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TESI DI LAUREA

Design and Development of a New Circularity Potential Index Metrics for the Textile Industry: The Case of OVS SpA

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To my parents
and friends

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Abstract

Globally, the textile industry is one of the most resource-intensive sectors, and it is mostly characterized by a linear economy where the majority of garments ends up in landfill or incineration at the end of its life. OVS S.p.A., one of Italian fashion retailers, has developed Eco Valore, which allows customers to discover how much water is used in the manufacturing process, the carbon footprint, and the circularity score at the product level of each garment sold on its e-commerce site. The method to measure circularity was developed in 2019 with a scoring tool called CPIT (Circular Potential Index for Textile), which assigns a 1-10 score to quantify the circularity of a product. As the model was developed based on earlier methodological assumptions from a general Product Environmental Footprint (PEF) and a new Product Environmental Footprint Category Rules (PEFCR) for apparel and footwear was published in 2025, several methodological gaps and room for improvements have been identified and a new method for CPIT is developed. Key methodological changes include replacing the deterministic end-of-life assumption with a probabilistic allocation to recycling (R2), energy recovery (R3), and disposal (RD) pathways, incorporates recycling quality factors, replaces penalty factors with PEFCR-based disruptor criteria, and modification of the existing normalization anchors. The new method is applied to OVS database to evaluate its practical implementation and compare the results with the previous methodology.

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Introduction

The fashion industry is one of the largest and most polluting industries in the world, with the production and distribution of fast fashion contributing significantly to environmental degradation and social injustice (Heinze, 2020; Caniato et al., 2012). In the EU in 2020, textile consumption accounts for the fourth-highest negative impact on the environment and on climate change, the third highest for water and land use, and the fifth highest in terms of raw material use and greenhouse gas emissions from a global life cycle perspective (European Environment Agency 2022).

At the same time, there is a growing recognition of the need for sustainability in the fashion industry, with consumers increasingly demanding more sustainable and responsible practices from fashion companies (Khan et al. 2025). OVS, one of the leading Italian fashion retailers on the Italian clothing market, has developed Eco Valore, which allows customers to discover how much water is used in the manufacturing process, the carbon footprint, and the circularity score at the product level of every OVS garment sold on the e-commerce site (OVS S.p.A. and CESQA, University of Padua 2023).

The method to measure circularity was developed in 2019 with a scoring tool called CPIT (Circular Potential Index for Textile), which assigns a 0-10 score to quantify the circularity of a product. As the model was developed based on earlier methodological assumptions from a general Product Environmental Footprint (PEF) and a new Product Environmental Footprint Category Rules (PEFCR) for apparel and footwear was published in 2025, several methodological gaps and room for improvements have been identified such as: the deterministic assignment of products to a single end-of-life (EoL) pathway, the exclusion of disposal as a potential EoL option, and the assumption of perfect substitution (1:1) between recycled and virgin materials, without accounting for quality loss.

This thesis aims to address these gaps by updating the CPIT methodology in line with the 2025 PEFCR guidelines, with the objective of reflecting more realistic end-of-life scenarios and improving the robustness of circularity quantification. The study is structured around the following research questions:

1. How do updated PEFCR guidelines influence the modelling of end-of-life scenarios in the CPIT scoring?

2. To what extent do methodological refinements (split pathways, disposal inclusion, and quality loss assumptions) affect the circularity scores of textile products?

3. How do different anchoring and normalization approaches influence the interpretation and comparability of CPIT results?

1 Context Analysis and Literature Review

The chapter contains the background on how circularity assessment is increasingly needed in the textile sector and how it is currently approached in research, industry, and policy. The environmental pressures related to the textile industry will be highlighted, followed by the key concepts of circular economy in textile. The chapter also reviews the European policy landscape related to it, and finally, examines existing circularity scoring frameworks/methods, with a focus on the Product Environmental Footprint (PEF) and the recently published Product Environmental Footprint Category Rules (PEFCR) for Apparel and Footwear.

1.1 Fashion Industry and Global Environmental Burdens

In recent years, the fashion industry has received a rising amount of criticism due to its both social and environmental impact. The fashion industry is responsible for up to 10% of global carbon emissions and is predicted to emit nearly 2.8 billion tonnes of GHG emissions annually by 2030 (Niinimäki et al. 2020) and according to Ellen MacArthur Foundation, it is estimated that the textile industry will account for a quarter of the world's carbon emissions by 2050 if it continues along this path (Ellen MacArthur Foundation n.d.).

The rise and emergence of fast fashion, with its business model of rapid manufacturing of massive amounts of clothes at the lowest and most competitive prices, has made the issue worse by increasing the material throughput in the system. For instance, fashion brands are now producing almost twice the amount of clothing today compared with before the year 2000 (Remy and Speelman 2016).

In Europe, a 40% increase in clothing purchases was observed during the period 1996–2012. For example, in Italy, more new clothes are bought per person per year, quantified as 14.5 kg (Dahlbo et al. 2017). In parallel, the average garment-use time has decreased by 36% compared to 2005 which suggests disposal after little use (Ellen MacArthur Foundation 2017). As shown in Figure 1.1, by the 2010s, textile production growth overtook world-population growth due to the rise of fast fashion.

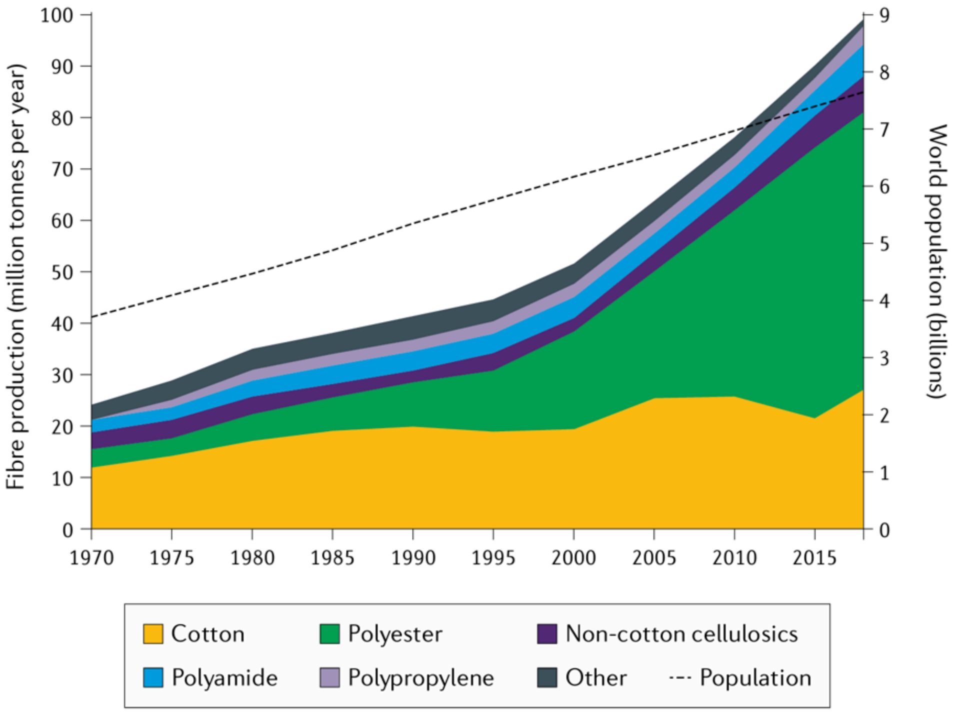


Figure 1.1: Growth in global population and textile production by fibre type, with silk and wool represented together as 'other' (Niinimäki et al. 2020)

Globally, around 92 million tonnes of textile waste are accumulated at different phases of their life cycles. Among those, 50% is released at a post-consumption level, with only 15-20% of it being collected for reuse and recycling, while the rest is discarded in landfills for dumping and/or incineration, which leads to a higher carbon footprint, energy consumption, and loss of raw materials (Shamsuzzaman et al. 2025).

Beyond greenhouse gas emissions and waste generation, fashion industry places significant pressure on freshwater resources and contributes to chemical pollution across its value chain. It was estimated that the industry consumes 93 billion cubic meters of water annually, discharges 20% of the global industrial wastewater, and 200,000 tons of untreated dyes which puts the industry as the second largest water-polluting industry in the world.

1.2 Circular Economy in Textile Sector

Circular economy, in contrast to the linear economy with its take-make-waste model, has become an important principle to address environmental issues in the various industries. According to Ellen MacArthur Foundation, the circular economy is based on three principles: Eliminate Waste and Pollution; Circulate products and materials; and Regenerate Nature. It encompasses strategies that intervene at various levels, from material, product, business, to system. At material levels, circularity involves using renewable, recyclable, and non-toxic inputs that can safely cycle within biological or technical systems, such as the adoption of recycled fibres or bio-based materials in manufacturing (Ellen MacArthur Foundation n.d.).

At the product level, circularity emphasises longevity, durability, repairability, and modularity. For example, each product should be made with long use in mind, with long lasting quality, by using durable materials, quality manufacturing techniques, high quality trimmings, as well as designing to ensure that products can be repaired (United Nations Environment Programme 2023).

As for the business level, innovations are related to a change in narrative for the textile industry, across brand campaigns and advertising, as well as traditional and social media. For example, businesses can create an innovative circular and low impact business model and set and deliver targets on shifting their business revenue and investment from linear to circular and more sustainable business models. They can design products intentionally for circular models and emotional and physical longevity (United Nations Environment Programme 2023).

And last, system-wide interventions are not less essential to address structural barriers that can hinder circularity in textile sector. An effective system that coordinates different stakeholders across design, manufacturing, consumption, waste management, and policy is essential to achieve a closed-loop textile system. Extended Producer Responsibility (EPR) schemes, mandatory separate textile collection, eco-design regulations, and Digital Product Passports (DPPs) are some of the examples.

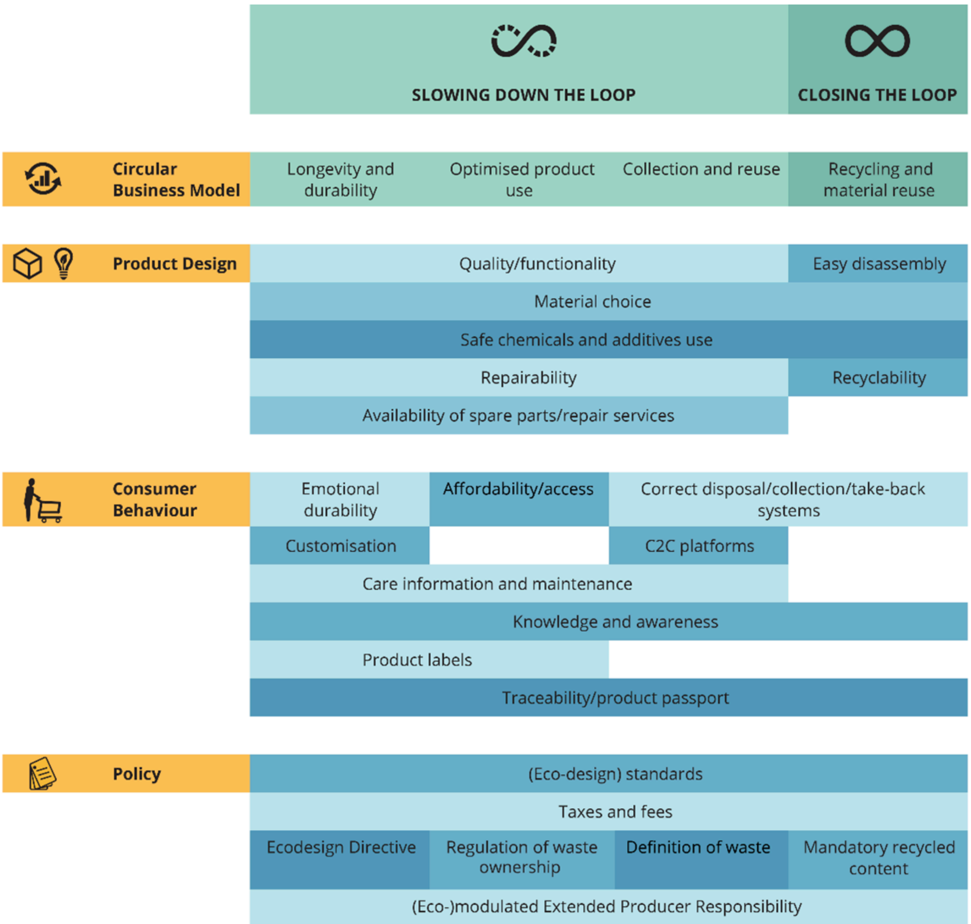


Figure 1.2: Overview of linkages between the circular business model, product design, consumer behaviour and policy (European Environment Agency 2022)

1.3 Circular Economy throughout Textile Value Chain

The textile and fashion industry has a long and complex supply chain. From agriculture, chemical manufacturing to the manufacturing of clothes itself is spread out globally and often, each step of garment production occurs in a different country. Understanding the value chain is important to identify environmental impacts and opportunities for circularity in its life cycle.

At each stage, the fashion industry exerts impacts. In terms of greenhouse gas emissions, textiles are responsible for fifth largest climate impact among household consumption coming after housing food, and transport, with a total of 121 million tonnes CO_2-eq or 250 kg CO_2-eq per person in EU in 2020 (European

Environment Agency 2022).

Research done on the contribution of the different life cycle stages to the climate impacts of Swedish clothing showed that about 80% of the total climate change impact of textiles occurs in the production phase, 17% in the use phase, and 3% during end of life (Östlund et al. 2020).

In the production phase, greenhouse gas emissions came from fibre production, yarn and fabric production, dyeing and finishing steps, and confectioning. During this phase, the climate impact differs according to the type of fibres. For instance, generally, cotton fibres have the lower CO_2 emissions (kg/kg fibre) compared to synthetic fibres such as nylon and acrylic, as they have a fossil origin and use up large energy consumption during production (European Environment Agency 2022). However, from a cradle to gate analysis from raw material extraction to manufactured greige fabric, cotton often represent higher environmental burden than polyester due to its intensive water use and manufacturing steps of spinning and weaving which require substantial energy (Van Der Velden et al. 2014).

For the distribution phase, emissions are typically caused by transport and retail activities, whilst the use phase is caused by clothes laundry activities such as washing, drying, and ironing. And last, for End-of-Life treatment, the emissions came from activities related to disposal, collection, sorting, and landfilling or waste to energy process. Even though the impact of the End-of-Life phase is relatively low, it has a significant resource and economic loss as only little amount is recycled thus there is a loss of potential to decrease impacts across all stages (United Nations Environment Programme 2023).

End-of-Life management is an essential component of a circular textile system, especially for post-consumer textile waste. The transition from consumer use to waste generation occurs at a fast pace; for example, the use life of three types of clothing (T-shirts, knit collared shirts, and woven pants) in six countries (China, Germany, Italy, Japan, the UK and the USA) averaged only 3.1 to 3.5 years per garment, which led to an increase in landfill textile waste (Niinimäki et al. 2020).

EcoTLC mentioned that post consumer textile waste scenarios are divided into 2 categories of those collected and sorted separately and those collected with municipal solid waste. Separately collected waste is then divided into 3 main streams of reuse, wipers and insulation whilst those collected with municipal solid waste go into two general streams of incineration with energy recovery and landfill (Quantis 2025).

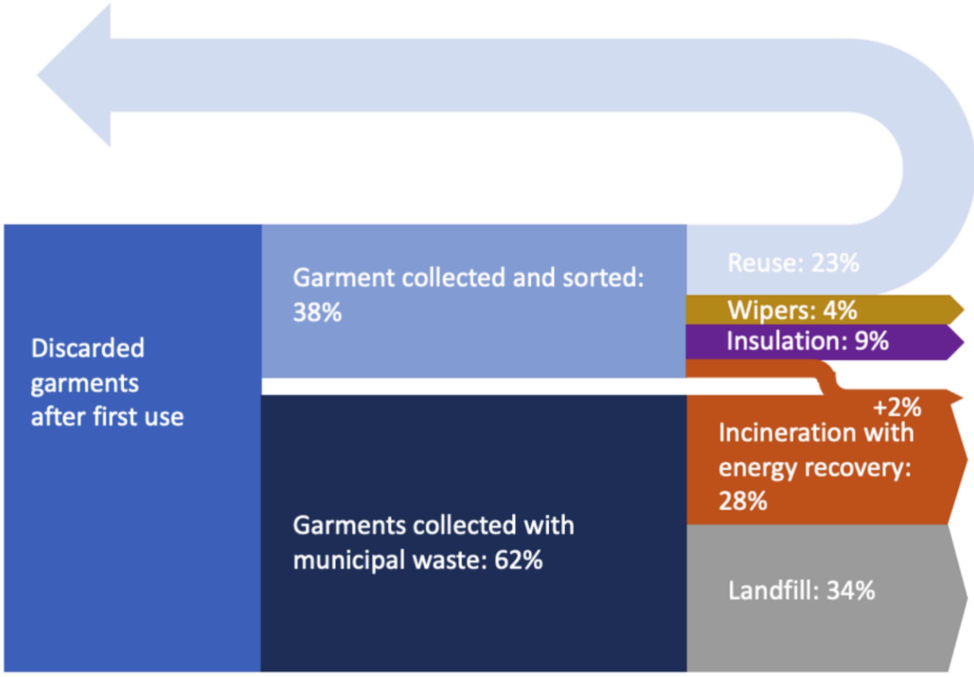


Figure 1.3: Post-consumer apparel scenarios (Quantis 2025)

Given the accelerating turnover of garments and the high portion of landfilling and incineration over reuse and recycling, it highlights the inefficiencies within the current linear model and the urgency of implementing circular strategies to reduce overall impact of the industry.

Textile companies are increasingly embracing CE practices, driven by the rising of environmental awareness and the opportunity of gaining competitive advantage through sustainable products that enhance corporate reputation and appeal to the increasing number of environmentally aware consumers. However, despite the growing momentum around circularity in the textile sector, significant barriers continue to constrain the progress. Challenges related to the management of textile waste from collection, handling, and segregation remain as major obstacle. Additionally, many garments are produced using mixed materials with varying characteristics and structures to achieve specific functional properties which makes waste sorting more difficult. The obstacle is further compounded by the lack of recycling technology capable of processing mixed materials, different colors, and multi-layer textile products. For instance, at the technological level, textile-to-textile recycling, which is the most desirable closed-loop pathway is still commercially limited. While chemical recycling technologies to process cellulosic and synthetic blends are advancing, the scalability is hindered by high costs, limited infrastructure, and again, the complexity of the garment blends.

These barriers highlight that the transition to a circular textile system remains a work in progress, requiring coordinated efforts across technology, business models, and consumer engagement.

1.4 European Policy Landscape

In 2020, the European Green Deal was established, creating the EU's roadmap to achieve the goal of becoming a climate-neutral continent by 2050 through policies aimed at reducing net greenhouse gas emissions by at least 55% by 2030. One of the main building blocks of the European Green Deal is the Circular Economy Action Plan, which focuses on keeping resources in the EU economy for as long as possible through design and production, with measures along the entire life cycle of products (European Commission n.d.).

In 2022, as a part of the Circular Economy Action Plan, the European Commission adopted the EU strategy for sustainable and circular textiles with the aim of improving how we produce and consume textiles, as their impact on the environment continues to grow. One of the actions that was done by the commission is the implementation of the "Eco-design for Sustainable Products Regulation" (ESPR), which was proposed in 2022, where a framework to set eco-design requirements for products, including textiles, was created (European Commission n.d.).

The ESPR aims to replicate the success that was achieved with the Energy Labelling Framework, but on a broader scale for a much wider range of products. ESPR, with its strong focus on product information, will be a powerful tool to help consumers make more informed choices, thus creating a behavioural change that can bring more environmental sustainability benefits beyond regulating minimum performance (European Commission 2025).

According to the communication from the European Commission published in April 2025 on the Eco-design for sustainable products and energy labelling working plan for 2025-2030, textile ranked 1st as products to be prioritized in the inclusion to the working plan due to its high potential to improve product lifetime extension, material efficiency and to reduce impacts on water, waste generation, climate change and energy consumption. It was indicated that the timeline for the adoption will be in 2027 (European Commission 2025).

The ESPR will provide the possibility to set mandatory requirements for all physical products on the EU market to be more sustainable, such as durability, reusability, upgradability, repairability, energy and resource efficiency, recycled content, etc (European Commission 2025).

1.4.a Digital Product Passport

Some of the tools being developed by the commission include the Digital Product Passport (DPP), which has the aim to enhance transparency across product value chains by closing the gap between consumers demands for transparency and lack of reliable data through making accessible information on a product's origin, materials, environmental impact, and disposal recommendations (European Commission 2025).

The DPP will allow consumers, businesses and relevant public authorities, to share relevant data about a product's sustainability, durability and other environmental aspects thus helping them in making informed decisions and eventually, increase the demand for sustainable products, support innovation and reduce environmental impact.

The DPP requirement will become mandatory starting in 2027 for priority product groups, including textiles, with full rollout expected by 2030. Additionally, in April 2025, the commission also rolled out two new legal acts establishing horizontal rules which standardise sustainability criteria and provide businesses with a clear framework to innovate and compete in EU's evolving circular economy (European Commission 2025).

Some of the data that must be contained in the DPP to comply with ESPR comprise of categories such as: product identification, performance information, substances of concern, instructions for use, maintenance, and end-of-life treatment, sustainability information on recycled and renewable material content, and details on microplastic release, modularity and repairability, and recyclability and circularity (European Commission 2024).

1.4.b Relevance for Fashion Retailers

For fashion retailers operating in, specifically, European markets are expected to shift toward circularity and environmental transparency. Not only driven by voluntary sustainability commitments, but also by regulatory, market, and consumer pressures. In addition to the need to reduce the environmental impacts across the supply chain, there's an emerging requirement for these retailers to also demonstrate traceability, durability, recyclability, and responsible end-of-life management of their products. Due to these reasons, tools to quantify product-level sustainability performance are not only beneficial in the point of view of internal requirements but also strategic compliance and market positioning tools.

Additionally, from a regulatory standpoint, as mentioned in 1.4. The European Commission has placed textiles among the priority product groups to be targeted by the ESPR and the future Digital Product Passport (DPP). The soon-to-be-established regulations will require fashion retailers to substantiate environmental claims by using standardised methodologies.

In parallel, consumer expectations are shifting, with consumers increasingly favoring environmentally friendly and socially responsible clothing (Khan et al. 2025). According to a study by Schiaroli et al. (2024), companies should make the sustainable characteristics of products easy to recognize (e.g., clarifying sustainable messages and using easy-to-understand labels) to make it easier for consumers to differentiate sustainable products from the traditional alternatives. Therefore, there's an increasing need for science-based scoring tools that is easily communicated to consumers.

1.5 Measuring Circularity

This section provides a brief overview of existing circularity frameworks/methodologies especially in the textile sector to illustrate the diversity of options and practices. Ranging from international standards such as the ISO 5900 series, to voluntary methodologies like Circulytics and the Global Circularity Protocol, and finally to the EU-harmonised Product Environmental Footprint (PEF) and its sector-specific PEFCR for Apparel and Footwear. Together, these systems provide the key basis for how circularity is measured today and inform the updates developed in this thesis.

1.5.a Overview of Existing Standards & Methodologies

ISO 5900 Series

International Organizations for Standardization (ISO) is well known to establish standards of best practices to be followed for many types of activity. It is voluntary and are used by companies and policymakers as a reference point. In May 2024, ISO published the ISO 5900 series on circular economy (International Organization for Standardization 2024).

ISO 59020, in particular, gives guidance and requirements for measuring and assessing circularity performance. The standards provide standard indicators as well as complementary methods to be followed. The scale of the framework is applicable to various system from regional level, interorganizational level, organizational level, and product level. The framework consists of 3 stages, which are boundary setting, circularity measurement and data acquisition, and circularity assessment and reporting (International Organization for Standardization 2024).

In the circularity measurement and data acquisition stage, key core circularity indicators, both the mandatory and optional ones are listed. The mandatory indicators are divided into two categories which are resource inflows (reused content, recycled content, and renewable content of an inflow) and resource outflows (reused product from outflow, recycled material from outflow, recirculation of outflow in the biological cycle). Optional indicators include average lifetime of product or material relative to industry average, renewable energy consumed, indicators related to water use and discharge, material productivity, and resource intensity index (International Organization for Standardization 2024).

Circulytics

In 2020, Circulytics was launched by Ellen MacArthur Foundation which offered companies individual performance assessment of their circularity performance if they submitted the required data. In 2023, the platform is closed for submission as the foundation encouraged companies to follow European Sustainability Reporting Standards (ESRS 5) for the circularity performance. However, circulytics methodology to quantify the performance is still available for reference, as there are some circular economy metrics, particularly under resource inflow and resource section that is not included in ESRS E5 (Ellen MacArthur Foundation 2021a).

The data submission was done through the submission of a form which consists of questions of 11 themes which are divided into 2 categories of enablers and outcome. For the enablers category it includes themes that "enables" company wide transformations such as strategy and planning, innovation, people and skills, operations, and external engagement. Whilst outcome category includes themes that can capture the circularity of the company at present such as products and materials, services, plant property and equipment assets, water, energy, and finance (Ellen MacArthur Foundation 2021b).

Global Circularity Protocol

Global Circularity Protocol (GCP), is a global voluntary framework that is designed to provide organizations with standard method for measuring, managing, and communicating their circularity performance and associated impacts. The framework was a result of collaboration between over 80 organizations and coordinated by World Business Council for Sustainable Development (WBCSD) in partnership with the One Planet Network (OPN), hosted by the United Nations Environment Programme (UNEP) (World Business Council for Sustainable Development and One Planet Network 2025).

The framework is a step-by-step process which is applicable to different scales (material, product, business unit, or organization level). The framework follows five stages which includes: Frame (defining the objectives, use case, assessment level, and progressive user journey level), prepare (define organizational and operational boundaries, value chain mapping to identify circularity hotspots, and determine material impacts, risks, and opportunities (IROs), measure (select indicators, collect data, and calculate performance metrics, manage (translate results into action by analysing performance, prioritizing interventions based on IROs, developing an action roadmap, and establishing strategic governance structures), communicate (share assessment results with external stakeholders (investors, regulators, customers, and value chain partners) (World Business Council for Sustainable Development and One Planet Network 2025).

Stage 3 is most relevant to measure circularity in the product level. Stage 3 is split into two categories, circular performance assessment and circular value and impact assessment. The two categories consist of four modules of indicators which are based on WBCSD's Circular Transition Indicator (CTI) (World Business Council for Sustainable Development and One Planet Network 2025).

1. Close the Loop module: measures the effectiveness of material retention in productive use, specifically focusing on sourcing and recovery. Indicators consist of % Circular Inflow, % Circular Outflow, % Material Circularity, % Critical Materials

2. Narrow and Slow the Loop Module: measures resource efficiency by reducing the material volume used and extending the useful life of products. Indicators consist of % Absolute Dematerialization, % Relative Dematerialization, Actual Lifetime

3. Value the Loop Module: quantifies the financial outcomes generated by circular strategies. Indicators include Circular Material Productivity and Material Circularity Revenue

4. Impact of the Loop Module: assesses how circular strategies affect broader sustainability outcomes, requiring three key calculations. Indicators include GHG Impact, Nature Impact, and Social Impact.

The GHG Impact indicator, in particular, measures emissions savings from circular sourcing and recovery. It provides a high level of GHG emissions savings by evaluating trade-offs when applying circular strategies. It uses "allocation, cut-off by classification" system model which allows non-virgin material users and producers to benefit from inputs that carry no production-related emissions burden, while also incentivizing primary material producers to support product and material recovery to reduce emissions from landfill and incineration. For closed-loop recycling system the GCP uses the following formulas:

Inflows

In the inflow side, the formula evaluates a scenario in which a product contains inflow sourced from multiple recovery strategies (for example using recycled material as opposed to virgin).

$$\textit{Savings on inflow} = (M_t \times GHG_c) - (M_c \times GHG_c) - (M_l \times GHG_l) \tag{1.1}$$

Mt = total mass material

GHGc = emissions factor of sourcing the secondary material (kgCO2/kg)

Mc = circular inflow mass (e.g., reused or recycled)

GHGl = emissions factor of sourcing the linear material (kgCO2/kg)

Ml = linear inflow mass

Outflows

$$Absolute\ Savings = GHG_l(M_c - M_t) \tag{1.2}$$

Mt = total mass material

GHGl = emissions factor of the linear recovery method: incineration, landfill

Mc = circular outflow mass

Product Environmental Footprint (PEF) and PEFCR for Apparel & Footwear

The Environmental Footprint (EF) methods consist of Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF). They were developed by the European Commission in 2013 and provide guidelines and rules to help companies quantify their environmental performance and assess its environmental impacts of their products throughout the life cycle. It is recommended by the commission to use it as a common way of measuring and communicating the environmental performance of products/organisations (Quantis 2025).

In 2019, the apparel and footwear project was selected by the European Commission, which prompted the establishment of the Technical Secretariat (TS) to create Product Environmental Footprint Category Rules (PEFCR) specifically for the apparel and footwear category. The project kicked off in 2020, and in April 2025, the TS voted to approve the final apparel and footwear PEFCR, which concludes five years of development. It is a key step to harmonize the assessment of environmental impact through a unified rule to obtain the product environmental footprint. It defines system boundaries, life cycle stages, datasets, impact categories, and modeling assumptions for aspects such as recycled content, energy recovery, and material quality losses (PEF Apparel Footwear 2025).

One of the component of the PEFCR for textiles is its approach to end-of-life (EoL) modelling, implemented through the Circular Footprint Formula (CFF). The CFF provides a way to account for recycled material inputs, recycling outputs, energy recovery, disposal, and changes in material quality across multiple product life cycles (Quantis 2025).

Regulatory-wise, PEFCR is also a tool recognized by the European Commission and is closely linked to the major regulations such as Eco-design for Sustainable Products Regulation (ESPR), the Green Claims Directive, and the Corporate Sustainability Reporting Directive (CSRD).

The Circular Footprint Formula in the PEFCR modelled the end-of-life of products as well as the recycled content. It is a formula that combines the use of recycled materials as inputs in production and the recyclability of materials at the end-of-life stage. The formula considers both material flows and quality factors to ensure that the environmental benefits of circularity are not overstated. The formula itself consists of three main parts that calculates environmental impacts involving recycling, recovery, and end-of-life, it is a summation of three primary components of material, energy, and disposal (Quantis 2025).

1. **Material**: accounts for environmental inventory related to the usage of materials which include primary material input (non-recycled/non-reused virgin resources), secondary material input (materials sourced from re-

cycled content), material recycling process (impact associated with the process of recycling the material), and credit for avoided primary material (benefit from substituting virgin material with recycled input through allocation factor of burden and credits).

$$\begin{aligned}(1-R_1)E_v + R_1 \times \left(AE_{\text{recycled}} + (1-A)E_v \times \frac{Q_{\text{sin}}}{Q_P}\right) \\ +(1-A)R_2 \times \left(E_{\text{recyclingEOL}} - E_v^* \times \frac{Q_{\text{sout}}}{Q_P}\right)\end{aligned} \tag{1.3}$$

2. **Energy**: Impact of energy recovery from the product at its end-of-life. Key elements include the LHV (Lower Heating Value) of the material and energy efficiency factors.

$$(1-B)R_3 \times \left(E_{ER} - LHV X_{ER,\text{heat}} E_{SE,\text{heat}} - LHV X_{ER,\text{elec}} E_{SE,\text{elec}}\right) \tag{1.4}$$

3. **Disposal**: Measures the environmental impact associated with fraction of material that is not recycled/reused or recovered energy and goes to disposal.

$$(1-R_2-R_3) \times E_D \tag{1.5}$$

1.5.b Framework Selection

The landscape of circularity and environmental assessment methods are gaining a lot of traction. Frameworks such as ISO 59020, Circulytics, and the Global Circularity Protocol can provide valuable structures to evaluate circularity, with variation in scope, system boundaries, and methodological depth.

While ISO 59020 provides a standardised indicator set applicable across scales, it does not provide sector-specific default values or life cycle inventory guidance, meaning its application at the product level requires significant additional modelling assumptions. Circulytics, as a company-level tool, is not designed for product-level scoring and has been discontinued for new submissions. The GCP offers a more structured product-level methodology and includes a GHG impact module but similarly lacks apparel-specific parameters and has not been formally recognised in EU regulatory frameworks.

The PEFCR for Apparel and Footwear published in 2025, offers the most suitable basis for updating the CPIT for several reasons. First, it provides sector-specific default values, allocation factors, quality ratios, and end-of-life pathway assumptions tailored to textile products. Second, it is formally recognised by the

European Commission and is closely linked to emerging EU legislations such as the ESPR, the Green Claims Directive, and the CSRD. Third, its Circular Footprint Formula (CFF) was the foundation which the original CPIT was built, meaning that aligning updates with the latest PEFCR improve the existing methodology rather than completely changing it. For these reasons, this thesis uses the PEFCR as the main methodological reference for the updated CPIT.

2 Object of the Study

This chapter includes a case study on OVS S.p.A and its Circular Potential Index for Textile (CPIT), following the theoretical and regulatory context that was elaborated in Chapter 1. This chapter provides an overview of the company and its sustainability strategy and the existing CPIT which will be updated and evaluated in Chapter 3.

2.1 Company Profile: OVS

OVS is a leading fashion retailer in Italy with over 2,200 stores worldwide. It was born in Venice in 1972 as a division of Coin S.p.A and then expanded its presence in Italy and eventually Gruppo Coin transferred the business unit to the newly formed Oviesse S.r.l, a subsidiary of Gruppo Coin S.p.A of that transformed into Oviesse S.p.A in 2005. Since then, the company grew and acquired/created more brands as follows:

1. OVS: Leading Italian brand in the clothing market with around 1,300 stores.

2. OVS Kids: Brand with target audience of children 0-15 years old, with presence in Italy and abroad.

3. Piombo: Contemporary brand of clothing for men, women and children, designed by Massimo Piombo.

4. Upim: Italian family department store, offering wide and varied options

ranging from clothing for the whole family, to beauty and home

5. Blukids: a brand specialising in clothing for children aged 0 to 15.

6. Les Copains: Italian brand, acquired by OVS S.p.A. in 2022

7. Croff: Italian brand for home decoration

8. Stefanel: Contemporary clothing brand dedicated to women, famous for the design and quality of its knitwear

With more than 2,200 stores worldwide and tens of thousands of products across many different categories, its product choices have a significant environmental impact making it both necessary and challenging to assess its performance in terms of environmental sustainability.

2.2 OVS Sustainability Strategy and Eco-Valore

Mentioned in OVS's sustainability report, the company's sustainability commitment is structured around the 4 key pillars in their sustainability plan:

- Design for circularity
- Being fair and transparent
- Design a better work
- Making fashion a better choice

The fourth pillar of *making fashion a better choice* is most directly relevant to this thesis, as it includes the company's efforts to improve its product level transparency and provide consumers with information needed to make an informed decision.

Eco Valore

As a part of *making fashion a better choice* sustainability pillar, one of OVS's plans to reach one of its macro-objectives of "Adaptation of the Green Claim Directive" and "New product traceability available to customers" is through an initiative called "Eco Value" or *Eco Valore*.

Eco Value allows OVS to communicate each garment's information on the materials of composition, the supplier who produced it, and the impact calculated on three key indicators, which are:

1. Water consumption: the amount of water used to produce the garment
2. CO_2 Emissions from product production phase
3. Circularity Index: a value ranging from 1 (least circular) to 10 (most circular).

Since 2021, the Eco Value index has been applied to all the products on OVS's e-commerce.

Figure 2.1: Example of Eco Valore of a 100% wool sweater in OVS e-commerce

Other than Eco Valore, OVS also has initiatives that focus on the collection of used garments, which is a part of its circularity efforts. Since 2022, for instance, OVS has been in partnership with Humana People to People Italia. Customers can take back clothing items to over 800 OVS stores and where 87% of the items go to reuse and resale markets, 10% goes to production of recycled fibres, and 3% goes to disposal.

2.3 Review of the Original CPIT Methodology

The CPIT that is used by OVS to calculate and communicate the circularity index of its garments was developed by CESQA of the University of Padua, where some preliminary studies regarding recycling processes and existing circularity measurement methods on textiles were made. The study were made to replace a previous one in Eco Valore, which was based on general considerations regarding the possibility of a textile going to be recycled at the end of its life, considering the fibre type, number of fibres, and number of components. The update improved the previous version by also focusing on garment life cycle stages with the most significant impact on circularity: raw material origin and the end-of-life treatment, considering the current state of textile recycling and recovery.

The CPIT adapts the Circularity Footprint Formula (CFF) proposed by the European Commission to model the end-of-life in the Product Environmental Footprint, modifying it to produce a normalised 0-10 circularity score scale. In the index, three core formulas are employed, with parameter definitions provided in the Appendix:

$$CPIT = \left(10 - 10\frac{MCFF - PCFF^*}{LFF^* - PCFF^*}\right) \cdot P \tag{2.1}$$

1. Linear Footprint Formula (LFF): Represent the worst-case scenario, a textile's impact at its linearity, assuming the garment is made entirely from traditional raw materials and will go to disposal at its end-of-life.

$$\text{LFF} = E_v + E_D \tag{2.2}$$

2. Potential Circular Footprint Formula (PCFF): Represent the best-case scenario the textile's impact at its theoretically most circular self, assuming a garment is made from secondary or innovative raw materials and will go to their best end-of-life option.

$$\begin{aligned} \text{PCFF} &= (1 - R_1)E_0 + R_1 E_{\text{Recycled}} \\ &+R_2(1-A)\left(E_{\text{RecyclingEoL}} - E_{v^*}\frac{Q_{\text{sout}}}{Q_p}\right) \\ &+R_3 E_v\left(E_{\text{ER}} - \text{LHV}X_{\text{ER,heat}}X_{\text{SE,heat}} - \text{LHV}X_{\text{SE,elec}}E_{\text{SE,elec}}\right) \end{aligned} \tag{2.3}$$

3. Modified Circular Footprint Formula (MCFF): Calculates the impact at the garment's actual state, considering its actual raw material and considering that it will go to its best end-of-life option.

$$\begin{aligned} \text{MCFF} &= (1 - R_0 - R_1)E_v + R_0 E_0 + R_1 E_{\text{recycled}} \\ &+R_2(1-A)\left(E_{\text{recyclingEoL}} - E_{v^*}\frac{Q_{\text{sout}}}{Q_p}\right) \\ &+R_3 E_v\left(E_{\text{ER}} - \text{LHV}X_{\text{ER,heat}}E_{\text{SE,heat}} - \text{LHV}X_{\text{ER,elec}}E_{\text{SE,elec}}\right) \end{aligned} \tag{2.4}$$

2.3.a Data Sources and Key Assumptions

The OVS database provides information on the material composition of an item while emission information was gathered from various data sources in the literature and SimaPro. The study highlighted some assumptions that were necessary to make the formulas functional with the available data. These assumptions are:

1. Economic considerations were excluded

2. Closed-loop recycling was avoided by system expansion, while allocation for open loop recycling was made considering the Circular Footprint Formula's general guidelines.

3. A substitution of 1 to 1 is assumed. Which means that the quality of the recycled material (Qsin and Qsout) is equal to the quality of the virgin material (Qp), which does not account for quality degradation during recycling.

4. At end-of-life, each product is assumed to go to its best option with closed-loop recycling treated as the most favourable destination in terms of emissions avoided, followed by open-loop recycling and energy recovery.

2.3.b Penalty Factor

A penalty was imposed based on the number of components. The goal of the penalty is to consider for garment complexity. The higher the number of components, the more complex a garment is and the more difficult it is to recycle, thus, the higher the probability of the item going to a non-closed-loop end-of-life destination. In the formula below, n is the number of components, and P is bounded between 0.5 and 1, which can lead to the decrease of circularity index score by half. It was noted that Zip, buttons, labels, and stamps were not considered, as their presence is not reported in OVS database.

$$P = -0.1n + 1.1 \tag{2.5}$$

From the previous result, the penalty is the main driver of the distribution of the scores as it increases the spread of scores across the 0–10 range rather than causing them to cluster around similar values.

Table 2.1: Number of components for each functional macro commodity.

Fun. Macro Commodity	**Number of components [-]**
bath	1
beachwear	3
blazers	6
boxer	3
bras	4
briefs	3
cut and sewn	2
denim	6
dresses	2
dressing	4
miscellaneous	3
new-born	2
nightgown	2
outerwear	6
pyjamas	2
set	2
shirt	6
skirt	2
socks	1
suits	6
textile	1
tricot	4
trousers	6
under	2

2.3.c End-of-life assumptions

According to the study, the End-of-life (EoL) assumptions represents the strongest assumption of the study and was necessary since there was no available data. From the current CPIT method, the EoL destination is determined through a deterministic approach that assigns 100% of the item to a single EoL pathway, which is assumed to be the best available option in terms of circularity and impact avoided.

The choice of EoL destination is made by choosing the process which offers the greatest reduction in emissions (i.e., the most circular option), measured in kilograms of equivalent. The hierarchy was, from best to worse:

1. Closed-Loop Recycling: found to be the most convenient in terms of emissions avoided. This includes mechanical recycling (e.g., wool, cotton) or chemical recycling (e.g., certain polyester or polyamide blends).

2. Open-Loop Recycling: Less convenient than closed-loop recycling, such as transformation into insulation material.

3. Energy Recovery: Less convenient than open-loop recycling.

4. Disposal: Represents the worst case in terms of emissions and is generally not considered as an EoL option for the calculation of the Modified Circular Footprint Formula (MCFF) and Potential Circular Footprint Formula (PCFF), as the model assumes better options exist.

The decision criteria to decide which EoL destination the item is selected using compositional criteria which are summarized in Table 2.2.

For example, if an item is composed of more than 10% of Acrylic it will be assumed that the EoL destination of the item will go to open-loop recycling.

Table 2.2: End of Life Destination Emission

End of Life potential Destination	Emission [$kgCO_2$, eq/kg]	Criteria and Disruptors
Energy recovery	0.23	If metal or glass is present
Open-loop Recycling	-0.216	Elastane + Polyurethane >2%
Open-loop Recycling	-0.216	Acrylic > 10%
Open-loop Recycling	-0.216	Silk is present
Mechanical Recycling Cotton	-2.422	≥ 98% Cotton
Chemical Recycling of Cellulose	-1.032	Cotton + Flax + lyocell + Modal + Viscose + Ramie + Bamboo ≥ 98%
Chemical Recycling of PA	-6.133	Polyamide = 100%
Mechanical Recycling of PET	-0.241	Polyester = 100% or >= 98%
Mechanical Recycling of Wool	-14.37	Alpaca + Cashmere + Mohair + Wool + Merino Wool + Virgin Wool >= 98%
Chemical Recycling Cellulose-polyester Blend	-0.636	(Cotton + Flax + lyocell + Modal + Viscose + Ramie + Bamboo) + Polyester >= 100%
Chemical Recycling Cellulose Blend	-0.70	(Cotton + Flax + lyocell + Modal + Viscose + Ramie + Bamboo) >= 80%
Chemical Recycling Polyester Blend	-0.399	Polyester >= 80%
Open-loop Recycling	-0.216	None of the above

2.4 Anchor

As shown on Equation 2.1, the CPIT formula are "anchored" by two scores: PCFF* and LFF*. These values are used to normalize the results onto a 0-10 scale, allowing the products in the database to be ranked. PCFF* represents the best-performing product, defined by the minimum PCFF of a product found in the database, while LFF* represents the worst performing product, defined as the maximum LFF found in the database.

Silk was identified as an outlier because its emission is a lot higher than the other materials. Therefore, silk was excluded when determining the LFF*. After the exculsion of silk, the LFF* from the original method and the corresponding database was reported to be 21.98 kg of CO_2eq, corresponding to an item that is made wholly from 100% wool. Meanwhile, PCFF* was reported to be -7.39 kg of CO_2eq which corresponds to an item made from 100% of mechanically recycled wool.

For products that contains silk, the CPIT was set to 0 based on the justification that their high impact was not comparable to the rest of the products in the database.

2.5 Limitations and Room for Improvement in the Current CPIT Methodology

As was also acknowledged in the original development of CPIT, certain assumptions and simplifications were made to make the model functional and operational (OVS S.p.A. and CESQA, University of Padua 2023). While it was an important first step to quantify circularity at the product level, it also limits the accuracy and realism of the results. Several gaps have been identified that open room for improvement.

1. End-of-Life Modelling

   In the current CPIT, it is assumed that 100% of the product is assigned to go to its best option of a certain EoL pathway (e.g., closed-loop recycling, open-loop recycling, or energy recovery). The deterministic approach oversimplifies reality, as typically, textile wastes are distributed across multiple pathways. In Europe, for instance, only 1% of textile waste is recycled (Interreg Europe 2024) with the majority going to open-loop recycling, energy recovery, or disposal.

2. Exclusion of Disposal Pathways

   Landfilling without energy or material recovery is a common end-of-life route in textile waste management globally, however, it is not included in the current CPIT, which leads to an optimistic representation of circularity that does not reflect actual market conditions. The exclusion is significant given that most of the textile waste ends up in landfill making disposal one of the dominant end-of-life scenarios.

3. Assumption of 1:1 substitution in recycling

   The current model assumes that recycled fibres replace virgin fibres in equal amounts (Qsin/Qp = 1 and Qsout/Qp = 1), which neglects issues such as quality loss during recycling and performance differences between virgin and recycled fibres. For example, in practice, mechanical recycling of cotton reduces fibre length which results in lower quality output. In addition, the material recovered at end-of-life may not fully substitute the virgin material it replaces.

4. Normalization Anchor

   The scoring scale of the current CPIT is defined by the minimum PCFF and maximum LFF found in the product database, excluding silk as an outlier. Although using actual data distribution to define the scale of the score is a method that is commonly used in sustainability scoring system (Pollesch and Dale 2016), and it enables consumers to compare products across different macro commodity, the scores are not comparable to different database seasons. As the portfolio changes, so will the anchors values change, since new products with either better or worse performance may be introduced. Additionally, the anchor also contributes to the clustering issue that is briefly mentioned in section 2.3.b. This is partly due to the composition of the OVS product portfolio, which primarily consists of cotton-based products. The emissions associated with the least sustainable cotton option (virgin cotton) remain significantly lower than the LFF* anchor value, which is based on a 100% wool product. As a result, a large share of products is mapped close to the upper end of the 0–10 scale. As a result, most products receive relatively high scores, limiting the system's ability to meaningfully differentiate performance between products. This indicates that the anchoring definition plays a central role in both score distribution and comparability and therefore requires reconsideration.

5. Penalty

   The penalty factor P reduces CPIT scores based on estimated garment complexity which is approximated through the number of components per macro commodity. While garment complexity and material circularity are related concepts, e.g. a more complex garment will affect its end-of-life potential, the way the complexity is captured through the penalty introduces several limitations. The penalties are applied uniformly at category level rather than product level and dominate score differentiation more than the underlying circularity formula making the final score reflects garment construction complexity more strongly than the material circularity potential.

3 Methodology

This chapter will elaborate the methodology developed to update the CPIT in alignment with Product Environmental Footprint Category Rules for Apparel and Footwear (PEFCR). Building on limitations identified in Chapter 2, the new method will address five key areas: the end-of-life modelling approach, the inclusion of disposal pathway, the incorporation of material quality factors, the exclusion of the penalty factors and redefinition of normalization anchors.

3.1 Goal, Scope, Functional Unit, and System Boundaries

The goal of this study is to update OVS's Circularity Potential Index for Textile by aligning its end-of-life modelling approach with the recently published Product Environmental Footprint Category Rules (PEFCR) for Apparel and Footwear developed by the European Commission's JRC. The specific objective is, as also mentioned in previous chapter, to address the methodological gaps in the previous index model which includes the deterministic allocation of end-of-life pathways, exclusion of disposal scenarios and the 1:1 substitution assumption for recycled materials. By integrating the PEFCR, the study aims to model a more realistic circularity potential scores for textile products produced by OVS. Additionally, a revised normalization framework is proposed.

The scope of the analysis mainly revolves around the end-of-life stage of textile garments as it is the focus of CPIT and the area where improvements are most methodologically relevant. As with the previous methodology of CPIT, the system boundaries and the considered life cycle stages remain the same, which are: extraction and production of raw materials, yarn production, and the end-of-life. Other life cycles stages such as clothing production, distribution, and use phase, are excluded.

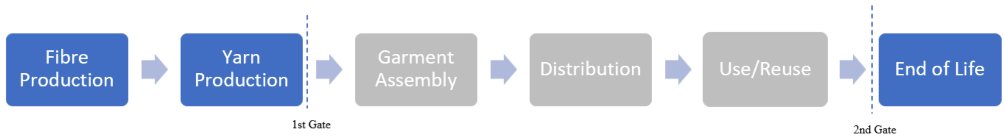


Figure 3.1: Life Cycle Stages of Textile

The CPIT was designed as a circularity potential scoring tool and not a full environmental footprint LCA and its primary scope is end-of-life modelling and material flows. Due to these reasons, stages like distribution and consumer use were not originally part of the model and remain outside the scope of this update. Additionally, reliable data availability and consistency, such as consumer behaviour which relates to the use phase, are highly variable, thus excluding them avoids introducing even more uncertainty into the method.

The functional unit adopted in this study is defined as one garment item of OVS S.p.A., with results expressed per kilogram of product considering composition proportional to the actual declared composition.

3.2 Product Scope

The Eco Valore is applied to all item in OVS's e-commerce. For this thesis, the analysis focuses on the garment categories that constitute the 27 macro commodities used internally by OVS for product classification. These macro categories include a variety of textile products such as shirts, knitwear, trousers, outerwear, dresses, etc.

3.3 Overview of the Updated CPIT Methodology

Based on the limitations identified in Chapter 2, the methodology was updated in four areas:

1. End-of-life modelling: Incorporation of probabilistic pathways to represent actual end of-life scenarios by assigning different percentages of a product's material to different end-of-life scenarios based on PEFCR rates and the presence of recyclability disruptors. A textile product would be modelled

as having multiple potential fates, each with its own associated impact and quality considerations. Additionally, the inclusion of disposal as a possible pathway in end-of-life scenarios is incorporated, reflecting the reality that substantial share of textile waste is landfilled.

2. Quality Factors: Quality-adjusted substitution factors were introduced to account for the reduced substitution potential of recycled materials relative to their virgin counterparts.

3. Penalty Factors: The penalty factor was removed from the CPIT calculation. Product specific recyclability barriers are instead partially captured through the PEFCR disruptor criteria, which affect end-of-life pathway allocation.

4. Normalization Anchors: The original database-dependent anchoring approach was reassessed due to its sensitivity to portfolio composition and seasonal variation. To address these limitations, alternative anchoring approaches were explored and compared. The evaluated approaches and their implications for score interpretation and comparability are discussed in 3.6.2.

The changes for each formula component (MCFF, LFF, and PCFF) are summarized in table below:

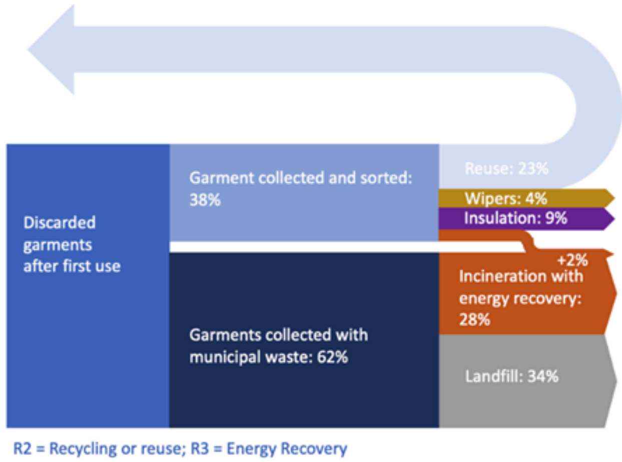
Table 3.1: Modification Summary

Component	***Life Cycle Stage***	***Assumption***	***Current CPIT***	***Modification***	***References***
MCFF and PCFF	EoL	R2: Fraction of material that will be recycled	100% to a certain pathway	Split the pathway based on the presence of disruptors	PEFCR (Quantis, 2025)
	EoL	R3: Fraction of material that is used for energy recovery	100% to a certain pathway	Split the pathway based on the presence of disruptors	PEFCR (Quantis, 2025)
	EoL	Disposal: $(1-R_2-R_3) \times E_D$	Not considered	Inclusion in the formula	
	EoL	Qsout/Qp: Quality of the outgoing secondary material/quality of the primary material	Not considered	Inclusion in the formula	PEFCR (Quantis, 2025)
MCFF, PCFF, and LFF	Raw materials & Pre-Processing	Qsin/Qp: Quality of the ingoing secondary material/Quality of the primary material	Not considered	Inclusion in the formula	PEFCR (Quantis, 2025)
	Raw materials & Pre-Processing	Penalty	Considered	Excluded	

3.4 Updated End-of-Life Modelling

One of the main modifications to the model is to replace the 100% deterministic end-of-life route with a split pathway based on the presence of disruptors, as defined in the PEFCR for Apparel and Footwear. The main End-of-life pathway of the new model is split into recycling (insulation and wiper), energy recovery, and disposal, with default values shown in Figure 3.2.

In the PEFCR-based modelling of post-consumer textile waste, separately collected textiles are typically directed into multiple pathways which includes reuse, mechanical recycling, energy recovery, and disposal. Reuse involves garments being resold or donated for continued use. Mechanical recycling can produce secondary applications such as wiping cloths (wiper) or insulation materials which represents common low-grade recycling outputs. This distribution varies depending on geographic context and dataset assumptions. In this study, the PEFCR default values will be used which is shown in Figure 3.2.



Status in CFF Formula	Rate of End-Of-Life scenario (excluding reuse)
R2_Wipers	5%
R2_Insulation	12%
R3	39%
1 – R2 – R3	44%

Figure 3.2: Post-consumer apparel scenarios & definition of R2 and R3 parameters for the CFF (Quantis 2025)

Textile-to-textile recycling, which would represent the most circular closed-loop pathway by recovering fibres for use in new garments, is not included as an end-of-life pathway in the modification of the CPIT calculation. While chemical and mechanical textile-to-textile recycling technologies exist and are advancing, they remain limited in scale. Including it would overstate the realistic circularity potential of products given the current infrastructure.

However, as the technology scales up, this pathway could be incorporated in the future.

The criteria for whether a certain item is qualified to go the recycling pathway (insulation and wiper) are determined through the presence of disruptors, which are elaborated in Table 3.2.

Table 3.2: Recyclability Disruptors (Quantis 2025)

<table>
<tr><th>Nr.</th><th>Main Disruptors</th><th>R_2 (Wiper)</th><th>R_2 (Insulation)</th></tr>
<tr><td>1</td><td>Less than 80% cotton</td><td>0</td><td>12%</td></tr>
<tr><td>2</td><td>Products with more than 5% elastane</td><td rowspan="2">5%</td><td rowspan="2">0</td></tr>
<tr><td>3</td><td>Coating, flocking, imprint, glue</td></tr>
<tr><td>4</td><td>Products with electrical/electronic equipment</td><td rowspan="3">0</td><td rowspan="3">0</td></tr>
<tr><td>5</td><td>Products with metallic fibres</td></tr>
<tr><td>6</td><td>Multicomposition of the textile part (>2 materials)</td></tr>
<tr><td>7</td><td>Particular knitting (jacquard, warp)</td><td>0</td><td>12%</td></tr>
</table>

Disruptors number 3,4, and 7 in 3.2 will not be evaluated as the product database doesn't provide enough information.

3.4.a End-of-Life Parameters

The end-of-life component of the updated CPIT model considers four possible pathways: recycling into wipers, recycling into insulation, energy recovery, and disposal. Each pathway is associated with specific emission factors, quality ratios, and recovery parameters used in the Circular Footprint Formula calculations. An Environmental Footprint (EF) database exists that contains the parameters required for this model. However, access to this database was not available for this study, which represents one of the key limitations. Therefore, the parameter values used in this study were sourced from existing literature and are summarized in Table 3.3.

Table 3.3: End-of-Life Parameters (Semba et al. 2020; Quantis 2025; City of Winnipeg 2011; Violano and Cannaviello 2023; Henning and Palzer 2014)

Pathway	Parameters	Value	Unit	Source/remarks
Wipers	E*v, wipers	4.61	kg CO_2-eq/kg	(Semba et al., 2020)
	Qsout/Qp	0.30	-	(Quantis, 2025)
	Erec, wipers	0.05	kg CO_2-eq/kg	(Semba et al., 2020)
Insulation	E*v, insulation	1.20	kg CO_2-eq/kg	(City of Winnipeg, 2011)
	Qsout/Qp	1.00	-	(Quantis, 2025)
	Erec, insulation	0.863	kg CO_2-eq/kg	(Violano & Cannaviello, 2023)
Energy Recovery	E_{ER}	0.759	kg CO_2-eq/kg	Ecoinvent (GWP100 IPCC 2021)
	X_{ERheat}	30%	%	(Henning & Palzer, 2014)
	E_{SEheat}	0.0372	kg CO_2-eq/kWh	Ecoinvent (GWP100 IPCC 2021)
	X_{ERelec}	30%	%	(Henning & Palzer, 2014)
	ES_{Eelec}	0.375	kg CO_2-eq/kWh	Ecoinvent (GWP100 IPCC 2021)
	LHV	varies	kWh/kg	Dependent on each material.
Disposal	ED	0.985	kg CO_2-eq/kg	Ecoinvent (GWP100 IPCC 2021)

3.5 Incorporation of Quality Factors

The Circular Footprint Formula includes two quality factors that account for differences in quality between virgin and recycled materials. These factors are used to adjust the environmental credits associated with recycled inputs and recycled outputs, recognising that recycled materials often cannot fully substitute virgin materials on a one-to-one basis.

1. Qsin/Qp: Quality of incoming secondary material relative to primary material. This factor scales the residual virgin-material term (1-A)Ev, which represents the portion of recycled input not credited directly to the user under the allocation factor A.

$$R_1 \times \left(AE_{\text{recycled}} + (1 - A)E_v \times \frac{Q\sin}{Qp} \right) \tag{3.1}$$

2. Qsout/Qp: Quality of outgoing secondary material relative to primary material. This factor scales the residual virgin-material substitution term E*v,i, applied within the end of-life recycling credit. Since Qsout/Qp is directly linked to recycling pathways, its values are presented together

with the end-of-life parameters in Table 3.3.

$$\sum_{i}^{n} R_{2,i}(1-A)\left(E_{\text{recyclingEoL},i} - E^{*}_{v,i} \times \frac{Q_{sout}}{Q_p}\right)_i \tag{3.2}$$

Both ratios are capped at a maximum value of 1, indicating that recycled material cannot provide greater functionality than the corresponding virgin material. The inclusion of quality factors is particularly important for mechanically recycled fibres, where material properties often deteriorate during recycling processes.

3.5.a Production-stage Quality Factors

The Qsin/Qp ratio is applied to recycled inputs and only affects products containing recycled material. In the original CPIT methodology, this ratio was assumed to be equal to 1, implying perfect substitution between recycled and virgin materials. In the updated methodology, quality factors from the PEFCR were adopted to better reflect the actual substitution potential of recycled fibres.

The allocation and quality assumptions used for recycled inputs are presented in Table 3.4.

Table 3.4: Allocation and Quality Assumptions (Quantis 2025)

Fiber or Material Type	Scope for Ev	Origin of Recycled Material	A	Qsin/Qp	Erecycled
Synthetic polyester – Recycled Polyester fibres	Production of virgin polyester fibres	Textile PET fibres (via mechanical recycling)	0.80	0.75	Impacts of collection, sorting, clothes preparation for recycling, shredding and recycling textile PET fibres into polyester fibres
Synthetic (polyester excluded) - Recycled synthetic fibres	Production of virgin synthetic fibres	Textile synthetic fibres	0.80	0.75	Impacts of collection, sorting, clothes preparation for recycling, shredding and recycling textile synthetic fibres into fibres
Natural Fibres Cellulosic – Recycled Cellulosic fibres	Production of cellulosic virgin fibres	Textile Product	0.80	0.50	Impacts of collection, sorting, clothes preparation for recycling shredding of textiles and recycling into recycled cellulosic fibres
Natural Fibres Wool – Recycled Wool	Production of virgin clean wool	Textile Product	0.80	0.65	Impacts of collection, sorting, clothes preparation for recycling shredding of textiles and recycling into recycled wool fibres

3.6 CPIT Score Reformulation

While the modifications described in Sections 3.4 and 3.5 update the environmental modelling assumptions underlying the Circular Footprint Formula, additional changes were made to the CPIT scoring framework itself. These modifications address two limitations identified in Chapter 2: the dominant influence of the penalty factor on score differentiation and the dependence of score outcomes on database-specific normalization anchors.

3.6.a Removal of the Penalty Factor

In the original CPIT methodology, a penalty factor was applied to account for product characteristics that may hinder recycling, such as material blends, trims, coatings, or complex garment construction. The penalty values were assigned at the macro commodity level and applied uniformly to all products within a category, regardless of their individual characteristics.

This approach introduces two limitations. First, products with different material compositions and circularity attributes may receive the same penalty value solely because they belong to the same product category. Second, the penalty is applied as a direct score deduction rather than being integrated into the underlying circularity assessment, limiting the transparency of how product level characteristics influence circularity performance.

To address this limitation, the penalty factor was removed from the revised methodology. Product-specific recyclability constraints are instead partially represented through the PEFCR disruptor criteria, which influence end-of-life pathway allocation and recycling outcomes.

3.6.b Alternative Anchoring Approaches

The original CPIT methodology uses database-derived normalization anchors based on the lowest PCFF value and highest LFF value observed within the analysed product portfolio. While this approach enables relative comparison within a dataset, it also introduces sensitivity to portfolio composition and seasonal variation. Consequently, identical products may receive different scores when evaluated in different product portfolios. To address these limitations 2 alternative anchoring approaches is evaluated:

1. Macro-Commodity Anchoring: Separate normalization anchors are established for each macro commodity group. Products are therefore bench-

marked against others within the same category rather than against the entire product portfolio. This approach improves within-category comparability but remains dependent on the composition of the underlying database.

2. Item-Level Anchoring: Each product is evaluated relative to its own theoretical best and worst-case circular versions. The resulting score reflects the proportion of circularity potential achieved by the product and is independent of the performance of other products. This approach increases score stability over time but reduces direct comparability between products with different circularity potentials.

These approaches differentiate from the previous CPIT scoring methodology, in which products were ranked across the entire database regardless of its functional macro commodity. As a result, it compares the circularity performance of fundamentally different product functions such as comparing trousers and T-shirts. The implications of each anchoring approach for score distribution, comparability, and interpretation are evaluated in Chapter 4 after which a score communication framework is proposed and tested.

3.7 Circular Footprint Formula Components

The Circular Footprint Formula (CFF) consists of several parameters that describe material flows, recycling processes, allocation assumptions, and end-of-life scenarios. These parameters are used across the Material Circularity Footprint Formula (MCFF), Product Circularity Footprint Formula (PCFF), and Linear Footprint Formula (LFF) calculations.

While some parameters are specific to individual formula components, many are shared across multiple calculations. Understanding these parameters is essential for interpreting how recycled content, recycling rates, disposal pathways, quality factors, and emission factors influence the final circularity score.

Table 3.5: Circular Footprint Formula Components

Table 7 Circular Footprint Formula Components

Category	***Parameter***	***Description / Purpose***	***Data Type***	***Data Source***	***Role in Updated Methodology***
Product Characteristics	Fibre Type	Fibre classification (cotton, polyester, wool, etc.)	Categorical	OVS Database	Determines emission factors and EoL pathway assumptions
	Fibre Process	Process-specific emission factors related to yarn dyeing and spinning	Categorical	OVS Database + Literature	Refines fibre production emissions by integrating process-level impacts
	Disruptor Presence	Presence of elements that hinder recycling	Categorical	OVS Database	Determines allocation between recycling, energy recovery, and disposal pathways
Input Parameters	Ev	Virgin material processing impact	Numerical	Ecoinvent, Literature	Fibre-specific impact factor
	E0	Impact of innovative materials	Numerical	Ecoinvent, Literature	Used when innovative material inputs are present
	R0	Burdens associated with innovative material production	Numerical (%)	OVS Database	Input to MCFF and PCFF
	R1	Fraction of recycled material	Numerical (0–1)	OVS Database	Input to MCFF and PCFF
	Qsin/Qp	Quality of incoming recycled material relative to virgin material	Numerical (0–1)	PEFCR	Introduced from PEFCR to account for quality loss of recycled inputs
	Erecycled	Burdens associated with recycled material production	Numerical	Literature	Applied when recycled inputs are present
End-of-Life Parameters	R2	Fraction allocated to recycling (Wiper & Insulation pathway)	Numerical (%)	PEFCR	Updated EoL modelling
	R3	Fraction allocated to recycling (insulation pathway)	Numerical (%)	PEFCR	Updated EoL modelling
	1 − R2 − R3	Fraction allocated to disposal and/or energy recovery	Numerical (%)	PEFCR	Updated EoL modelling
	Erecycling,EoL	Impact of end-of-life recycling processes	Numerical	Literature	Includes collection, sorting, and recycling burdens

	Qsout/Qp	Quality of outgoing recycled material relative to virgin material	Numerical (0–1)	PEFCR	Introduced from PEFCR to account for quality retention after recycling
	ED	Disposal impact (landfilling)	Numerical	Ecoinvent	Added to updated EoL modelling
	XER	Energy substitution ratio	Numerical	Literature	Used in energy recovery calculations
	EER (heat, electricity)	Avoided energy production impacts	Numerical	Literature	Used in energy recovery calculations
Cross-Cutting Parameters	A	Allocation factor for burdens and credits	Numerical	PEFCR	Applied throughout MCFF and PCFF calculations

Table 3.5 summarizes the main parameters used in the CFF calculations and their definitions. The parameters presented in are derived from multiple data sources. The OVS product database serves as the primary source of product-specific information, including material composition, fibre types, recycled content, and product characteristics used to identify recyclability disruptors. The Product Environmental Footprint Category Rules (PEFCR) provide the allocation factors, quality factors, and end-of-life pathway assumptions adopted in the updated methodology. Environmental impact data for virgin materials, recycled materials, recycling processes, and disposal pathways were obtained from the Ecoinvent database and literature, while energy recovery parameters were sourced from the literature. Together, these inputs form the basis for the MCFF, PCFF, and LFF calculations described in the following section.

3.8 Calculation Procedure

This section describes the implementation of the CPIT methodology and the calculation procedure used to derive MCFF, PCFF, LFF, and CPIT scores for the OVS 2024 product portfolio.

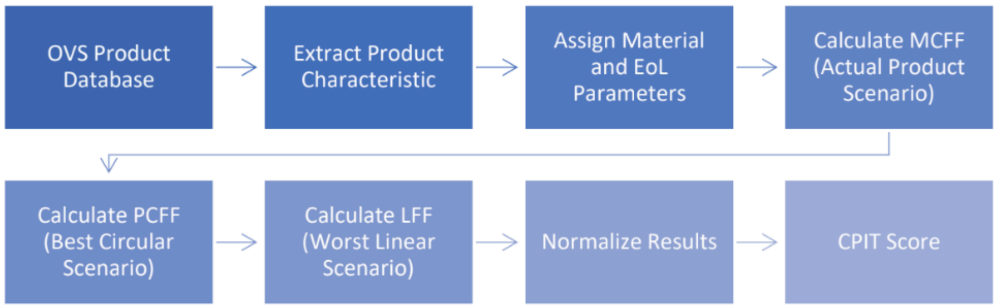
3.8.a Data Processing & Implementation

All calculations were implemented in Python using the pandas and NumPy libraries. The calculation workflow was developed to process the OVS product database and automate the computation of MCFF, PCFF, LFF, and CPIT scores for all products. The implementation incorporated both the original CPIT methodology and the updated methodology proposed in this study to enable direct comparison between scenarios and sensitivity analyses of individual methodological modifications.

The original CPIT methodology was implemented in MATLAB and was therefore reconstructed in Python to allow a consistent comparison with the updated methodology. The reconstruction followed the original calculation logic while adapting it to the structure of the current OVS product database. Where necessary, emission factors and material mappings were updated to reflect the most recent dataset and ensure comparability between the original and revised approaches.

3.8.b Calculation Workflow

The calculation process consisted of four main stages. First, product composition data, recycled content information, and product characteristics were extracted from the OVS database and linked to the corresponding environmental impact factors and PEFCR assumptions. Second, MCFF values were calculated to quantify the environmental impacts associated with the actual material composition of each product. Third, PCFF values were calculated by incorporating end-of-life pathway allocations, recycling credits, disposal impacts, and quality factors. Finally, LFF values were calculated to represent the equivalent linear reference scenario, and the resulting MCFF, PCFF, and LFF values were converted into CPIT scores using the selected normalization approach.



The following sections describe each calculation stage in detail.

3.8.c Calculation of Modified Circular Footprint Formula (MCFF)

The MCFF represents the environmental impacts associated with the actual circularity performance of a product. The calculation incorporates the product's material composition, recycled content, fibre-specific emission factors, quality factors, and end of-life pathway allocation determined by the presence of recyclability disruptors. In the updated methodology, the calculation additionally incorporates material-specific quality factors for recycled inputs as defined by the PEFCR.

$$\begin{aligned} MCFF = {} & (1 - R_0 - R_1)E_v + R_0E_0 + R_1\left(AE_{\text{recycled}} + (1-A)E_v\frac{Q_{sin}}{Q_p}\right) \\ & + \sum_{i=1}^{n} R_{2,i}(1-A)\left(E_{\text{recyclingBoLi}} - E^*_{v,i}\frac{Q_{sout,i}}{Q_p}\right) \\ & + R_3\left(E_{ER} - LHVX_{ER,\text{heat}}E_{SE,\text{heat}} - LHVX_{ER,\text{elec}}E_{SE,\text{elec}}\right) \\ & + (1 - R_2 - R_3)E_D \end{aligned} \tag{3.3}$$

3.8.d Calculation of Potential Circular Footprint Formula (PCFF)

The PCFF reflects the product's environmental impact at its best-case scenario state, when avoiding the use of virgin material and replacing it with its sustainable counterpart. End-of-life pathways are determined using the same decision rules applied in the MCFF calculation. The PCFF serves as the lower environmental impact reference and represents the circularity potential that can theoretically be achieved under the defined methodological assumptions.

$$
\begin{aligned}
PCFF = (1-R_1)E_0 + R_1\left(AE_{\text{recycled}} + (1-A)E_v\frac{Q_{\text{sin}}}{Q_p}\right) \\
+ \sum_{i=1}^{n} R_{2,i}(1-A)\left(E_{\text{recyclingBOL},i} - E^{*}_{v,i}\frac{Q_{\text{sout},i}}{Q_p}\right) \\
+ R_3\left(E_{ER} - LHV X_{ER,\text{heat}}E_{SE,\text{heat}} - LHV X_{ER,\text{elec}}E_{SE,\text{elec}}\right) \\
+ (1-R_2-R_3)E_D
\end{aligned}
\tag{3.4}
$$

3.8.e Calculation of Linear Footprint Formula (LFF)

The LFF reflects the product's environmental impact at its worst-case scenario state, when the item is made wholly from virgin material with disposal at its end-of-life. For products containing recycled or innovative materials, the corresponding conventional virgin material is used as a substitute to construct the linear reference scenario. The LFF serves as the upper environmental impact reference and represents the least circular configuration achievable for the product under the defined methodological assumptions.

$$
LFF = E_v + E_D \tag{3.5}
$$

3.8.f Calculation of CPIT

Following the calculation of the Modified Circular Footprint Formula (MCFF), Potential Circular Footprint Formula (PCFF), and Linear Footprint Formula (LFF), CPIT scores were calculated by normalizing the actual product performance between its circular and linear reference scenarios. MCFF represents the environmental impacts associated with the actual product configuration, PCFF represents the theoretical best-case circular scenario, and LFF represents the theoretical worst-case linear scenario.

The normalization procedure transforms the environmental impact values into a circularity score, where products performing closer to the preferred circular scenario receive higher scores, while products performing closer to the linear scenario receive lower scores. Depending on the anchoring approach being evaluated, the normalization boundaries were defined either at the database level, macro-commodity level, or product level.

For the final scoring framework, the normalized score was expressed on a scale of 0–10 to communicate the extent to which a product achieves its circularity potential. In addition, category-based rankings were generated to enable comparison between products belonging to the same macro commodity group.

$$CPIT = \left(10 - 10\frac{MCFF - PCFF^{*}}{LFF^{*} - PCFF^{*}}\right) \tag{3.6}$$

3.8.g Scenario and Sensitivity Analysis

To evaluate the influence of individual methodological modifications on the CPIT methodology, a series of scenario and sensitivity analyses were performed. Different calculation scenarios were developed by selectively modifying key methodological components while keeping the remaining assumptions unchanged.

The evaluated modifications included:

- Incorporation of probabilistic end-of-life pathways and disposal scenarios;
- Introduction of material-specific quality factors;
- Removal of the penalty factor;
- Alternative normalization and anchoring approaches.

For each scenario, MCFF, PCFF, LFF, and CPIT scores were recalculated for the complete OVS 2024 product portfolio. The resulting changes were compared across scenarios to assess the influence of individual methodological adjustments and their contribution to the final CPIT scores.

Table 3.6: Calculation Scenarios

Analysis	Reference Scenario	Comparison Scenario
EoL Sensitivity	Original deterministic EoL; no quality factors (Qsout/Qp = Qsin/Qp= 1)); penalty removed	EoL split; Qsout/Qp embedded in EoL modelling; Qsin/Qp excluded; penalty removed
Quality Factor Sensitivity	EoL split; Qsout/Qp embedded in EoL modelling; Qsin/Qp excluded; penalty removed	EoL split; both Qsout/Qp and Qsin/Qp included; penalty removed
Penalty Factor Sensitivity	EoL split; both Qsout/Qp and Qsin/Qp included; penalty removed	EoL split; both Qsout/Qp and Qsin/Qp included; penalty included
Anchoring Assessment	EoL split; both Qsout/Qp and Qsin/Qp included; penalty removed; database-wide anchoring	EoL split; both Qsout/Qp and Qsin/Qp included; penalty removed; alternative anchoring approach

4 Results & Discussion

This chapter will show the result of the calculation scenarios with its methodological adjustments. A proposed score communication framework will also be proposed and tested to the product portfolio.

4.1 Overview of Analysed Products

The database that was used for the study is the 2024 OVS Product Database. The database contains 41,137 unique item codes distributed across 27 macro commodity categories. In the database, each item is described by its item code, fibre type composition, component weights, and production process information. Among the categories, "Cut & Sewn Knitwear" shows the most variety with over 11,000 item codes, followed by "Trousers" and "Tricot knitwear".

As for the composition, cotton represents the largest share of materials used within the OVS database, followed by polyester and polyamide. In addition, 74.4% of the items contains wholly virgin material, followed by 18.4% of items contains innovative materials and 7.4% contains recycled materials.

Virgin materials are the fibres that is produced from primary raw materials without recycled content or additional verified attributes. Recycled materials are fibres produced from pre consumer or post-consumer waste streams through a recycling process. Innovative materials refer to non-recycled fibres that have additional verified attributes, certifications or sourcing program that distinguish them from the conventional virgin version. Examples include organic cotton,

Cotton made in Africa® cotton, regenerative cotton, FSC-certified cellulosic fibres, TENCEL™ lyocell, TENCEL™ modal, etc.

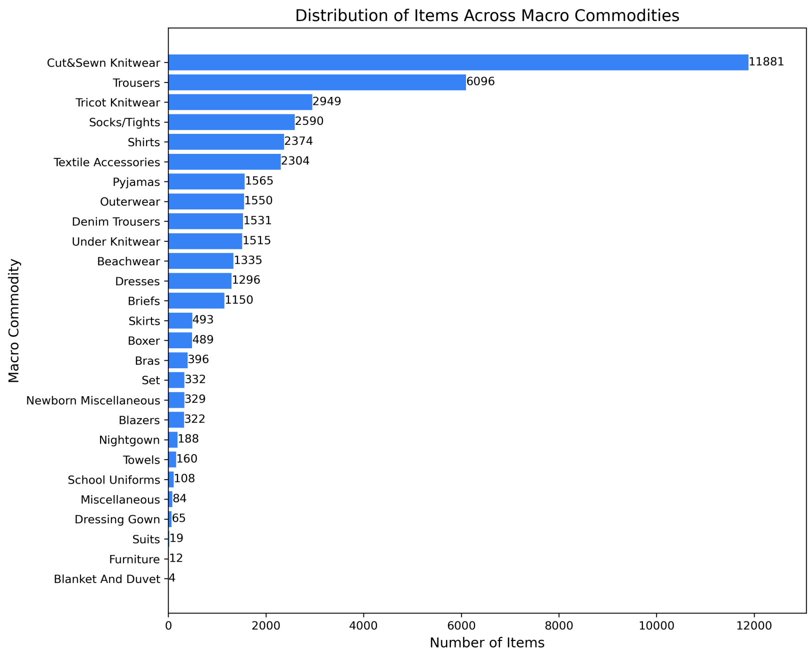


Figure 4.1: Number of Items per Macro Commodity

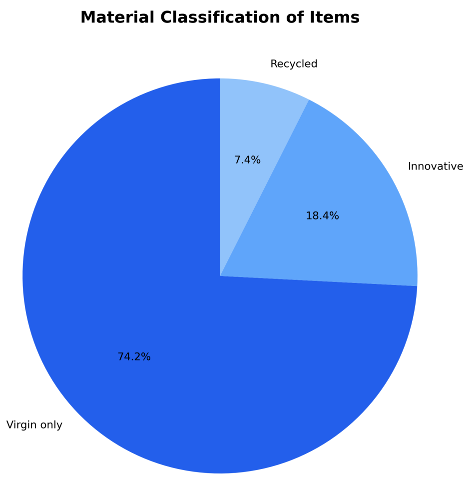


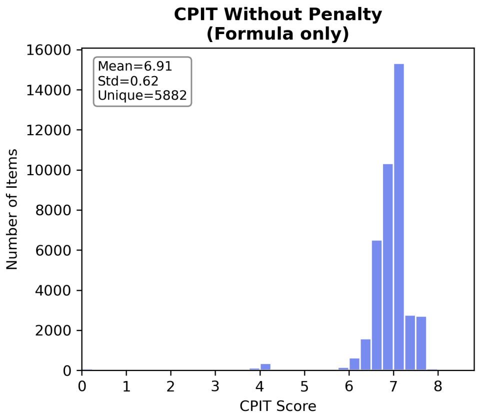
Figure 4.2: Item Classification

4.2 Baseline Assessment: Original CPIT Methodology

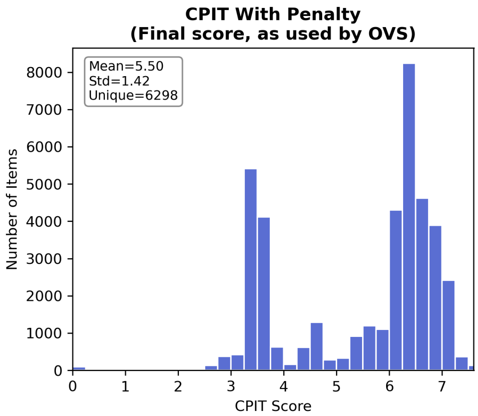
4.2.a Score Distribution and Penalty Effects

The score distribution obtained using the original CPIT methodology is shown in Figure 4.3. As discussed in Chapter 3, the original methodology relies on database-wide normalization anchors and incorporates a penalty factor intended to account for garment complexity.

Figure 4.3 shows the CPIT score distribution before the penalty is applied. The score cluster heavily in the upper range with a mean of 6.91 and standard deviation of 0.62. This cluster is primarily driven by the normalization anchors and portfolio composition. The LFF* anchor is set by a 100% wool item while approximately 70% of OVS's portfolio consists of cotton-based products with a significantly lower emission factors than wool. As a result, many items are scored near the top of the scale which makes it difficult to meaningfully differentiate the performance between products based on the formula alone.



(a) CPIT without Penalty



(b) CPIT with Penalty

Figure 4.3: Comparison of CPIT with and without the penalty factor using the original methodology.

The addition of penalty factor partially addresses the clustering. As shown in Figure 4.3, there's a substantial increase in score dispersion (the standard deviation increasing from 0.62 to 1.42).

4.2.b End-of-Life Assumptions in the Original Method

The original CPIT methodology assigns each product to a single end-of-life pathway based on its material composition. Figure 4.4 presents the distribution of these pathways across the OVS product portfolio.

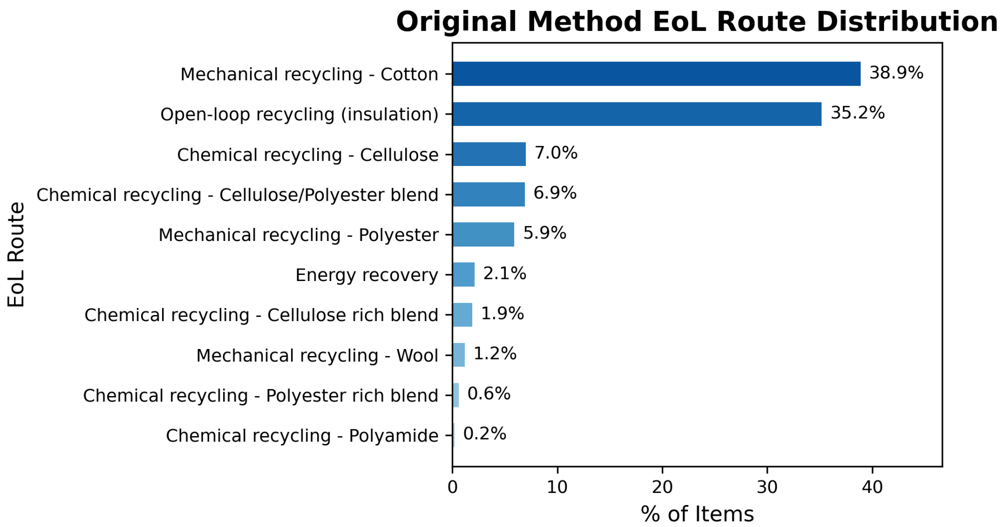


Figure 4.4: Original Method EoL Route Distribution

A substantial share of products is allocated to mechanical cotton recycling, which reflects the predominance of cotton within the portfolio. While other products are assigned to pathways such as insulation recycling or chemical recycling for selected fibre blends.

As only a single pathway is assigned to each product, the methodology assumes that the most favourable recycling option will be achieved at end-of-life. This assumption results in a highly optimistic representation of textile waste management. Current European textile waste systems are still dominated by energy recovery and disposal, while closed-loop fibre-to-fibre recycling processes accounts for only a small fraction.

4.3 Sensitivity Analysis of Individual Methodological Modifications

In this section, the results of the scenarios of sensitivity analysis in Table 3.6 is presented. First, the impact of the end-of-life modelling change is examined. Second, the influence of quality factors is analysed. Third, the effect of penalty factors assessed and finally, the proposed anchoring system and score communication approach are introduced and discussed.

4.3.a Effect of End-of-Life Pathway Modelling

Under the original methodology, each product was deterministically assigned to a single best EoL pathway based on the item's composition. The resulting EoL emission ranged from best case of -14.37 kg CO_2-eq/kg for items going to mechanical recycling of wool to the worst case of +0.23 kg CO_2-eq/kg for items directed to energy recovery, while disposal was not considered as a possible destination within the MCFF and PCFF.

In the updated methodology, the single pathway is replaced by a split pathway approach, where products are distributed across four possible pathways divided into insulation, wiper, energy recovery and disposal, depending on the material composition and the presence of disruptors. As a result, the resulting EoL emissions ranges from +0.38 kg CO_2-eq/kg (100% acrylic item distributed across insulation, energy recovery, and disposal pathways) to +0.87 kg CO_2-eq/kg (92% elastane and 8% polyamide item distributed across energy recovery and disposal pathways) with a portfolio wide mean EoL emission increases from -1.343 kg CO_2-eq/kg to 0.540 kg CO_2-eq/kg which confirms that the split-pathway model is, on average, less optimistic than the original deterministic assignment.

Table 4.1: Emission Differences between Original Single Pathway and Split Pathway

Method	Most Favorable			Least Favorable		
	Item	Pathway	Emission	Item	Pathway	Emission
Original: Single Pathway	100% Wool	Mechanical recycling - Wool	-14.37 kg CO_2-eq/kg	Item containing metal fibre	Energy Recovery	0.233 kg CO_2-eq/kg
Updated: Split Pathway	100% Acryclic	12% Insulation, 39% Energy Recovery, 49% Disposal	+0.38 kg CO_2-eq/kg	92% Elastane, 8% Polyamide	39% Energy Recovery, 61% Disposal	+0.87 kg CO_2-eq/kg

Table 4.2: Emission Differences between Original Single Pathway and Split Pathway

As shown in Figure 4.5, in this portfolio, 48% of items qualify for both insulation and wiper recovery, since they contain no metallic fibres, no more than two materials, no more than 5% elastane, and over 80% cotton; 24% qualify for insulation only, meeting the same criteria but has lower the 80% cotton content; 5% qualify for wiper only; and the remaining 23% qualify for neither, leaving energy recovery and disposal as their only available pathways.

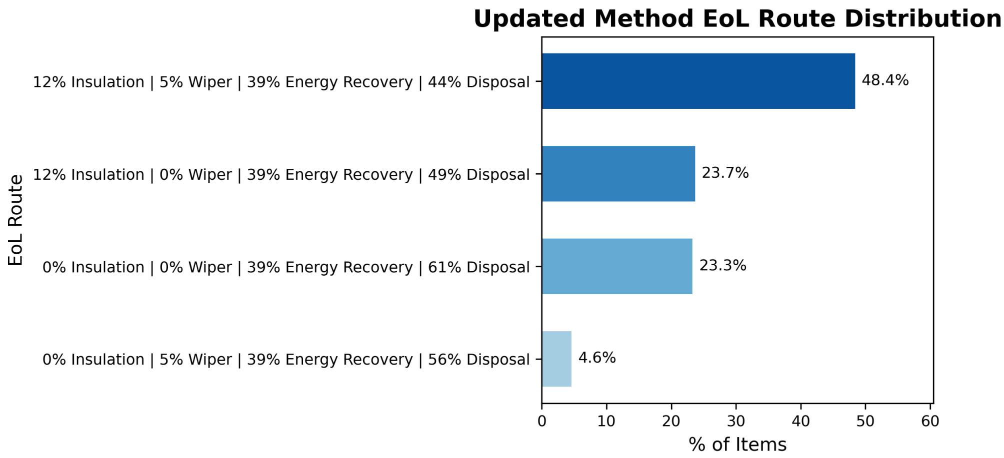


Figure 4.5: Updated Method EoL Route Distribution

Pathway eligibility alone, however, does not predict an item's emissions outcome. The lowest emission item in the portfolio, at +0.38 kg CO_2-eq/kg, is 100% acrylic and eligible only for insulation, energy recovery, and disposal, not the broader insulation-and-wiper category. By contrast, an 82% cotton, 18% acrylic skirt that is eligible for all four pathways, including wiper, results in a higher emission of +0.47 kg CO_2-eq/kg. The explanation lies in the material's lower heating value (LHV): acrylic has a substantially higher LHV than cotton, so items with greater acrylic content generate larger energy recovery credits, which can outweigh the advantage of qualifying for additional recycling routes.

Despite the general increase of EoL emissions between the original and updated methodology, the updated methodology resulted in the mean score change of 1.52 points across the portfolio, with 98.6% of products receiving higher CPIT scores and 1.2% of products receiving lower scores. At first glance, the result seems counterintuitive, as higher emissions would generally be expected to reduce the circularity performance.

This can be explained by a shift in the anchor values. Under the original methodology, the PCFF* anchor is strongly influenced by product assigned to mechanical wool recycling which resulted in a highly optimistic anchor value of -12.43 kg CO_2-eq/kg. In contrast, the split pathway approach produces a less optimistic value of +1.37 kg CO_2-eq/kg (item containing 55% cotton and 45% flax), reflecting a more realistic EoL destination considering the current technological availability. As a result, the normalization range are reduced, and the scale is compressed resulting to many products being positioned relatively higher within the scale despite having an increase of emissions. This finding highlights the strong influence of anchor definition to the final CPIT scores.

The items that receive lower CPIT scores are predominantly wool-based items (cashmere, wool, merino wool, and lambswool), which resist the overall upward shift because they lose the large recycling credit they previously received under mechanical wool recycling.

As textile collection, sorting, and recycling technologies continue to develop, additional end of-life pathways may become commercially viable and available at scale, and the split pathway method is adaptable and can be updated to reflect future waste management conditions by adjusting the pathway allocation to include new routes.

4.3.b Effect of Quality Factors

To evaluate the effect of including quality factors (Qsin/Qp) into the Circular Footprint Formula, the effect is isolated by comparing the updated model with quality factors against the same model without the quality adjustments while keeping all other methodological assumptions constant. Qsout/Qp are included in both as it is embedded in the split EoL model.

Across the portfolio, the MCFF changed for 7.4% of items which matches the share of portfolio that contain recycled input materials. While PCFF changed for 98% of the items in portfolio. MCFF reflects the recycled content in an item while PCFF represents the item's best-case scenario where every item is modelled as if it were made from its recycled or innovative counterpart, whether or not it actually is. Due to most fibres have recycled or innovative counterpart available, the quality ratio affects nearly the whole portfolio when looking at PCFF.

On average the change in MCFF is very small, from 9.37 kg CO_2-eq/kg average MCFF when excluding Qsin/Qp to 9.35 kg CO_2-eq/kg average of MCFF when including Qsin/Qp. PCFF, on the other hand, dropped more noticeably from 6.73 kg CO_2-eq/kg when excluding Qsin/Qp to 6.00 kg CO_2-eq/kg when including Qsin/Qp (about 11% lower). This result might seem counterintuitive at first, since a quality adjustment would normally be expected to make lower quality-material look worse, not better. However, this logic is rooted in how the Circular Footprint Formula (CFF) allocates environmental "costs" for the recycled content used. Instead of acting as a reduction of an environmental credit, the quality ratio is applied to the inherited virgin material burden share which exists because the formula does not allow the user of recycled material to claim zero impact for the material's origin. Aportion of the virgin material acquisition emissions (Ev), determined by the allocation factor (A), is still "charged" to the current production system. The quality ratio serves as a scaling factor for this charge to reflect the physical reality that low quality recycled fibers cannot perform the same function as high-quality virgin fibers. Because this inherited burden is a cost rather than a benefit, a lower-quality ratio (<1) mathematically shrinks that cost, making the initial material footprint lower than it would be if a perfect 1-to-1 quality substitution were assumed.

Despite the significant effect on PCFF values, the impact on the CPIT score was relatively limited with an average score decrease from 8.41 without Qsin/Qp to 8.39 when including Qsin/Qp, a reduction of 0.025 points, or about 0.3%. As both the product footprints and the anchor values shift in the same direction, part of the increase in PCFF is absorbed during the score calculation.

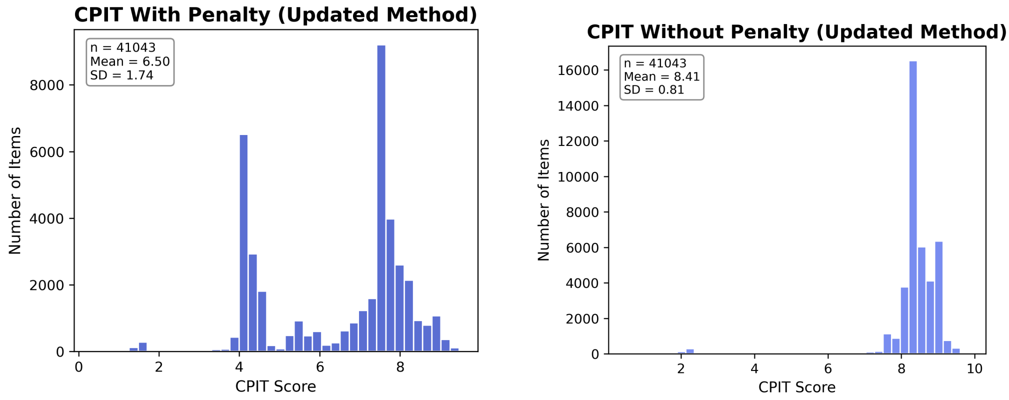
Although the impact on final CPIT scores was limited, the inclusion of quality factors remains important from a methodological perspective. The original assumption of perfect substitution does not reflect the quality losses that often occur during recycling processes. By incorporating quality-adjusted substitution ratios, the updated methodology better reflects the intended application of the Circular Footprint Formula, which recognizes that recycled materials may not always provide the same functional performance as virgin materials.

4.3.c Effect of Penalty Exclusion

To evaluate the influence of the penalty factor on CPIT outcomes, the updated methodology was compared with an identical version without the penalty factor. All other assumptions, including the revised end-of-life modelling and quality factors, were kept the same in order to isolate the effect of the penalty factor on the final score.

The results show that removing the penalty factor in the updated method produces similar patterns to the original methodology without penalties. As shown in Figure 4.6, CPIT scores without the penalty remain clustered, while adding the penalty increases the spread of scores. This suggests that the penalty factor has an effect on improving score differentiation, even in the updated methodology that already includes split end-of-life pathways and quality factors.

While the penalty factor successfully reduces score clustering, it also appears to dominate the final scoring outcome. Products with similar compositions and end-of-life characteristics can receive different scores solely due to differences in garment complexity classifications. As a result, the broad macro-commodity category of the penalty factors may become a stronger determinant of circu-



(a) CPIT with Penalty

(b) CPIT without Penalty

Figure 4.6: Comparison of the updated CPIT methodology with and without the penalty factor.

larity performance than the circular footprint itself, potentially overshadowing product-specific attributes.

As noted earlier, removing the penalty factor brought the issue of score clustering, which limits clear communication of results. This clustering is mainly caused by the anchoring approach and the large share of cotton products in the dataset. This issue is therefore addressed by adjusting the anchoring method, as discussed in the next section.

4.4 Assessment of Alternative Anchoring Approaches

As was analyzed in the previous sections, CPIT results are sensitive to the choice of normalization anchors. The original methodology relied on database-wide derived anchors from the best and worst performing product in the whole product portfolio which introduced several limitations. One of the main limitations is how the resulting scores are dependent on the composition of the database and may change over time as products are added or removed from the portfolio. In addition, the same product can receive different scores across seasons despite no change in its underlying circularity performance.

To address these limitations, three alternative anchoring approaches were evaluated: database wide anchoring, macro-commodity anchoring, and item-level anchoring. Each approach was assessed based on its ability to provide meaningful differentiation between products, maintain score stability over time, and support communication of circularity performance to consumers and internal stakeholders.

The following table compare the strengths and limitations of each approach before the result are discussed in the following sections.

Table 4.3: Strength and Limitations of Alternative Anchoring Approaches

Anchoring Approach	Reference Point	Score Interpretation	Main strength	Main Limitations
Database-wide	Best and worst products in the entire portfolio	Relative position within the portfolio	Enables portfolio-wide benchmarking	Highly sensitive to portfolio composition and seasonal changes
Macro-commodity	Best and worst products within the same macro commodity	Relative position within the product category	Improves comparison between functionally similar products	Still dependent on category composition and seasonal changes
Item-level	Product's own theoretical best- and worst-case scenarios	Degree of circularity potential achieved by the product	Stable over time and independent of other products	Best-case scenario may not be technically or commercially feasible in practice

4.4.a Database-Wide Anchoring

The updated CPIT methodology was first evaluated using the same database-wide anchoring approach applied in the original methodology. Under this approach PCFF* and LFF* are defined as minimum PCFF and maximum LFF observe across the entire portfolio, excluding silk-containing item as an outlier (96 items in the current portfolio).

With the updated end-of-life modelling, quality factors, and penalty removal applied, the database-wide anchors were found to be PCFF* = 1.108 kg CO_2-eq/kg and LFF* = 51.614 kg CO_2-eq/kg, corresponding to a tricot knitwear item composed of 68% alpaca, 30% recycled polyamide, and 2% elastane. Alpaca carries the second-highest virgin material emission factor in the dataset after silk (60.07 kg CO_2-eq/kg). Both anchor values increased relative to the original methodology (PCFF* = -7.39 kg CO_2-eq/kg, LFF* = 21.98 kg CO_2-eq/kg), which reflects the more conservative end-of-life assumptions introduced in the split-pathway model.

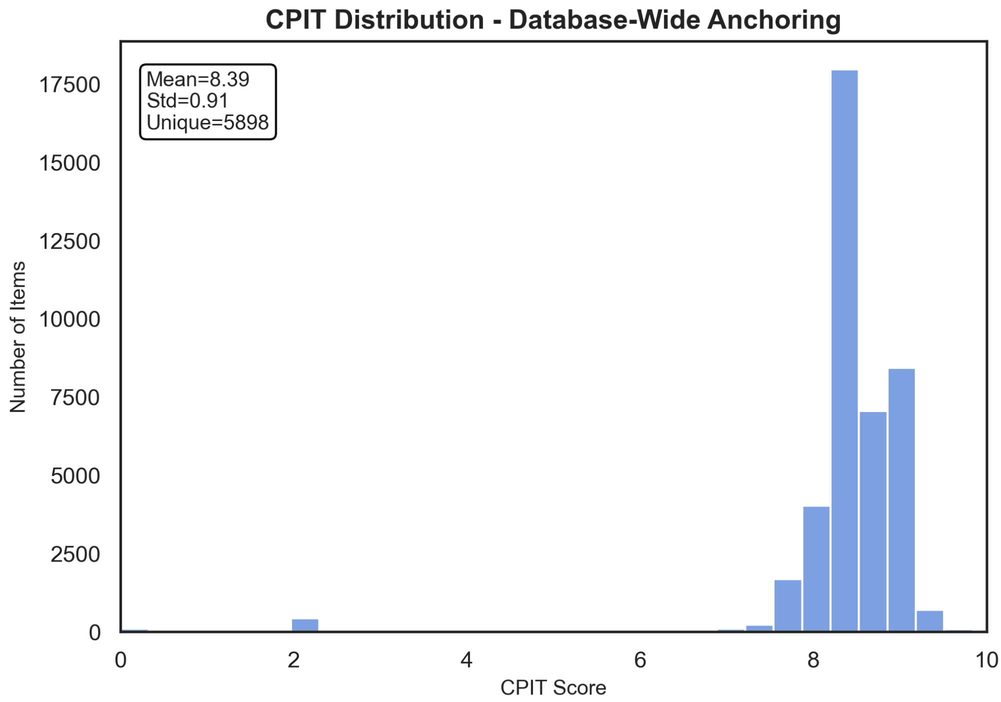


Figure 4.7: Updated Methodology CPIT Score Distribution with Database-Wide Anchors

As shown in Figure 4.7, the resulting CPIT shows a mean of 8.39 and standard deviation of 0.91, with 5,898 unique score values across the portfolio (silk items excluded from the distribution and assigned a CPIT of 0). As with the original methodology, the database-wide approach also causes the clustering in the upper end of the 0-10 scale which is caused by the portfolio composition dominated by cotton which have a comparatively lower emission than the worst performing product in the database (item containing alpaca). The clustering limits the ability to meaningfully differentiate circularity performance between products which motivates the exploration of other anchoring approaches which will be discussed in the coming sections.

4.4.b Item-Level Anchoring

The item-level anchoring approach defined PCFF* and LFF* using the product's own PCFF and LFF values. Each item is scored against its own theoretical best-case (fully recycled material) and worst-case (fully linear, virgin only source, disposal EoL) which are independent to other products in the database.

Using this anchoring changes the meaning of the score. Rather than comparing products against each other, the score reflects how much of a product's own circularity potential has been achieved. Since the reference points are product-specific, scores remain stable over time and will not be affected by changes in portfolio composition.

Applying this approach to the OVS 2024 portfolio resulted in the mean score of CPIT of 2.55 with a standard deviation of 2.50 (Figure 4.8). The lower score suggests that most products in the portfolio achieve only a limited share of their theoretical circularity potential which is consistent with the portfolio composition where 74% of products are made entirely from virgin materials.

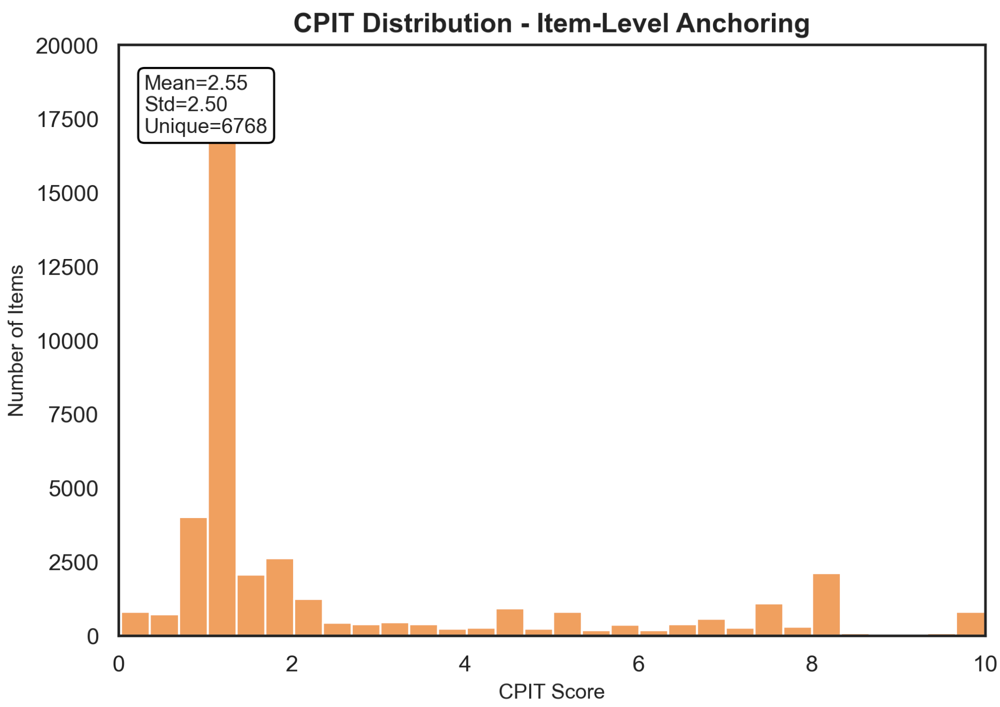


Figure 4.8: CPIT Distribution – Item-Level Anchoring

The main advantage of the item-level anchoring is that it provides a stable and portfolio independent measure of improvement potential. However, it doesn't allow comparability between products in the database since a score of 7 for one product does not necessarily represent the same level of a score of 7 for another since each score is calculated relative to a different reference point.

A further limitation is that the best-case scenario represented by the PCFF may not always be achievable in practice. Currently, the calculation assumes that every fibre in a product can be replaced by a recycled or innovative alternative according to the allocation and quality factors it has. While such alternatives are available for some fibres, they might be limited for others especially to reach the desired product performance.

In addition, the PCFF should be interpreted as a theoretical best-case scenario based on the assumptions of the model, which may not always be achievable in practice. Therefore, a low item-level score may reflect limitations in the availability of recycled materials rather than poor product design alone.

4.5 Macro-Commodity Anchoring

The macro-commodity anchor, the PCFF* and LFF* were calculated separately for each macro commodity category rather than the product portfolio as a whole. To improve the sample size and avoid unstable anchors in macro commodity that only have limited item codes, some of the current macro commodity groups are merged by aggregating smaller categories with similar function into one.

Table 4.4: Merged Macro Commodity Groups

Merged Group	Original Group	Number of Items	Max LFF	Min PCFF
Outerwear	Outerwear	1,550	34.55	1.16
Set	Set	332	13.67	4.57
Beachwear	Beachwear	1,335	15.58	3.53
Skirts	Skirts	491	36.82	1.16
Dresses	Dresses	1,294	25.27	2.59
Trousers	Trousers	6,091	32.41	1.11
Denim Trousers	Denim Trousers	1,531	11.24	4.50
Miscellaneous	Miscellaneous, Newborn Miscellaneous	413	21.73	1.15
Textile Accessories	Textile Accessories	2,267	47.95	2.39
Socks/Tights	Socks/Tights	2,590	28.28	3.50
Shirts	Shirts	2,359	29.65	2.53
Home Textile	Towels, Furniture, Blanket And Duvet	173	12.35	3.74
Knitwear	Tricot Knitwear, Under Knitwear, Cut & Sewn Knitwear	16,315	51.61	2.27
Nightwear	Nightgown, Dressing Gown, Pyjamas	1,818	11.95	3.84
Suits & Blazers	Suits, Blazers, School Uniforms	447	19.32	3.85
Underwear	Bras, Briefs, Boxers	2,035	15.53	3.84

The resulting macro-commodity specific anchors varied substantially across product groups as shown in Table 4.4. This indicate that different product categories have distinct circularity potential ranges. Categories with narrow anchor ranges (such as Denim Trousers and Nightwear) show particularly compressed score distributions, as the difference between the best and worst performing products is limited as the category consists of items with similar compositions.

Looking at the whole portfolio, the resulting score distribution shows a mean score of 7.53 with a standard deviation of 1.86, with scores clustering between 7 and 9. The cluster at the upper end shows that within most macro commodity groups, the majority of products perform relatively well compared to the worst-case product in the category.

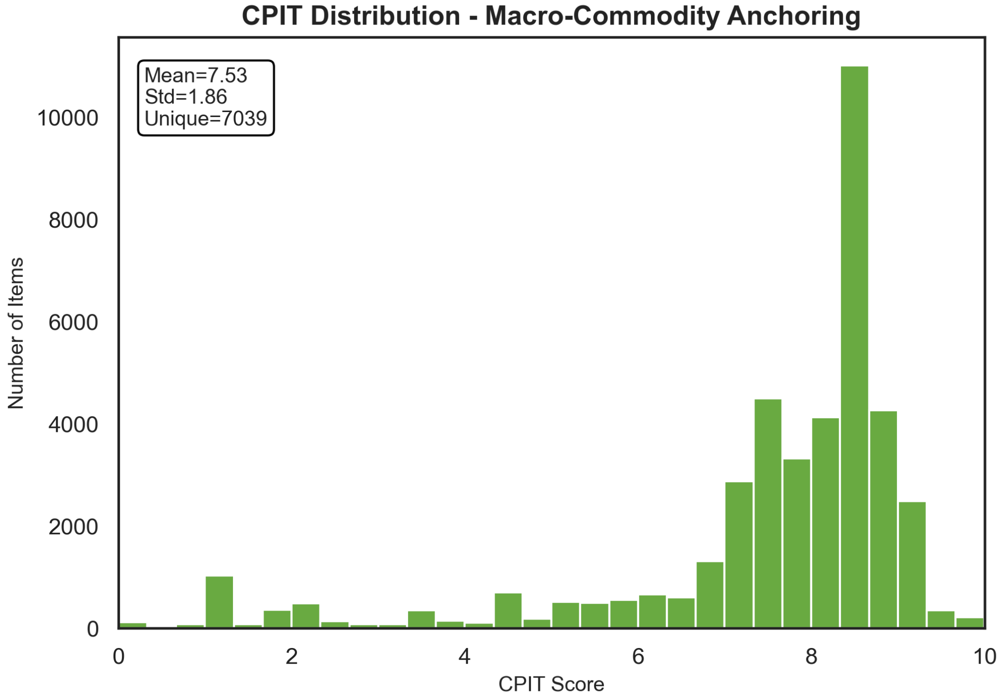


Figure 4.9: CPIT Distribution – Macro Commodity Anchoring

A more detailed example of category specific anchors is a product made of 100% Organic Cotton received a score of 9.20 when classified as under knitwear, but 7.98 when classified as boxer. Even though both products have the same material composition, the score differs as they are evaluated relative to other products within the same functional category.

It should also be noted that macro-commodity anchoring achieves a structurally similar outcome to the penalty factor removed from the original methodology, though through a different mechanism. Both approaches resulted in items belonging to the same macro commodity receiving a shared category-based adjustment. The penalty achieved this by applying a fixed multiplier which corrects a score already computed against the database-wide anchors. Macro-commodity anchoring, on the other hand, achieves a comparable effect through the category specific anchors before the score is calculated. The key difference lies in what determines the category-level adjustment. The penalty relied on external proxy for garment complexity which might hinder recycling (number of components per macro commodity). While macro-commodity anchoring derives its reference points directly from the same MCFF, PCFF, and LFF calculations applied to every individual product which means that the category adjustment remains grounded in the CFF methodology instead of a separate correction term.

4.5.a Comparison of Anchoring Approaches

The anchoring approaches have different influences on the distribution and interpretation of CPIT scores which is summarized in Table 4.5.

Table 4.5: Comparison of anchoring approaches.

Anchoring Approach	Mean	Std. Dev	Unique Scores
Database-Wide (No Penalty)	8.39	0.91	5898
Database-Wide (with Penalty)	6.48	1.77	6466
Macro Commodity	7.53	1.86	7039
Item-Level	2.55	2.50	6768

Database-wide anchoring (without penalty) resulted in the highest mean score and the lowest standard deviation, which indicates that most products clustered near the upper end of 0-10. Database-wide anchoring (with penalty) however, resulted in a mean score of 6.48 and a standard deviation of 1.77, showing that the penalty helped increase score differentiation. However, when anchors are defined at the macro-commodity level, compared to database-wide without penalty, the standard deviation increased to 1.86 while the mean score reduced to 7.53, suggesting improved differentiation between products by benchmarking them against functionally similar alternatives.

The largest change was observed with item-level anchoring, which produced the lowest mean score (2.55) and the highest standard deviation (2.50). Unlike the portfolio-based approaches, item-level anchoring evaluates each product relative to its own theoretical best- and worst-case circular versions. The wider score distribution indicates stronger differentiation between products, while the lower average score suggests that many products achieve only a limited proportion of their theoretical circularity potential despite receiving relatively high scores under portfolio-based approaches.

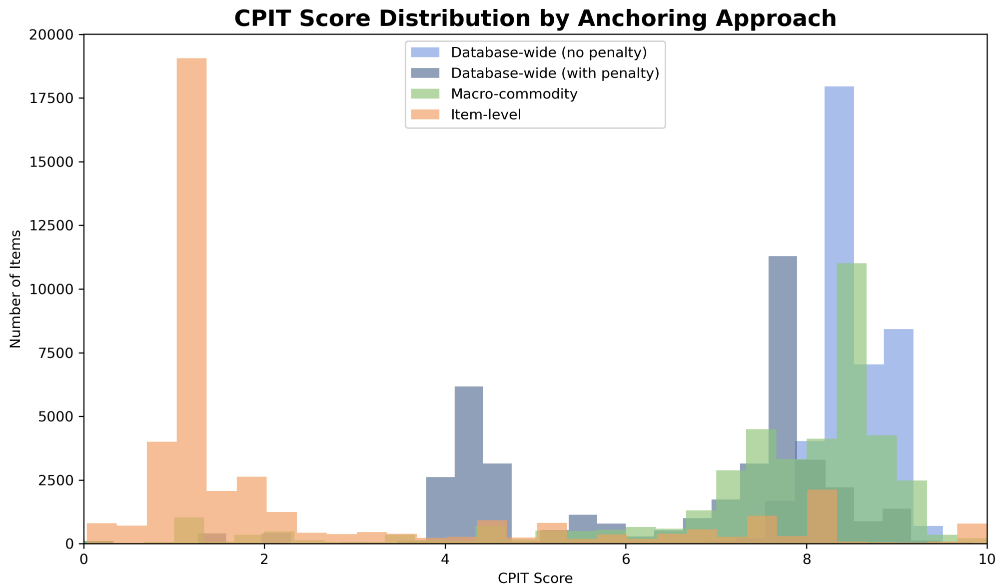


Figure 4.10: CPIT Score Distribution by Different Anchoring Approaches

Table 4.6: Comparison between four anchoring approaches

Item Code	Composition	Macro Commodity	DB-Wide (no penalty)	DB-Wide (with penalty)	Macro-Commodity	Item-Level
2358032	92% Elastane, 8% Polyamide	Socks/Tights	8.33	8.33	7.56	0.79

The item in Table 4.6 illustrates that the four scoring approaches do not always agree, and that their disagreement is informative. Under database-wide anchoring, the item scores 8.27, and the penalty leaves this unchanged, since Socks/Tights carries a penalty multiplier of 1.0. Under macro-commodity anchoring, evaluated against other products in its own category, the item still scores 7.44. Item-level anchoring, however, scores the same item at only 0.23. This difference reflects what each approach measures. Database-wide, with-penalty, and macro-commodity scores describe how a product compares to other real products currently in the portfolio, while the item-level score describes the distance between the product's actual composition and a theoretical version of itself made entirely from recycled or innovative materials. As discussed above, however, this theoretical best case is less commercially mature for elastane than for other fibres, which contributes to the unusually low item-level score for this product.

Overall, the results indicate a trade-off between comparability and differentiation. Database wide anchoring provides a common reference frame across all products but leads to substantial score clustering unless with the inclusion of penalty. Macro-commodity anchoring improves differentiation while maintaining comparability within product categories. Item-level anchoring provides the greatest differentiation and stability over time, although at the expense of direct comparability between products. These findings suggest that score distribution is influenced more strongly by the choice of anchoring approach than by the penalty factor itself and different anchoring approach have different interpretation that should be communicated to consumer.

4.5.b Proposed Score Communication Framework

The previous section showed that the choice of anchoring approach not only changes the numeric score a product receives but also how the score should be communicated an interpreted by a consumer browsing OVS's e-commerce site.

Database-wide or macro-commodity anchored scores tells consumers how a product perform relative to other products available for purchase, while item-level anchored scores communicate the extent to which a product's circularity potential has been achieved. As shown in 4.6, the different result between different anchors suggests how the different scores are informative, but they communicate different aspects of performance.

To capture both, a dual score communication framework can be done. It combines an item level score as the primary indicator coupled with a category relative ranking which is bounded by the macro commodity.

Table 4.7: Dual Score Communication Framework

Score	**Anchoring**	**Communication**
Primary Score (0-10 Scale)	Item-Level Anchors	The extent to which a product's circularity potential has been achieved
Category-relative indicator (A-E Label)	Macro-commodity	How the product performs compared with other products serving the same function.

The primary component is the item-level CPIT score on a 0–10 scale, derived from item-level normalization anchors. This score reflects the proportion of a product's theoretical circularity potential that has been achieved and remains stable over time regardless of changes in portfolio composition.

The secondary component is an A–E label derived from the percentile rank of the item-level score within each macro commodity group. Products are ranked against all other products belonging to the same macro commodity, and the label is assigned based on where the product falls within that distribution: the top 20% receive an A, the next 20% a B, and so on. Unlike the item-level score, this label is explicitly portfolio-dependent, and it communicates relative standing among products with the same function that a consumer might realistically be choosing between.

The limitation to the A-E label that is derived from the macro commodity group item level scores is its portfolio-dependency. The label assigned to a product may shift across seasons as the portfolio composition changes.

Together, the two components provide different but complementary information. A product may have a relatively low item-level anchor score but still receive an A label if it performs better than other products in the same category. This means it is the best available option within its product group, even if its overall circularity potential is limited. On the other hand, a product with a high absolute score may receive a C label if many competing products perform even better. In summary, The item-level can help OVS to understand which of their products can be improved while the A-E labels can communicate to consumers compare to other products in the portfolio which ones have reached its theoretical circularity potential.

Figure 4.11 presents the distribution of A–E labels across macro commodity groups as a percentage of total products per group and show the CPIT score range per group.

The majority of categories show a distribution close to 20% per band. Some deviations are observed in a small number of categories, most notably Knitwear, Shirts, Denim Trousers, and Underwear where the score distribution is highly compressed due to material homogeneity within those groups. In these categories, a large share of products shares near-identical item level scores, limiting the differentiation that the A-E rank can provide and reflects the characteristic of the portfolio.

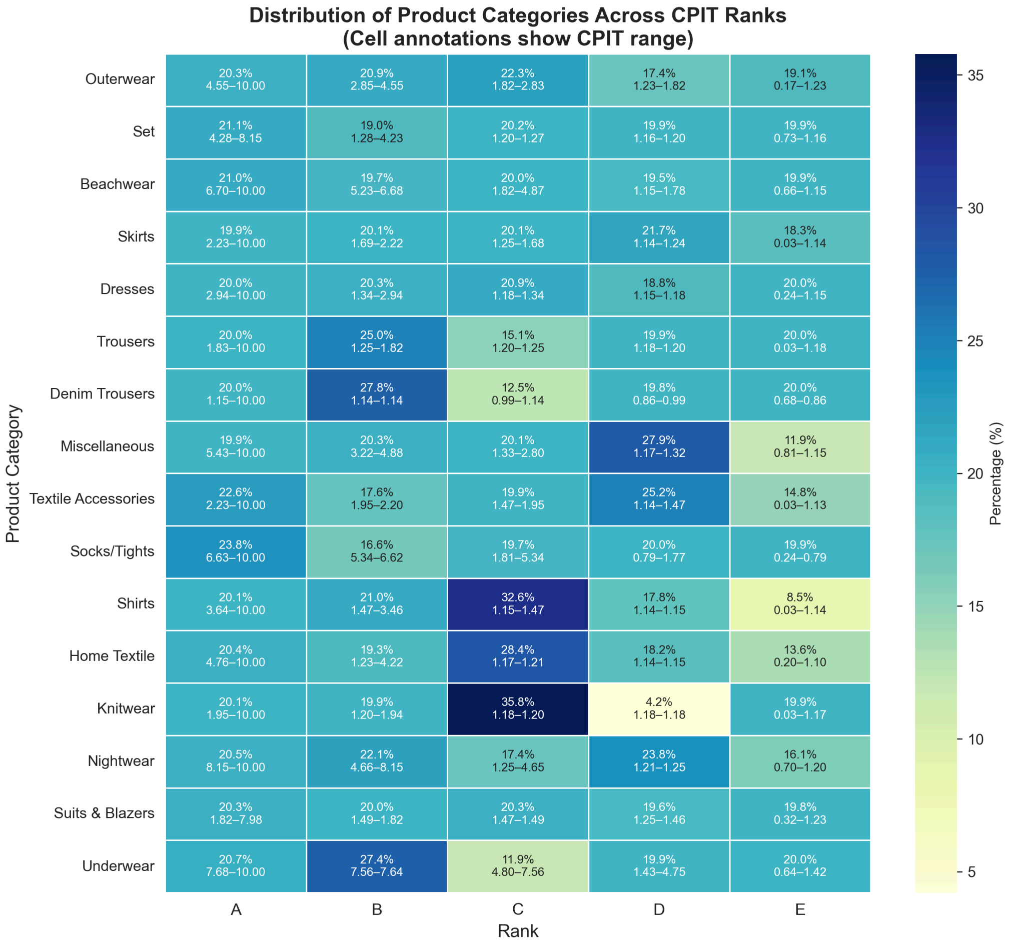


Figure 4.11: Distribution of Product Categories Across CPIT A-E Ranks

5 Limitations & Future Work

Although CPIT provides a structured approach for assessing material circularity and communicate it to consumers, it also has several limitations. The limitations are mostly related to the modelling choices and data availability. Given the limited of detailed product-specific data, several assumptions and simplifications were made to make sure that the method could be implemented.

Environmental modelling assumptions

The proposed methodology relies on default end-of-life split pathways defined by the Product Environmental Footprint Category Rules (PEFCR), which allocate products among fixed percentages. Although these values provide a harmonized basis for assessment, they may not accurately represent the actual fate of individual garments, collection efficiencies, or regional waste management practice. For instance, the current PEFCR does not yet define a default pathway for post-consumer textile-to-textile recycling. This reflects the limited commercial deployment of fibre-to-fibre recycling technologies at present. Consequently, this recycling route is not explicitly represented within the updated CPIT. However, recent literature suggests that textile-to-textile recycling is expected to expand substantially as recycling technologies mature and European circular textile policies are implemented (Sandin et al., 2025). Although current market shares remain relatively small, incorporating a default allocation for textile-to textile recycling, even at a low percentage based on the best available evidence, would provide a more realistic representation of emerging closed-loop textile systems.

Furthermore, although the updated CPIT replaces the deterministic 100% end-of-life allocation with probabilistic split pathways, the model remains inherently static. Each garment is evaluated over a single product life cycle before its material is distributed among recycling, energy recovery, and disposal pathways. Circularity, however, is intrinsically a multi-cycle phenomenon in which recovered materials continue to circulate through multiple product systems. A single-cycle representation may therefore underestimate the cumulative benefits of material recovery and the long-term circularity potential of textile products.

Scope of Assessment

The CPIT was intentionally designed to evaluate material circularity and therefore excludes several aspects that also contribute to product sustainability. For instance, the methodology does not consider the consumer use and reuse phase, despite the importance of durability, maintenance, repair, and product lifetime in determining the overall environmental performance of textiles.

In addition, the environmental assessment primarily reflects greenhouse gas emissions associated with material production and end-of-life management. Other important environmental impact categories, including biodiversity loss, water scarcity, eutrophication, toxicity, and pollution, are not explicitly incorporated. Thus, the CPIT score should not be interpreted as representing improvements across all dimensions of environmental sustainability.

Future Work

Several opportunities exist to further improve the Circular Potential Index for Textile (CPIT) as data availability, recycling technologies, and European regulatory frameworks continue to evolve. A priority is improving the end-of-life model. The current method uses default split pathways from the Product Environmental Footprint Category Rules (PEFCR). As more detailed regional and product-specific data become available, future versions of CPIT could replace these default values with more realistic end-of-life scenarios that better reflect differences in collection systems, sorting technologies, and waste management infrastructure. In particular, the emerging use of textile-to-textile recycling. Although this pathway is not yet included in the current PEFCR defaults, future updates should add textile-to-textile recycling using suitable allocation factors based on new industrial data and scientific studies.

From a communication perspective, experimental studies could investigate whether consumers find the scores easy to understand and useful when comparing products. Such studies would help determine whether the proposed communication strategy is clear, intuitive, and effective in supporting more informed purchasing decisions.

Finally, as product-level sustainability information becomes increasingly standardized, future work could investigate the integration of CPIT within the emerging Digital Product Passport (DPP) framework under the Ecodesign for Sustainable Products Regulation (ESPR).

Conclusions

This thesis has the aim to update the Circular Potential Index for Textile (CPIT) of OVS by aligning its methodology with the recently published Product Environmental Footprint Category Rules (PEFCR) for Apparel and Footwear while also improving the methodology used to communicate circularity performance. The study addressed five key methodological limitations of the original CPIT: deterministic end-of-life modelling, exclusion of disposal pathway as a possible end-of-life, the assumption of 1:1 quality substitution between virgin and recycled materials, the use of macro-category-based penalty factor and the exploration of alternatives normalization anchors.

The updated methodology introduces several changes with the aim to make the assessment reflect the current textile waste management practices better. First, the single pathway assignment of end-of-life route was replaced by a split pathways based on PEFCR default rates which divides it to recycling, energy recovery and disposal. The inclusion of disposal as one of the pathways provide a more realistic representation of post-consumer textile flows. Second, the quality factors were introduced for recycled materials to account for the reduced substitution potential of recycled materials compared with virgin materials.

In addition to the updates based on the PEFCR, the thesis also evaluated methodological changes to improve the interpretation and communication of CPIT scores. Alternative normalization approaches were explored which demonstrated that the choice of anchoring has a substantial influence on score interpretation. Database-wide anchoring provides comparison across the entire portfolio but is sensitive to seasonal changes, macro-commodity anchoring improves comparison among similar products but remains portfolio dependent, while item-level anchoring provides scores that reflect the proportion of circularity potential achieved by each individual product.

Based on these findings, a dual score communication framework is proposed. The item-level CPIT score communicates the extent to which a product achieves its theoretical circularity potential, while the A–E category rating is assigned according to the percentile rank of the item level score within the corresponding macro-commodity, allowing consumers to compare products within the same functional category.

Overall, the updated CPIT represents a methodological improvement over the original version while maintaining its practical objective of providing a simple product-level circularity indicator for consumers. By aligning the methodology with the latest PEFCR guidance and introducing more realistic assumptions regarding end-of-life management and recycled material quality, the revised framework strengthens the scientific basis of the index and increases its suitability for future applications within OVS.

A Appendix

A.1 Circular Footprint Formula Parameters Description

Table A.1: Description of the parameters used in the Circular Footprint Formula (Quantis 2025)

Parameter	Description
A	Allocation factor of burdens and credits between supplier and user of recycled materials.
B	Allocation factor of energy recovery processes; it applies to both burdens and credits.
Q_{sin}	Quality of the ingoing secondary material, i.e., the quality of the recycled material at the point of substitution.
Q_{sout}	Quality of the outgoing secondary material, i.e., the quality of the recyclable material at the point of substitution.
Q_p	Quality of the primary material, i.e., the quality of the virgin material.
R_0	Proportion of the material in the product that originates from primary (virgin) material.
R_1	Proportion of material in the input to production that has been recycled from a previous system.
R_2	Proportion of the material in the product that will be recycled (or reused) in a subsequent system. R_2 considers the inefficiencies in the collection and recycling (or reuse) processes and is measured at the output of the recycling plant.
R_3	Proportion of the material in the product that is used for energy recovery at end of life (EoL).
E_{recycled}	Specific emissions and resources consumed (per unit of analysis) arising from the recycling process of recycled (or reused) material, including collection, sorting, and transportation.
$E_{\text{recycling,EoL}}$	Specific emissions and resources consumed (per unit of analysis) arising from the recycling process at end of life, including collection, sorting, and transportation.
E_v	Specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material.
E_v^*	Specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.
E_{ER}	Specific emissions and resources consumed (per unit of analysis) arising from the energy recovery process (e.g., incineration with energy recovery or landfill with energy recovery).
$E_{\text{SE,heat}}$, $E_{\text{SE,elec}}$	Specific emissions and resources consumed (per unit of analysis) that would have arisen from the substituted heat and electricity sources, respectively.
E_D	Specific emissions and resources consumed (per unit of analysis) arising from disposal of waste material at the end of life of the analysed product, without energy recovery.

Continued on next page

Table A.1 continued from previous page

Parameter	Description
$X_{\mathrm{ER,heat}}$, $X_{\mathrm{ER,elec}}$	Efficiency of the energy recovery process for heat and electricity, respectively.
LHV	Lower Heating Value of the material in the product that is used for energy recovery.

A.2 Lower Heating Values (LHV) of Materials

Table A.2: Lower Heating Values (LHV) used for the energy recovery calculations.

Fiber	LHV (MJ/kg)	Source
ACETATE	15.357	(Dziok et al. 2024)
ACRYLIC	29.44	(Dziok et al. 2024)
ALPACA	20.07	(Dziok et al. 2024)
BAMBOO VISCOSE	15.15	(Dziok et al. 2024)
CASHMERE	20.07	(Dziok et al. 2024)
COCONUT	17.00	(Dziok et al. 2024)
COTTON	15.357	(Marafon et al. 2021)
DUCK DOWN	20.07	(Dziok et al. 2024)
DUCK FEATHERS	20.07	(Dziok et al. 2024)
ELASTANE	25.60	(Zevenhoven 2004)
ELASTODIENE	35.56	(Lorinț et al. 2024)
ELASTOMULTIESTER	21.80	(Dziok et al. 2024)
ETHYL VINYL ACETATE	42.80	(Arena et al. 2011)
FLAX	15.75	(Dziok et al. 2024)
HEMP	15.75	(Dziok et al. 2024)
LAMBSWOOL	20.07	(Dziok et al. 2024)
LYOCELL	15.36	(Dziok et al. 2024)
MERINO WOOL	20.07	(Dziok et al. 2024)
METAL FIBRE	–	–
MODACRYLIC	29.44	(Dziok et al. 2024)
MODAL	15.15	(Dziok et al. 2024)
MOHAIR	20.07	(Dziok et al. 2024)
OTHER FIBRES	–	–
PAPER	13.00	(Arena et al. 2011)
PLASTIC	30.00	(Arena et al. 2011)
POLYAMIDE	28.60	(Kijo-Kleczkowska et al. 2022)
POLYESTER	21.80	(Dziok et al. 2024)
POLYETHYLENE	42.80	(Arena et al. 2011)
POLYPROPYLENE	46.50	(Arena et al. 2011)
POLYURETHANE	25.60	(Zevenhoven 2004)
POLYVINYL CHLORIDE	16.40	(Hurley et al. 2016)
RAMIE	15.75	(Dziok et al. 2024)
REAL LEATHER	20.07	(Dziok et al. 2024)
SILICON	25.00	(Hurley et al. 2016)

Continued on next page

Table A.2 continued from previous page

Fiber	**LHV (MJ/kg)**	**Source**
SILK	20.07	(Dziok et al. 2024)
STRAW	14.50	(EA Energy Analyses 2018)
TEXTILE PAPER	13.00	(Arena et al. 2011)
VIRGIN WOOL	20.07	(Dziok et al. 2024)
VISCOSE	15.15	(Dziok et al. 2024)
WOOL	20.07	(Dziok et al. 2024)

**notes: Acetate and lyocell were approximated using cotton as a proxy for cellulosic fibre LHV; alpaca, cashmere, duck down, duck feathers, lambswool, merino wool, mohair, silk, and real leather were approximated using wool as a proxy due to their similar protein-based composition; bamboo viscose, modal, and viscose were approximated using viscose as a proxy; elastane was approximated using polyurethane as a proxy; elastodiene was approximated using rubber as a proxy; elastomultieste was approximated using polyester as a proxy; ethyl vinyl acetate (EVA) was approximated using polyethylene as a proxy; flax, hemp, and ramie were approximated using linen as a proxy; modacrylic was approximated using acrylic as a proxy; plastic was approximated using mixed plastic as a proxy; straw was approximated using a biomass-based proxy; textile paper was approximated using paper as a proxy; silicone was approximated using a synthetic polymer proxy; metal fibre was considered non-combustible and assigned an LHV of 0 MJ/kg; other fibres were excluded due to unavailable LHV data.*

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