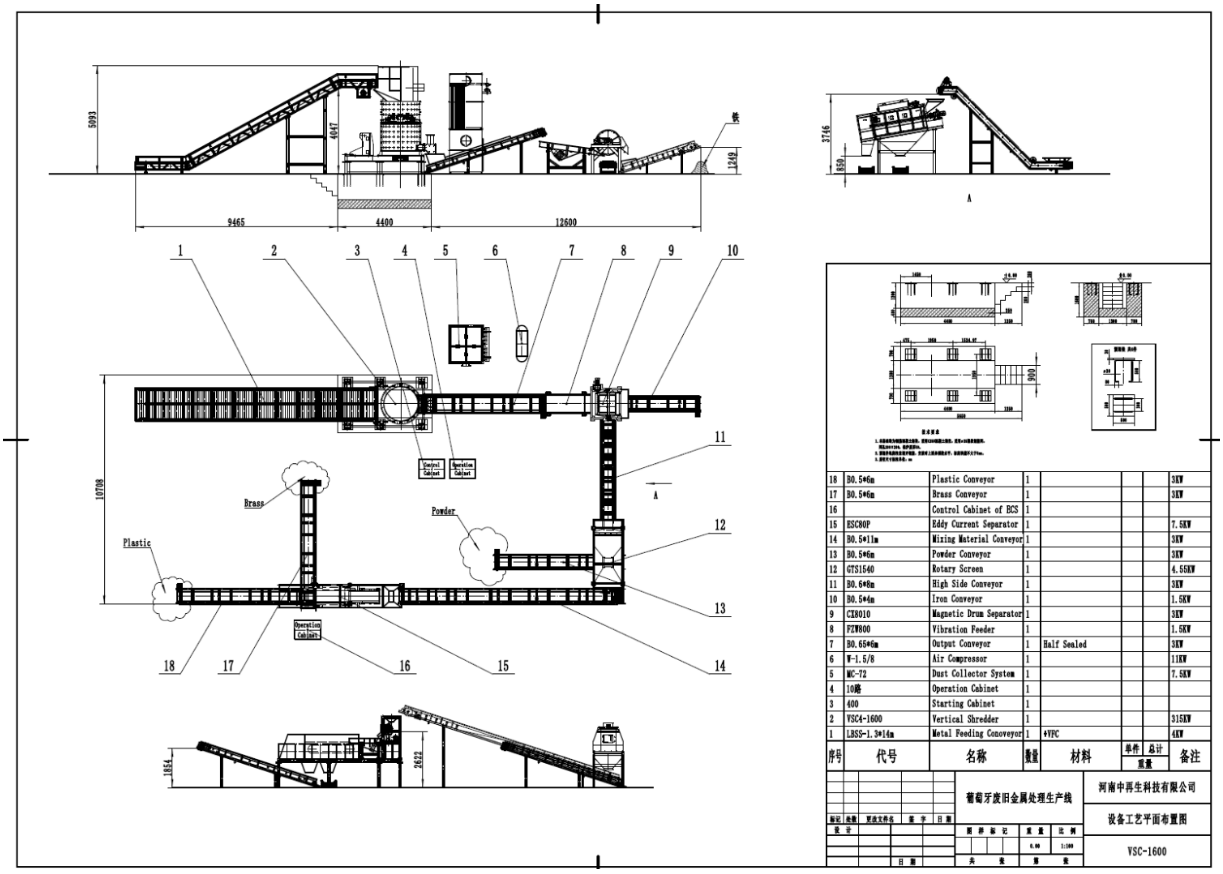
1. Title: How to get the pure brass from Water Meter Recycling Shredder

Link: https://www.youtube.com/watch?v=3D4P8Hjynak

2. Title: Recycling water meters van Vitens door Genius Metal recycling BV

Link: https://www.youtube.com/watch?v=R8kBUy8Kccs

Fig. 37 represents the typical shredder layout used in an RRF facility with its various sub-components, and Table 13 shows its energy consumption.



序号	代号	名称	数量	材料	单件	总计	备注
					重量		
18	B0.5*6m	Plastic Conveyor	1				3KW
17	B0.5*6m	Brass Conveyor	1				3KW
16		Control Cabinet of BCS	1				
15	ESC80P	Eddy Current Separator	1				7.5KW
14	B0.5*11m	Mixing Material Conveyor	1				3KW
13	B0.5*6m	Powder Conveyor	1				3KW
12	GTS1540	Rotary Screen	1				4.55KW
11	B0.6*8m	High Side Conveyor	1				3KW
10	B0.5*4m	Iron Conveyor	1				1.5KW
9	CX8010	Magnetic Drum Separator	1				3KW
8	FZW800	Vibration Feeder	1				1.5KW
7	B0.65*6m	Output Conveyor	1	Half Sealed			3KW
6	W-1.5/8	Air Compressor	1				11KW
5	MC-72	Dust Collector System	1				7.5KW
4	10路	Operation Cabinet	1				
3	400	Starting Cabinet	1				
2	VSC4-1600	Vertical Shredder	1				315KW
1	LBSS-1.3*14m	Metal Feeding Conoveyor	1	+VFC			4KW

Figure 37: Shredder assembly layout: Source ISC

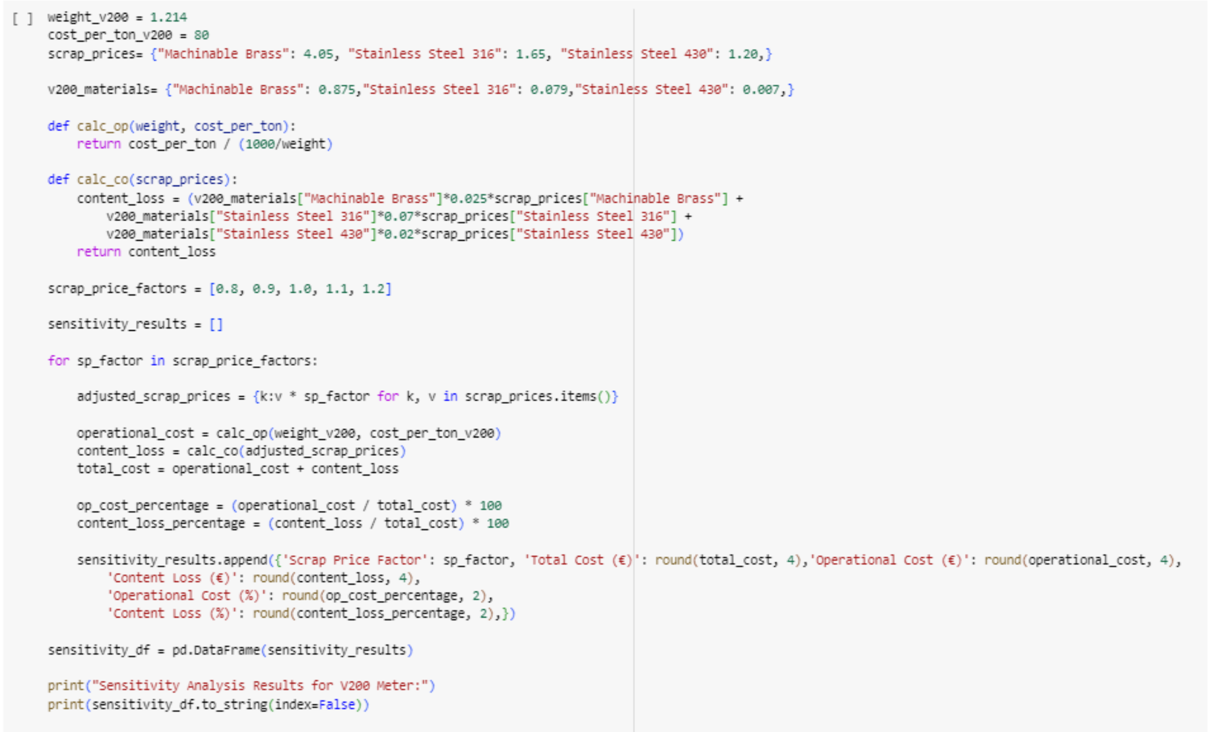
Table 13:Energy Consumption Water Meters in the Recycling System. Source: ISC

Component	Energy Consumption (kW)	Energy Consumption (MJ)
Belt Conveyor	2.2	7.92
Vertical Crusher	110.0	396.0
Vibrating Screen	3.0	10.8
Magnetic Separator	1.5	5.4
Eddy Current Separator	7.7	27.72
Belt Conveyor	2.2	7.92
Belt Conveyor	2.2	7.92
Belt Conveyor	2.2	7.92
Eddy Current Separator for Stainless Steel	15.6	56.16

E Section: Python codes

This section details all the codes used for data visualisation or calculations.

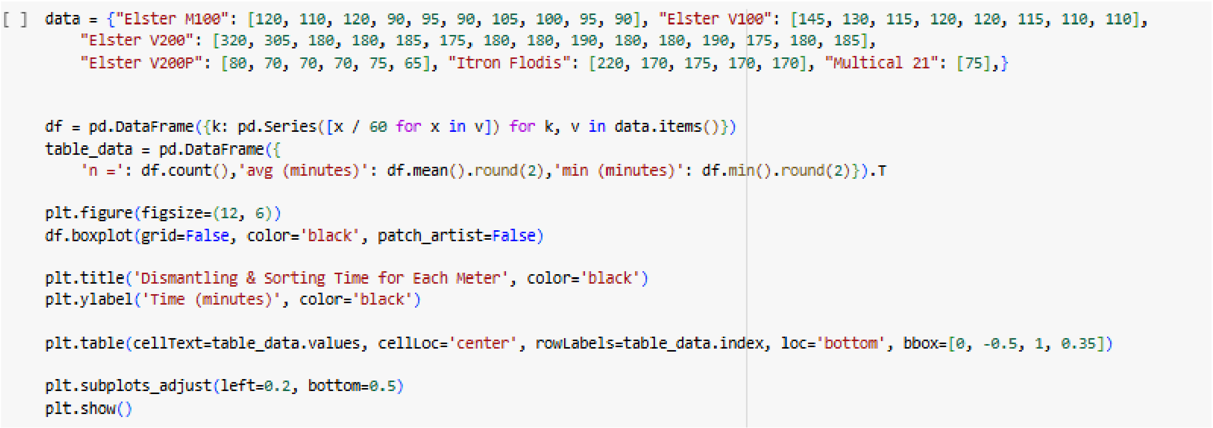
E.1 Sensitivity cost analysis



```python
weight_v200 = 1.214
cost_per_ton_v200 = 80
scrap_prices= {"Machinable Brass": 4.05, "Stainless Steel 316": 1.65, "Stainless Steel 430": 1.20,}

v200_materials= {"Machinable Brass": 0.875,"Stainless Steel 316": 0.079,"Stainless Steel 430": 0.007,}

def calc_op(weight, cost_per_ton):
    return cost_per_ton / (1000/weight)

def calc_co(scrap_prices):
    content_loss = (v200_materials["Machinable Brass"]*0.025*scrap_prices["Machinable Brass"] +
        v200_materials["Stainless Steel 316"]*0.07*scrap_prices["Stainless Steel 316"] +
        v200_materials["Stainless Steel 430"]*0.02*scrap_prices["Stainless Steel 430"])
    return content_loss

scrap_price_factors = [0.8, 0.9, 1.0, 1.1, 1.2]

sensitivity_results = []

for sp_factor in scrap_price_factors:

    adjusted_scrap_prices = {k:v * sp_factor for k, v in scrap_prices.items()}

    operational_cost = calc_op(weight_v200, cost_per_ton_v200)
    content_loss = calc_co(adjusted_scrap_prices)
    total_cost = operational_cost + content_loss

    op_cost_percentage = (operational_cost / total_cost) * 100
    content_loss_percentage = (content_loss / total_cost) * 100

    sensitivity_results.append({'Scrap Price Factor': sp_factor, 'Total Cost (€)': round(total_cost, 4),'Operational Cost (€)': round(operational_cost, 4),
        'Content Loss (€)': round(content_loss, 4),
        'Operational Cost (%)': round(op_cost_percentage, 2),
        'Content Loss (%)': round(content_loss_percentage, 2),})

sensitivity_df = pd.DataFrame(sensitivity_results)

print("Sensitivity Analysis Results for V200 Meter:")
print(sensitivity_df.to_string(index=False))
```

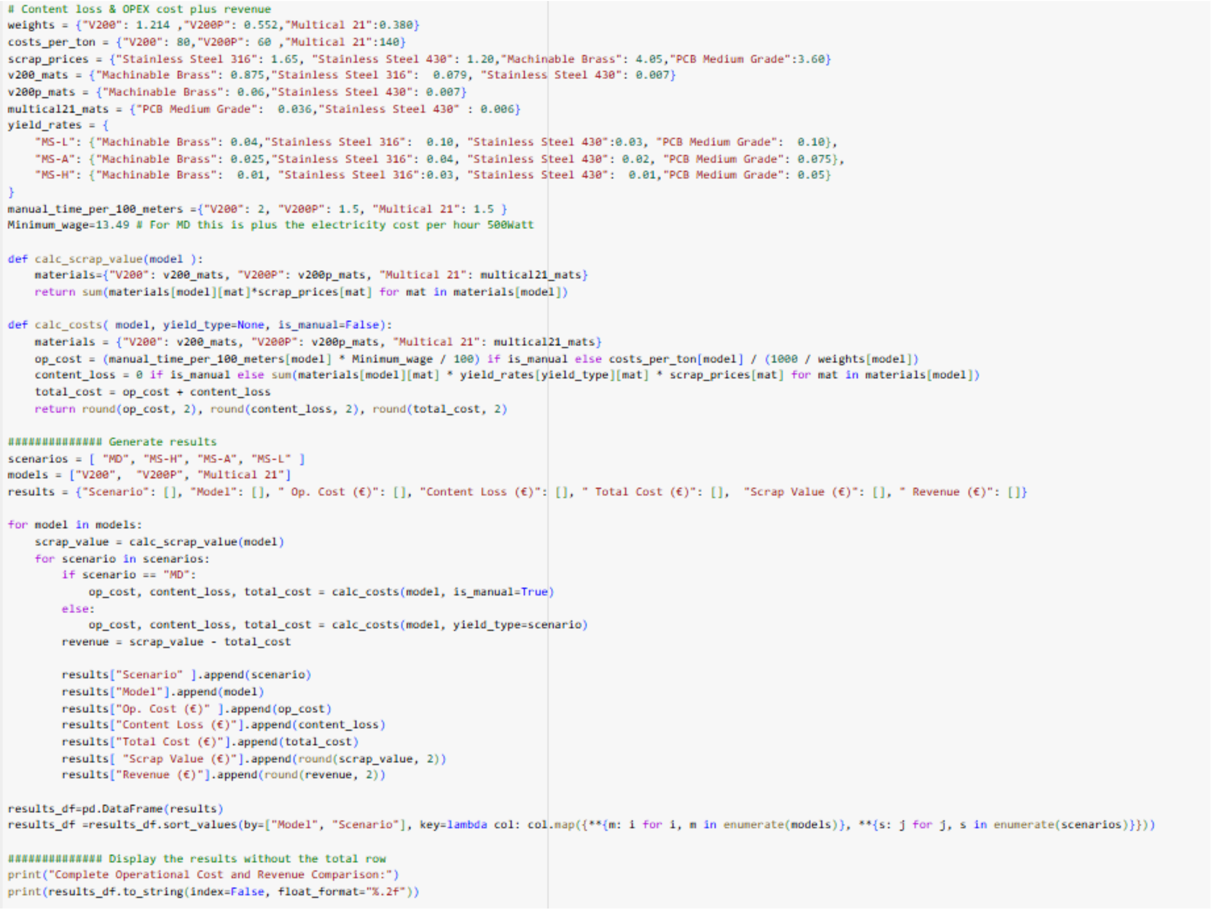
```python
plt.figure(figsize=(10, 6))
plt.plot(sensitivity_df['Scrap Price Factor'], sensitivity_df['Total Cost (€)'],marker='D',color='blue')

plt.title('Total Cost vs Scrap Price Factor (V200)', fontweight='bold')
plt.xlabel('Scrap Price Factor',fontweight='bold')
plt.ylabel('Total Cost (€)', fontweight='bold')
plt.grid(True)
plt.show()

####################################

plt.figure(figsize=(10, 6))
plt.plot(sensitivity_df['Scrap Price Factor'], sensitivity_df['Operational Cost (%)'],marker='D', label='Operational Cost (%)',color='green')
plt.plot(sensitivity_df['Scrap Price Factor'], sensitivity_df['Content Loss (%)'],marker='D', label='Content Loss (%)',color='red')

plt.title('OPEX/Content Loss vs Scrap Price Factor (V200)', fontweight='bold')
plt.xlabel('Scrap Price Factor', fontweight='bold')
plt.ylabel('Percentage Contribution (%)', fontweight='bold')
plt.grid(True)
plt.legend()
plt.show()
```

E.2 Dismantling time water meters



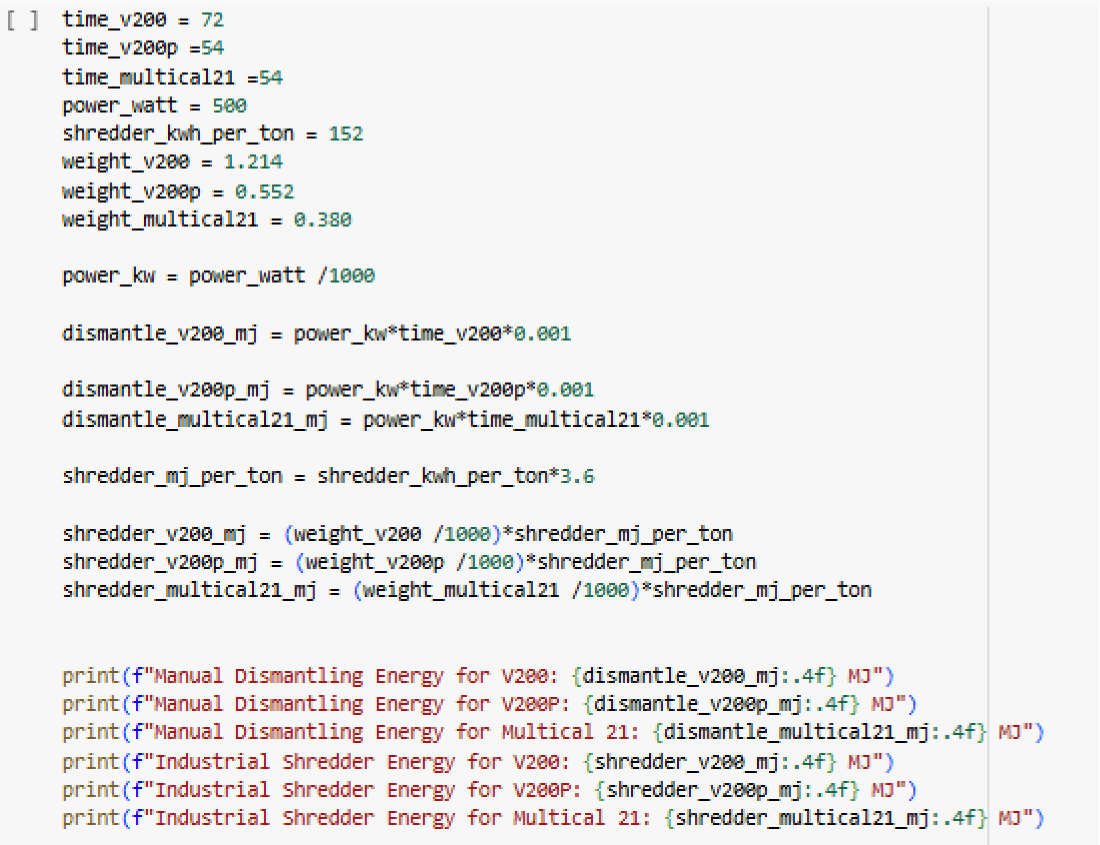
```python
data = {"Elster M100": [120, 110, 120, 90, 95, 90, 105, 100, 95, 90], "Elster V100": [145, 130, 115, 120, 120, 115, 110, 110],
    "Elster V200": [320, 305, 180, 180, 185, 175, 180, 180, 190, 180, 180, 190, 175, 180, 185],
    "Elster V200P": [80, 70, 70, 70, 75, 65], "Itron Flodis": [220, 170, 175, 170, 170], "Multical 21": [75],}


df = pd.DataFrame({k: pd.Series([x / 60 for x in v]) for k, v in data.items()})
table_data = pd.DataFrame({
    'n =': df.count(),'avg (minutes)': df.mean().round(2),'min (minutes)': df.min().round(2)}).T

plt.figure(figsize=(12, 6))
df.boxplot(grid=False, color='black', patch_artist=False)

plt.title('Dismantling & Sorting Time for Each Meter', color='black')
plt.ylabel('Time (minutes)', color='black')

plt.table(cellText=table_data.values, cellLoc='center', rowLabels=table_data.index, loc='bottom', bbox=[0, -0.5, 1, 0.35])

plt.subplots_adjust(left=0.2, bottom=0.5)
plt.show()
```

E.3 Content loss & OPEX



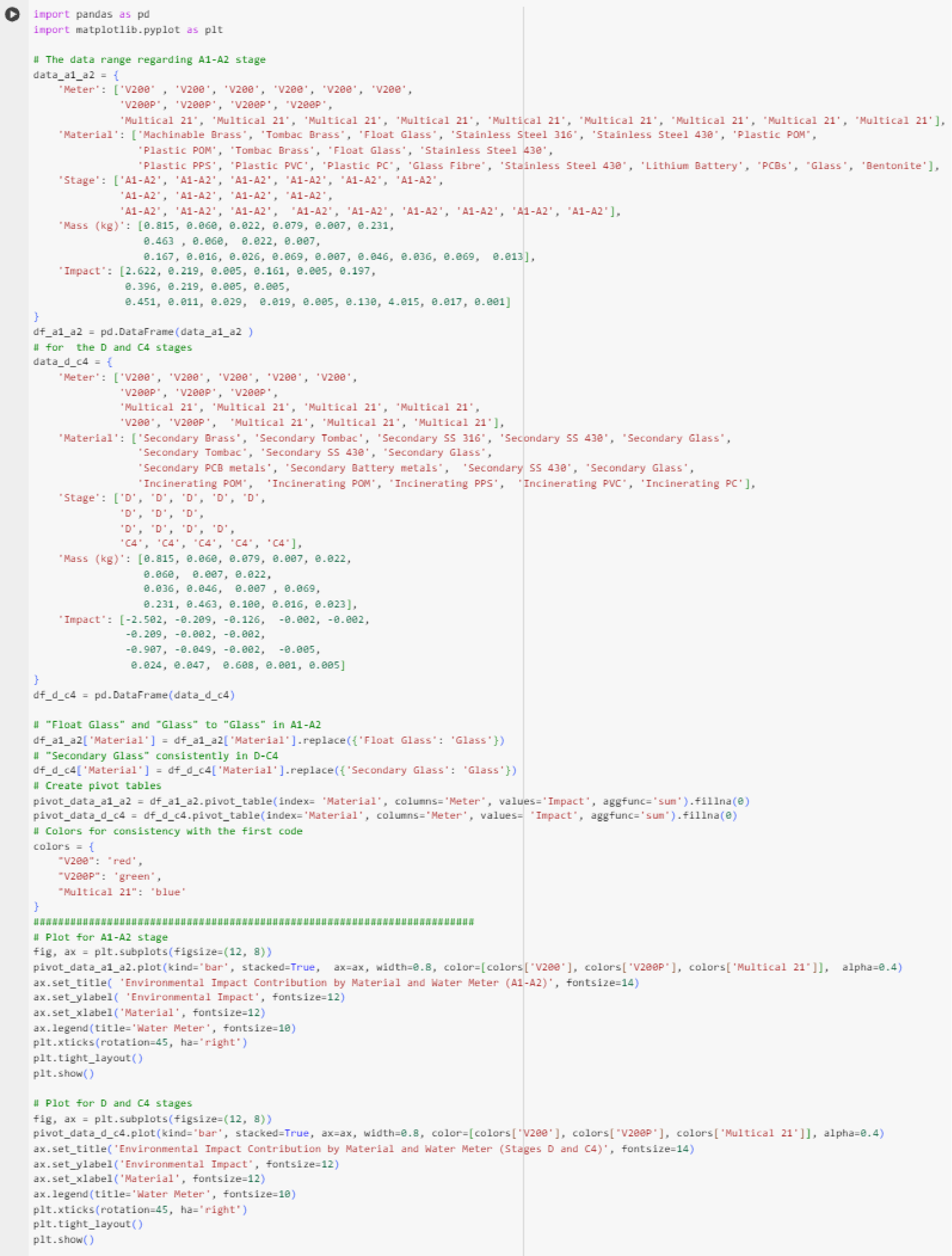
```
# Content loss & OPEX cost plus revenue
weights = {"V200": 1.214 ,"V200P": 0.552,"Multical 21":0.380}
costs_per_ton = {"V200": 80,"V200P": 60 ,"Multical 21":140}
scrap_prices = {"Stainless Steel 316": 1.65, "Stainless Steel 430": 1.20,"Machinable Brass": 4.05,"PCB Medium Grade":3.60}
v200_mats = {"Machinable Brass": 0.875,"Stainless Steel 316":  0.079, "Stainless Steel 430": 0.007}
v200p_mats = {"Machinable Brass": 0.06,"Stainless Steel 430": 0.007}
multical21_mats = {"PCB Medium Grade":  0.036,"Stainless Steel 430" : 0.006}
yield_rates = {
    "MS-L": {"Machinable Brass": 0.04,"Stainless Steel 316":  0.10, "Stainless Steel 430":0.03, "PCB Medium Grade":  0.10},
    "MS-A": {"Machinable Brass": 0.025,"Stainless Steel 316": 0.04, "Stainless Steel 430": 0.02, "PCB Medium Grade": 0.075},
    "MS-H": {"Machinable Brass":  0.01, "Stainless Steel 316":0.03, "Stainless Steel 430":  0.01,"PCB Medium Grade": 0.05}
}
manual_time_per_100_meters ={"V200": 2, "V200P": 1.5, "Multical 21": 1.5 }
Minimum_wage=13.49 # For MD this is plus the electricity cost per hour 500Watt

def calc_scrap_value(model ):
    materials={"V200": v200_mats, "V200P": v200p_mats, "Multical 21": multical21_mats}
    return sum(materials[model][mat]*scrap_prices[mat] for mat in materials[model])

def calc_costs( model, yield_type=None, is_manual=False):
    materials = {"V200": v200_mats, "V200P": v200p_mats, "Multical 21": multical21_mats}
    op_cost = (manual_time_per_100_meters[model] * Minimum_wage / 100) if is_manual else costs_per_ton[model] / (1000 / weights[model])
    content_loss = 0 if is_manual else sum(materials[model][mat] * yield_rates[yield_type][mat] * scrap_prices[mat] for mat in materials[model])
    total_cost = op_cost + content_loss
    return round(op_cost, 2), round(content_loss, 2), round(total_cost, 2)

############## Generate results
scenarios = [ "MD", "MS-H", "MS-A", "MS-L" ]
models = ["V200",  "V200P", "Multical 21"]
results = {"Scenario": [], "Model": [], " Op. Cost (€)": [], "Content Loss (€)": [], " Total Cost (€)": [],  "Scrap Value (€)": [], " Revenue (€)": []}

for model in models:
    scrap_value = calc_scrap_value(model)
    for scenario in scenarios:
        if scenario == "MD":
            op_cost, content_loss, total_cost = calc_costs(model, is_manual=True)
        else:
            op_cost, content_loss, total_cost = calc_costs(model, yield_type=scenario)
        revenue = scrap_value - total_cost

        results["Scenario" ].append(scenario)
        results["Model"].append(model)
        results["Op. Cost (€)" ].append(op_cost)
        results["Content Loss (€)"].append(content_loss)
        results["Total Cost (€)"].append(total_cost)
        results[ "Scrap Value (€)"].append(round(scrap_value, 2))
        results["Revenue (€)"].append(round(revenue, 2))

results_df=pd.DataFrame(results)
results_df =results_df.sort_values(by=["Model", "Scenario"], key=lambda col: col.map({**{m: i for i, m in enumerate(models)}, **{s: j for j, s in enumerate(scenarios)}}))

############## Display the results without the total row
print("Complete Operational Cost and Revenue Comparison:")
print(results_df.to_string(index=False, float_format="%.2f"))
```

E.4 Electricity consumption



```
time_v200 = 72
time_v200p =54
time_multical21 =54
power_watt = 500
shredder_kwh_per_ton = 152
weight_v200 = 1.214
weight_v200p = 0.552
weight_multical21 = 0.380

power_kw = power_watt /1000

dismantle_v200_mj = power_kw*time_v200*0.001

dismantle_v200p_mj = power_kw*time_v200p*0.001
dismantle_multical21_mj = power_kw*time_multical21*0.001

shredder_mj_per_ton = shredder_kwh_per_ton*3.6

shredder_v200_mj = (weight_v200 /1000)*shredder_mj_per_ton
shredder_v200p_mj = (weight_v200p /1000)*shredder_mj_per_ton
shredder_multical21_mj = (weight_multical21 /1000)*shredder_mj_per_ton


print(f"Manual Dismantling Energy for V200: {dismantle_v200_mj:.4f} MJ")
print(f"Manual Dismantling Energy for V200P: {dismantle_v200p_mj:.4f} MJ")
print(f"Manual Dismantling Energy for Multical 21: {dismantle_multical21_mj:.4f} MJ")
print(f"Industrial Shredder Energy for V200: {shredder_v200_mj:.4f} MJ")
print(f"Industrial Shredder Energy for V200P: {shredder_v200p_mj:.4f} MJ")
print(f"Industrial Shredder Energy for Multical 21: {shredder_multical21_mj:.4f} MJ")
```

E.5 Material Contribution



```
import pandas as pd
import matplotlib.pyplot as plt

# The data range regarding A1-A2 stage
data_a1_a2 = {
    'Meter': ['V200' , 'V200', 'V200', 'V200', 'V200', 'V200',
              'V200P', 'V200P', 'V200P', 'V200P',
              'Multical 21', 'Multical 21', 'Multical 21', 'Multical 21', 'Multical 21', 'Multical 21', 'Multical 21', 'Multical 21', 'Multical 21'],
    'Material': ['Machinable Brass', 'Tombac Brass', 'Float Glass', 'Stainless Steel 316', 'Stainless Steel 430', 'Plastic POM",
                 'Plastic POM', 'Tombac Brass', 'Float Glass', 'Stainless Steel 430',
                 'Plastic PPS', 'Plastic PVC', 'Plastic PC', 'Glass Fibre', 'Stainless Steel 430', 'Lithium Battery', 'PCBs', 'Glass', 'Bentonite'],
    'Stage': ['A1-A2', 'A1-A2', 'A1-A2', 'A1-A2', 'A1-A2', 'A1-A2',
              'A1-A2', 'A1-A2', 'A1-A2', 'A1-A2',
              'A1-A2', 'A1-A2', 'A1-A2',  'A1-A2', 'A1-A2', 'A1-A2', 'A1-A2', 'A1-A2', 'A1-A2'],
    'Mass (kg)': [0.815, 0.060, 0.022, 0.079, 0.007, 0.231,
                  0.463 , 0.060,  0.022, 0.007,
                  0.167, 0.016, 0.026, 0.069, 0.007, 0.046, 0.036, 0.069,  0.013],
    'Impact': [2.622, 0.219, 0.005, 0.161, 0.005, 0.197,
               0.396, 0.219, 0.005, 0.005,
               0.451, 0.011, 0.029,  0.019, 0.005, 0.130, 4.015, 0.017, 0.001]
}
df_a1_a2 = pd.DataFrame(data_a1_a2 )
# for  the D and C4 stages
data_d_c4 = {
    'Meter': ['V200', 'V200', 'V200', 'V200', 'V200',
              'V200P', 'V200P', 'V200P',
              'Multical 21', 'Multical 21', 'Multical 21', 'Multical 21',
              'V200', 'V200P',  'Multical 21', 'Multical 21', 'Multical 21'],
    'Material': ['Secondary Brass', 'Secondary Tombac', 'Secondary SS 316', 'Secondary SS 430', 'Secondary Glass',
                 'Secondary Tombac', 'Secondary SS 430', 'Secondary Glass',
                 'Secondary PCB metals', 'Secondary Battery metals',  'Secondary SS 430', 'Secondary Glass',
                 'Incinerating POM',  'Incinerating POM', 'Incinerating PPS',  'Incinerating PVC', 'Incinerating PC'],
    'Stage': ['D', 'D', 'D', 'D', 'D',
              'D', 'D', 'D',
              'D', 'D', 'D', 'D',
              'C4', 'C4', 'C4', 'C4', 'C4'],
    'Mass (kg)': [0.815, 0.060, 0.079, 0.007, 0.022,
                  0.060,  0.007, 0.022,
                  0.036, 0.046,  0.007 , 0.069,
                  0.231, 0.463, 0.100, 0.016, 0.023],
    'Impact': [-2.502, -0.209, -0.126,  -0.002, -0.002,
               -0.209, -0.002, -0.002,
               -0.907, -0.049, -0.002,  -0.005,
                0.024, 0.047,  0.608, 0.001, 0.005]
}
df_d_c4 = pd.DataFrame(data_d_c4)

# "Float Glass" and "Glass" to "Glass" in A1-A2
df_a1_a2['Material'] = df_a1_a2['Material'].replace({'Float Glass': 'Glass'})
# "Secondary Glass" consistently in D-C4
df_d_c4['Material'] = df_d_c4['Material'].replace({'Secondary Glass': 'Glass'})
# Create pivot tables
pivot_data_a1_a2 = df_a1_a2.pivot_table(index= 'Material', columns='Meter', values='Impact', aggfunc='sum').fillna(0)
pivot_data_d_c4 = df_d_c4.pivot_table(index='Material', columns='Meter', values= 'Impact', aggfunc='sum').fillna(0)
# Colors for consistency with the first code
colors = {
    "V200": 'red',
    "V200P": 'green',
    "Multical 21": 'blue'
}
#######################################################################
# Plot for A1-A2 stage
fig, ax = plt.subplots(figsize=(12, 8))
pivot_data_a1_a2.plot(kind='bar', stacked=True,  ax=ax, width=0.8, color=[colors['V200'], colors['V200P'], colors['Multical 21']],  alpha=0.4)
ax.set_title( 'Environmental Impact Contribution by Material and Water Meter (A1-A2)', fontsize=14)
ax.set_ylabel( 'Environmental Impact', fontsize=12)
ax.set_xlabel('Material', fontsize=12)
ax.legend(title='Water Meter', fontsize=10)
plt.xticks(rotation=45, ha='right')
plt.tight_layout()
plt.show()

# Plot for D and C4 stages
fig, ax = plt.subplots(figsize=(12, 8))
pivot_data_d_c4.plot(kind='bar', stacked=True, ax=ax, width=0.8, color=[colors['V200'], colors['V200P'], colors['Multical 21']], alpha=0.4)
ax.set_title('Environmental Impact Contribution by Material and Water Meter (Stages D and C4)', fontsize=14)
ax.set_ylabel('Environmental Impact', fontsize=12)
ax.set_xlabel('Material', fontsize=12)
ax.legend(title='Water Meter', fontsize=10)
plt.xticks(rotation=45, ha='right')
plt.tight_layout()
plt.show()
```