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On-Demand Knitting and Recycling: An LCA Study Investigating an Integrated Solution for Sustainable Woollen Jumpers

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Abstract

The purpose of this research is to reduce the environmental burden of textiles, specifically focusing on the production of Merino woollen jumpers. The study addresses two techniques to lessen the environmental burden: (1) recycling of wool garments by shredding or unravelling and (2) preventing the overstocking of products through on-demand knitting. The environmental burden is measured via LCA using Idemat. The results are reported in terms of eco-costs (EUR) and carbon footprint (kg CO_2-e). A cradle-to-gate analysis of recycling by either shredding or unravelling is compared with the use of virgin wool. The results are: EUR 3.53 in eco-costs and 21.93 kg CO_2-e as the carbon footprint for a virgin wool jumper to EUR 0.31 eco-costs and 1.56 kg CO_2-e for a recycled wool jumper and EUR 0.19 eco-costs and 0.89 kg CO_2-e for an unravelled wool jumper. Additionally, a cradle-to-grave calculation per wear was made, resulting in: EUR 0.045 and 0.278 kg CO_2-e, EUR 0.004 and 0.020 kg CO_2-e, and EUR 0.002 and 0.011 kg CO_2-e, respectively. A revenue-normalized comparison between on-demand knitting and mass production based on the eco-costs/value ratio (EVR) shows a 44% higher environmental impact for a mass production system.

Keywords: textiles; on demand; overstock; Life Cycle Assessment; fast-track LCA; Eco-Costs/Value Ratio (EVR); wool; knitting; digitalization

1. Introduction

1.1. Improving the Current Situation in the Fashion Industry

The fashion industry is unsustainable due to issues related to the depletion of materials, toxic emissions, and human exploitation [1–3]. Clothing consumption and textile waste generation per capita have increased year by year [4,5]. The dominant push model that enables the ultra-fast production of high quantities of garments sold at low prices [6] has led to an unhealthy production system [7]. The current push mechanism creates unnecessary waste in the form of overstocking of products that are often incinerated or landfilled [8,9]. As stated in the EU Strategy for Sustainable and Circular Textiles in 2022, under Paragraph 2.2, the EU intends to ban the destruction of unsold or returned textiles [10]. Subsequently, a briefing published in March 2024 by the European Environment Agency [11] provides an overview of the current state of affairs concerning the destruction of returned and unsold goods in Europe. Unsold goods refer to overstock (products that are produced but have

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never been distributed in the market) and obsolete inventory (products that are never bought by consumers). Overstock and obsolete products are the result of a mismatch between supply and demand. An estimated 20% of stock is unsold, although there is limited information published by companies due to a lack of transparency, and different percentages have been reported by different studies. According to one report, only 6–12% of this 20% is currently being downcycled or reused, with most stock being exported to Asia or Africa [11]. However, the data in this report are rather uncertain; thus, we have attempted to provide further clarity in Appendix A, which is used as guidance for this research.

As its mission to reduce the environmental burden, a start-up in Amsterdam (New Industrial Order (N.I.O.)) has created a circular production system for fashion brands by combining whole-garment, on-demand knitting with recycling strategies. This new business model is supported by software that translates 3D knitwear designs into machine-readable knit code. It functions as an interface layer between design environments (like CLO3D) and the proprietary programming languages used by leading knitting machines (e.g., Shima Seiki, and Stoll machines). The core of the system is a conversion engine, which analyses digital garment patterns and maps them to corresponding knitting operations, stitch types, and yarn paths. The whole-garment, on-demand knitting process of N.I.O. is characterized by closed-loop local manufacturing, which eliminates overstock and waste and requires less electricity than weaving (see Idemat tables) [12]. In addition, the use of recycled yarn eliminates the need for virgin wool, which has a higher environmental impact [13].

In this research, the LCA study (see Section 2, Method A) was conducted to investigate the environmental impacts of different systems for clothing production, specifically on-demand production of jumpers made of (i) virgin wool, (ii) recycled wool, and a possible new feedstock: (iii) unravelled wool. The EVR analysis (see Section 4, Method B) was performed to demonstrate the environmental advantages of the integrated solution compared with mass production while still maintaining revenue.

1.2. Research Questions

The research questions of the LCA and EVR studies were formulated as follows:

(a) What is the environmental impact of producing a virgin wool jumper?
(b) What is the environmental impact of producing a recycled wool jumper?
(c) Which recycling strategy (shredding or unravelling wool) is the best choice?
(d) What are the hotspots (most critical activities) of the new systems?
(e) What is the environmental gain of knitting on demand?

This study focused on the analysis of two important topics: the effect of recycling methods and the effect of on-demand knitting in reducing overproduction. The former was calculated using the method of LCA (Method A). The latter was calculated using the method based on the EVR [14] (Method B). The EVR method is LCA-based and has been used to analyse the buying behaviour of consumers. In this study, the EVR was used to understand the negative environmental effects of selling at a discount to tackle the overproduction of garments.

2. Method A: LCA to Assess the Effect of Recycling Methods

Goal and Scope

The goal of the LCA study was to (I) gain insight into the environmental impact of knitting on-demand systems for woollen jumpers; (II) identify the hotspots of virgin and recycled materials; and (III) gain understanding of the differences between shredding and conceptual unravelling recycling strategies. Three scenarios were investigated:

- Scenario 1 (S1): a jumper made of 100% virgin Merino wool from Australia;

- Scenario 2 (S2): a jumper made of mixed pre-/post-consumer recycled wool (ratio unknown) by shredding from Italy;
- Scenario 3 (S3): a jumper made of 100% recycled wool by unravelling of industrial waste from the Netherlands (or remanufacturing jumpers of clients).

For these three scenarios two cases have been studied: (a) a cradle-to-gate analysis with "a knitted wool jumper" as the functional unit and (b) a cradle-to-grave analysis (including washes) with "a knitted wool jumper" as well as "per wear" as the functional units.

The main reason to perform these two cases is that case (a) is rather straightforward, in contrast to case (b). This second case needs assumptions about "wears" and "washes" that depend on the country of the buyer and are often uncertain (e.g., for a lot of countries these data have not been measured). The sensitivity analyses (Section 4) are added to give some feel of how important assumptions are for the full LCA.

The knitted wool jumper was 300 g for size M and was knitted at 14 gauge with a 2-ply yarn. Scenario 1 employed a 416 dtex yarn (2-ply) and Scenario 2 a 1429 dtex yarn (2-ply), based on existing yarns currently on the market. In Scenario 3, a conceptual yarn was employed and, therefore, the exact dtex was unknown (Appendix B). Because unravelling preserves fibre length, the unravelled yarn fineness was expected to be close to that of the virgin wool yarn (416 dtex) and significantly finer than the shredded recycled yarn (1429 dtex). A conservative estimate of 600 dtex (2-ply) was therefore used for S3. The reference flow in the calculations was 5 jumpers, totalling 1.5 kg.

The lifetime of the Merino jumpers was assumed to be 79 wears, with 15.2 washes. The number of wears was based on a study of Wiedemann et al. [13] with data from Germany and the UK. Note that these data highly depend on the culture and the climate of a country: data for New Zealand in [15] show 181 wears and 21 washes. We assume that the Netherlands has the same wears and washes as Germany and the UK, but even within the EU different numbers of wears are to be expected. Cultural climate and wealth (the salary of the buyer) play a governing role. Climate also plays a role with regard to the electricity used for washing (e.g., natural or machine drying), where the carbon content per kWh is rather different for each country.

Another issue with regard to the number of wears is the quality of recycled wool. When it is unravelled wool, there is no reason to assume that the quality is significantly less than virgin, so there is no reason that the number of wears should be less than the norm of the calculations (i.e., 79 wears). The same applies for clients who return their jumpers for remanufacturing (e.g., for a new fashion or fit).

The quality of recycled yarns is subject to debate. Opinions and test outcomes range from "poor", as described in [16,17], to "very good", as can be found in the empirical test results described in Appendix B. So, when recycled wool has been shredded and spun, the business system needs stringent quality control to ensure that the quality is at least equal to the (perceived) quality of virgin wool.

The market niche of Merino wool buyers in Western Europe is characterized by the fact that these buyers choose a new garment far before the end of the technical life span of the old garment [15]. The number of wears is determined by the emotional/economic life span and depends on fashion and fit. The technical life span is not relevant here, so the number of wears is the same for all scenarios in this study.

The same applies for end-consumer waste wool: this type of material can only be accepted under stringent quality control requirements.

The energy that is required in the use phase is determined by the number of wears per wash—in this study, 5.2 (data from [13]). The sensitivity of this assumption is dealt with in Section 4.

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The system boundaries of the 3 scenarios (S1: virgin wool; S2: recycled wool; S3: unravelled wool) are presented in Figure 1. All three LCAs modelled an end-of-life recycling scenario considering a recycling rate of 39% in the Netherlands and a 61% incineration rate according to Idemat guidelines. The release of CO_2 from incineration at the end of life is counted as biogenic (zero net impact) because this biogenic CO_2 is circular due to the product's short life (<100 year). The recycled and unravelled yarn scenarios (S2 and S3, respectively) used a cut-off approach for the discarded garment, effectively not taking into account the impacts of virgin wool from the previous garment life. The applied cut-off approach is in line with EN15804 [18], similar to the ecoinvent "allocation cut-off by classification" [19], to clarify the benefit of the input of recycled material compared to virgin material. By these means, material depletion is avoided and reflected in the results; however, there are other allocation methods, such as allocation factor "A" in the PEFCR, that lead to different outcomes [20]. Note that other allocation rules do not affect the environmental benefit of the overall system shown in Figure 1. The detailed assumptions made and corresponding LCI data can be found in the Supplementary Materials. This study did not consider subsystems of (machine) manufacturing, nor sales or marketing-associated processes.

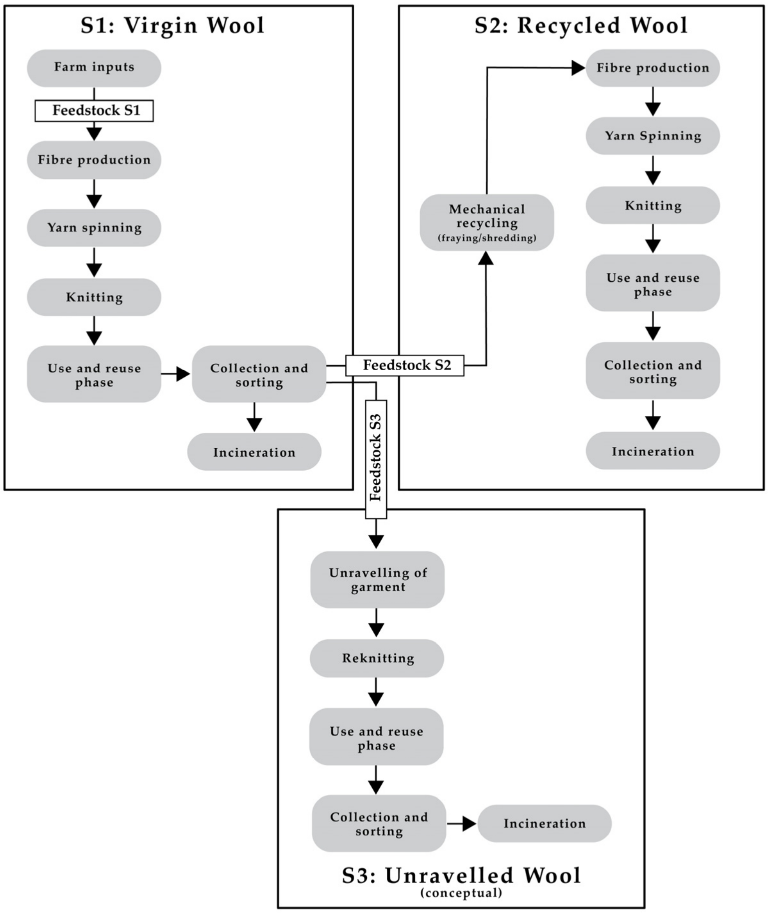

Figure 1. The system boundaries of the three scenarios (S1: virgin wool; S2: recycled wool; S3: unravelled wool) and the interdependence of the three types of yarns used.

The LCIA data were examined according to two indicators: carbon footprint and eco-costs [14]. The eco-costs method was selected as it is (a) a monetized version of the ecological footprint midpoints and (b) comprises 4 endpoints, namely, climate change, human toxicity, nature and biodiversity (including "plastic soup"), and resource scarcity. Some checks in ReCiPe H/A were conducted but are not presented in this paper because they did not add much extra information, as carbon footprint was found to be dominant (more than 60%) in this indicator system. Furthermore, the LCIA data of this study are from the Idemat database. In Idemat, the mass and energy balances are based on the most recent wool data available (from Wiedemann et al. [21], see Section 3.1). Idemat combines these data with the most recent data on energy (2024). In addition, Idemat has a range of data on spinning, weaving and knitting, provided for a wide range of different yarn thicknesses (dtex), which is essential to make accurate calculations for textiles.

3. Results of the LCA Calculations

3.1. Scenario 1 (Jumper Made from Virgin Merino Wool), Cradle to Gate and Cradle to Grave

The total environmental impact per knitted jumper in Scenario 1 amounts to EUR 3.51 in eco-costs and a carbon footprint of 21.86 kg CO_2-e from cradle to gate and EUR 3.53 and 21.93 kg CO_2-e from cradle to grave (Table 1). The highest impact comes from the raw material stage, estimated at EUR 3.19 in eco-costs and 20.18 kg CO_2-e for the carbon footprint, arising specifically from farming sheep for wool production. The Idemat data for "clean wool in Australia" were calculated based on the LCA study of Wiedemann et al. [19] on sheep farms, applying economic allocation to the co-production of wool and meat and including the scouring process for greasy wool. The manufacturing processes (in the Netherlands) comprise dyeing, spinning, digital design of the garment, and whole-garment knitting and finishing. During manufacturing, the highest carbon footprint comes from the dyeing process, accounting for 40% of the total impact in this category, followed by spinning at 31%. The impacts of transport, usage, and end-of-life (EoL) credit for combustion with heat recovery are low. The EoL recycling rate was calculated based on the average percentage (61%) of waste incineration for textiles in the Netherlands [22]. The details of the full inventory can be found in Tables S1–S6 of the Supplementary Materials.

Table 1. Results of Scenario 1. Assumptions for usage: 79 wears, 15.2 washes [13].

One Jumper (300 g)	Eco-Cost (EUR)	Carbon Footprint (kg CO_2-e)
Material	3.19	20.18
Manufacturing	0.29	1.57
Transport	0.03	0.11
Total, cradle to gate	3.51	21.86
Usage	0.06	0.36
EoL	−0.04	−0.29
Total, cradle to grave	3.53	21.93
Per wear	0.045	0.278

All values are rounded.

3.2. Scenario 2 (Jumper Made from Recycled Wool), Cradle to Gate and Cradle to Grave

In Scenario 2, the environmental impact amounts to EUR 0.29 in eco-costs and a carbon footprint of 1.50 kg CO_2-e per knitted jumper cradle to gate and EUR 0.31 in eco-costs and a carbon footprint of 1.56 kg CO_2-e cradle to grave (Table 2). The noticeable gap in environmental impact compared to Scenario 1 mainly arises from an absence of virgin wool input. Since the impact of the virgin jumpers was attributed to their previous lifetime (the cut-off rule), the impact of raw material in the recycled wool scenario was assumed to be 0. Consequently, the highest impact was observed for manufacturing. This category includes the sorting process, mechanical recycling, dyeing, spinning, digital design of the garment, and whole-garment knitting and finishing. The spinning process, accounting for 29% of the manufacturing carbon impact, is the biggest contributor, followed closely by the dyeing and knitting processes, both at 25%. The transport, usage, and EoL categories present similar results to Scenario 1. The details of the full inventory can be found in Tables S7–S9 of the Supplementary Materials.

Table 2. Results of Scenario 2. Assumptions for usage: 79 wears, 15.2 washes [13].

One Jumper (300 g)	Eco-Cost (EUR)	Carbon Footprint (kg CO_2-e)
Material	0.06	0.13
Manufacturing	0.22	1.29
Transport	0.02	0.07
Total, cradle to gate	0.29	1.50
Usage	0.06	0.36
EoL	−0.04	−0.29
Total, cradle to grave	0.31	1.56
Per wear	0.004	0.020

All values are rounded.

3.3. Scenario 3 (Jumper Made from Unravelled Wool), Cradle to Gate and Cradle to Grave

In Scenario 3, the total cradle-to-gate environmental impact per knitted jumper is EUR 0.17 in eco-costs with a carbon footprint of 0.82 kg CO_2-e. The cradle-to-grave results are EUR 0.19 in eco-costs and a 0.89 kg CO_2-e carbon footprint (Table 3). Similar to S2, there is a large drop in impact in the Material category due to the absence of virgin material input. The highest impacts come from the manufacturing processes, consisting of a pretreatment process, a recycling process, digital design of the garment, whole-garment re-knitting and finishing. Within this category, knitting makes up the biggest share of the carbon impact at 47%, followed by the pretreatment and finishing processes at 18% and 17%. The transport category has a very low impact, running only over short distances. The usage and EoL categories have the same results as in Scenario 1. The details of the full inventory can be found in Tables S10–S12 of the Supplementary Materials.

Table 3. Results for Scenario 3. Assumptions for usage: 79 wears, 15.2 washes [13].

One Jumper (300 g)	Eco-Cost (EUR)	Carbon Footprint (kg CO_2-e)
Material	0.06	0.14
Manufacturing	0.12	0.68
Transport	0.00	0.01
Total, cradle to gate	0.17	0.82
Usage	0.06	0.36
EoL	−0.04	−0.29
Total, cradle to grave	0.19	0.89
Per wear	0.002	0.011

All values are rounded.

3.4. Comparing Results

The cradle-to-grave results of Scenarios 1, 2, and 3 in terms of eco-costs are presented in Figure 2. A noticeable decrease of 91% in environmental impact can be observed between S1 and S2, stemming mainly from the use of virgin material in S1 and the cut-off criteria for recycled materials in S2 and S3. Similarly, a decrease of 95% is evident between S1 and S3 for the same reason, with an extra reduction for S3 in manufacturing since there is no dyeing process involved. A smaller decrease of 39% in environmental impact between S2 and S3 can be observed stemming from manufacturing and transport.

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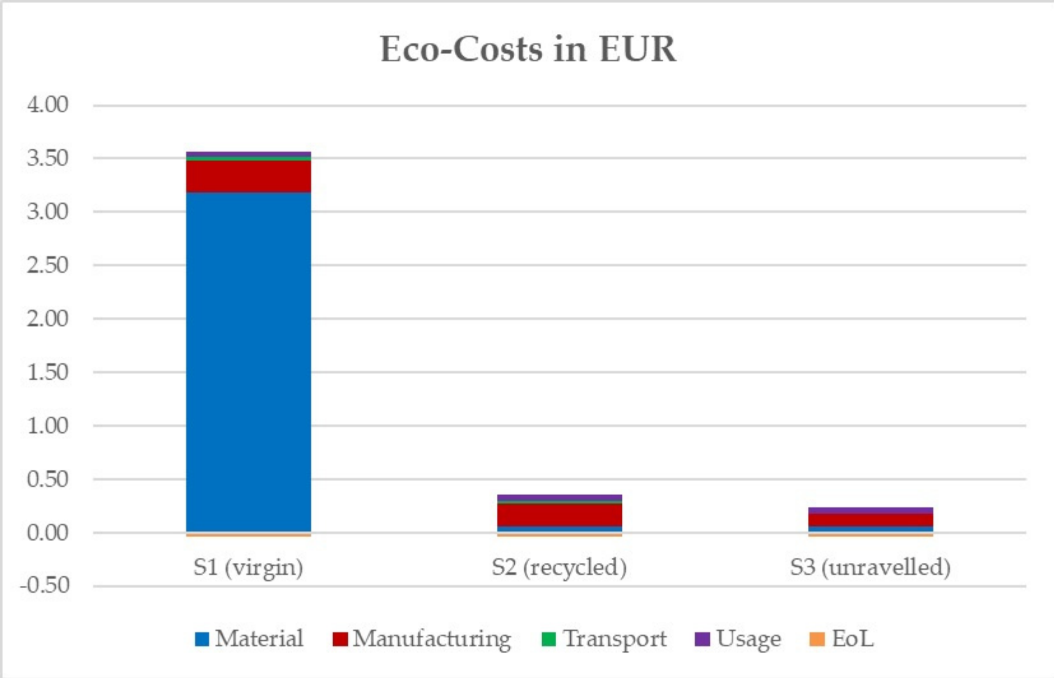

Figure 2. Diagram of the cradle-to-grave results in eco-costs of S1, S2 and S3 for one jumper (300 g).

Regarding manufacturing processes, a gradual decrease in eco-costs can be seen from S1 to S2 and S3. The main differences occur in the dyeing and spinning processes or the absence of these processes in S3. In S1, the impact of dyeing is approximately 59% higher than in S2 due to the choice of the representative dataset. The dyeing datasets used substitutes for the dyestuff and ethoxylate amine datapoints, as noted in the Supplementary Materials, due to a gap in the Idemat database, as well as the substitute for the antistatic oil used in the spinning and knitting processes across all scenarios. These substitutes may have a moderate impact on the results. The impact of the spinning process decreases by 25% from S1 to S2; the reason for this reduction lies in the difference in dtex between the S1 yarn (416 dtex) and S2 yarn (1429 dtex). Additionally, the absence of the spinning process in S3 also reduces the environmental impact for that scenario.

Transport decreases by 33% from S1 to S2; however, the largest decrease is from S1 to S3 at 97% and from S2–S3 at 95% due to the short, local transport distances in S3 compared to the international supply chains of S1 and S2.

The detailed results of these processes can be found in Tables S13 and S14 of the Supplementary Materials.

The same overall impact pattern can be seen in Figure 3 for carbon footprint. The percentages differ slightly from the eco-cost results since eco-costs represent the sum of impacts across multiple categories, whereas carbon footprint represents the impact of a single category. S1 shows a carbon footprint of 21.93 kg CO_2-e per knitted jumper, largely arising from the use of virgin wool raw material, while in S2, the total carbon footprint decreases by 93% to 1.56 kg CO_2-e. Compared with S1, the carbon footprint in S3 decreases by 96% to 0.89 kg CO_2-e. Between S2 and S3, the total carbon footprint decreased at a lower rate at 43%. The detailed results of these processes can be found in Tables S15 and S16 of the Supplementary Materials.

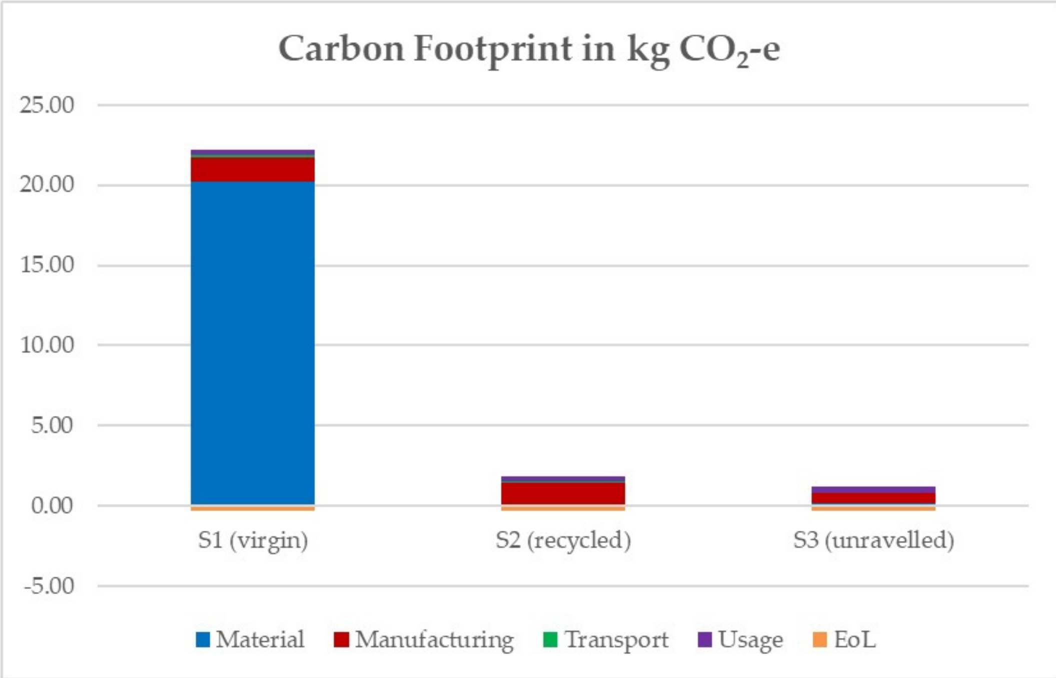

Figure 3. Diagram of the cradle-to-grave carbon footprint (CO_2-e) results of S1, S2 and S3 for one jumper (300 g).

The cradle-to-gate impact results presented in Tables 1–3 show that the usage and EoL phases represent a small share of the total cradle-to-grave impacts, for the eco-costs as well as for the carbon footprint. For example, the eco-costs of S1 usage and EoL represent only 1%, and for S3 they represent 10%. In other words: Under the assumption mentioned and for the scenarios under study, there is not a large difference between the impacts of a cradle-to-gate and a cradle-to-grave system.

4. Sensitivity Analysis

Worst- and Best-Case Scenarios

The sensitivity analysis includes three key parameters that are influential in the initial results: (a) virgin material input, (b) yarn count in the spinning process and (c) wears per wash ratio. For the standard scenario, an additional worst- and best-case scenario is presented:

- Scenario 1—The worst case (S1-WC) consists of a 20% higher virgin material impact, a fine 200 dtex 2-ply yarn and 4.2 wears per wash.
- Scenario 1—The best case (S1-BC) includes a 20% lower virgin material impact, a coarser 800 dtex 2-ply yarn and 6,9 wears per wash.
- Scenario 2—The worst case (S2-WC) consists of no virgin material impact due to the cut-off criteria, a finer 700 dtex 2-ply yarn and 4.2 wears per wash.
- Scenario 2—The best case (S2-BC) includes no virgin material impact due to the cut-off criteria, the same coarse 1429 dtex 2-ply yarn and 6.9 wears per wash.
- Scenario 3—The worst case (S3-WC) consists of no virgin material impact due to the cut-off criteria, no spinning process in which dtex variations can be reflected and 4.2 wears per wash.
- Scenario 3—The best case (S3-BC) includes no virgin material impact due to the cut-off criteria, no spinning process in which dtex variations can be reflected and 6.9 wears per wash.

The results of the analysis are shown as eco-costs in Figure 4 and carbon footprint values in Figure 5. The largest increases and decreases can be seen in Scenario 1, mainly due to the raw material category. Compared to the standard S1, S1-WC increased by 18.9% to EUR 4.20 and S1-BC decreased by 18.7% to EUR 2.87 in eco-costs. The carbon footprint of S1-WC increased by 19.5% and S1-BC decreased by 19.3%.

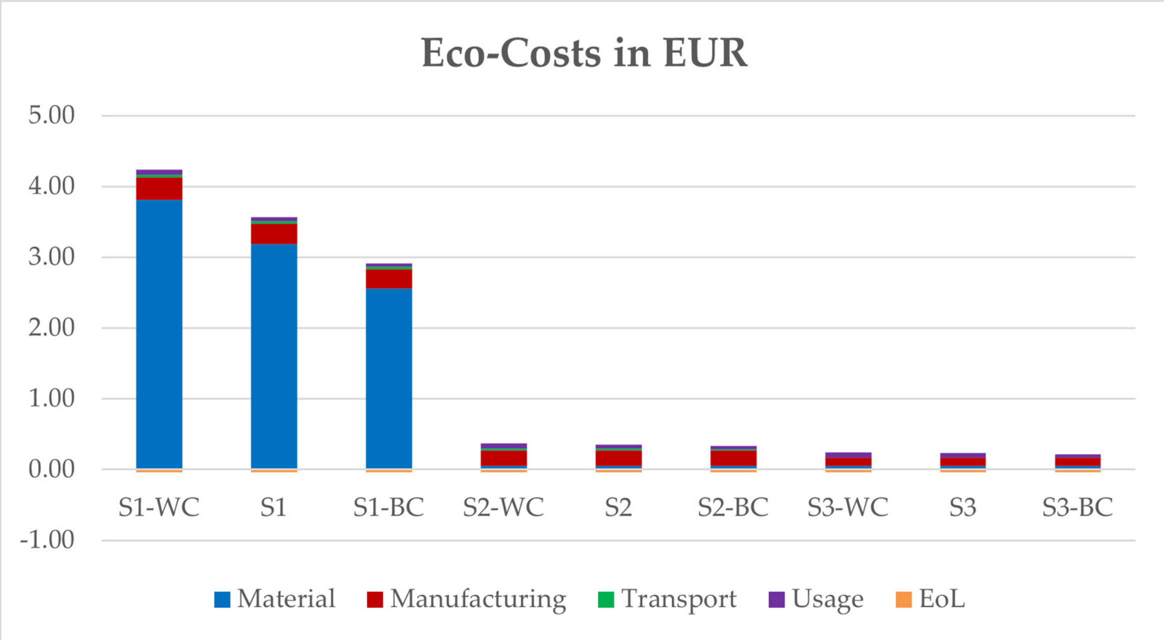

Figure 4. Diagram of the sensitivity analysis results displayed for S1, -2 and -3 showing worst-case (WC), standard and best-case (BC) scenarios regarding eco-costs.

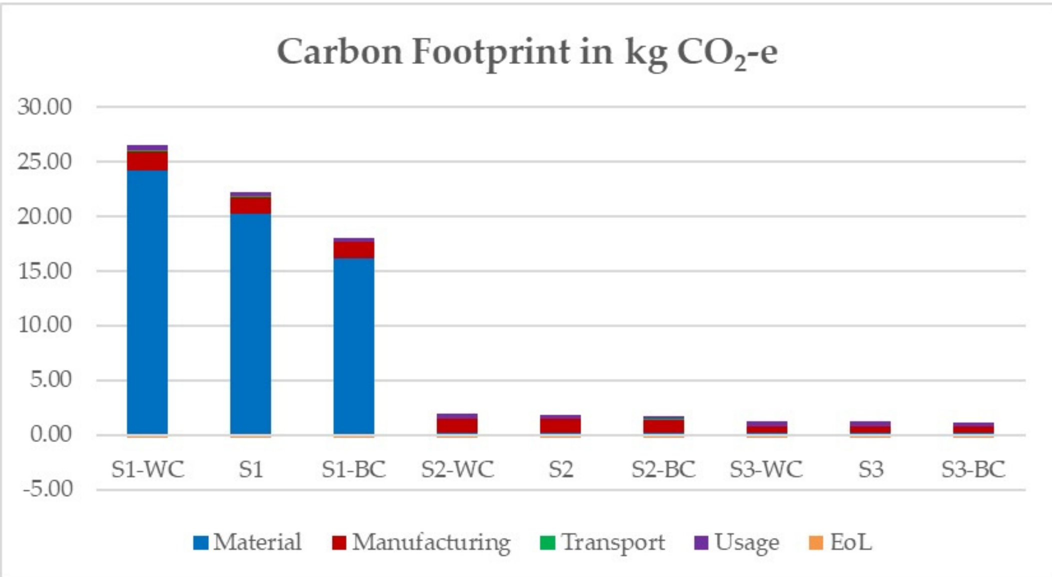

Figure 5. Diagram of the sensitivity analysis results displayed for S1, -2 and -3 showing worst-case (WC), standard and best-case (BC) scenarios regarding carbon footprint.

In Scenario 2, S2-WC increased by 4.7% to EUR 0.33 compared to the standard S2, while S2-BC decreased by 6.5% to EUR 0.29 in eco-costs. The carbon footprint increased in S2-WC by 5.8% and S2-BC decreased by 8.0% compared to standard S2.

Scenario 3 shows an increase of 7.7% to EUR 0.21 in S3-WC compared to the standard and a decrease in S3-BC of 7.7% to EUR 0.18 in eco-costs. The carbon footprint increased in S3-WC by 10.2% and S3-BC decreased by 10.2%.

The detailed results of the sensitivity analysis can be found in Tables S17–S21 of the Supplementary Materials.

5. Method B: The EVR Method to Calculate the Effect on Overproduction

5.1. The General Concept of the EVR

An LCA is commonly applied to calculate the environmental burden of production and product chains (from cradle to grave or cradle to cradle). The EVR method, however, is used to calculate the environmental burden associated with the buying patterns of consumers. Consumers can spend their money on either green products and services or on activities that are quite polluting (such as travelling by train versus travelling by plane). Therefore, EVR is an indicator used to reveal sustainable and (un)sustainable consumption patterns. In fashion, the eco-costs are an indicator of the environmental pollution associated with the clothes that people buy, while the value is the price that people pay the retailer. Sustainable fashion has low eco-costs in comparison with its price. For conventional fashion, it is the other way around.

5.2. The General Concept of "Budget Constraints"

Since most people cannot spent more money than they earn in their lifetime, they can buy only a limited number of products. That is called budget constraint. As an example, most people have a restricted amount of money left for shopping at the end of the month. At a discount rate of 50%, they can buy two items instead of one, which doubles the environmental burden. In general, discounting of retail prices is not good for the environment, since low product prices can fuel a consumption-oriented society that harms the environment. People should realize that fast fashion is enabled by low prices (otherwise, they could not afford to discard clothes so rapidly).

5.3. The Two-Dimensional Approach

The EVR method, in combination with the budgetary approach, has been used as a strategic analysis of sustainable strategies at the EU level, as shown in Figure 6 from [23].

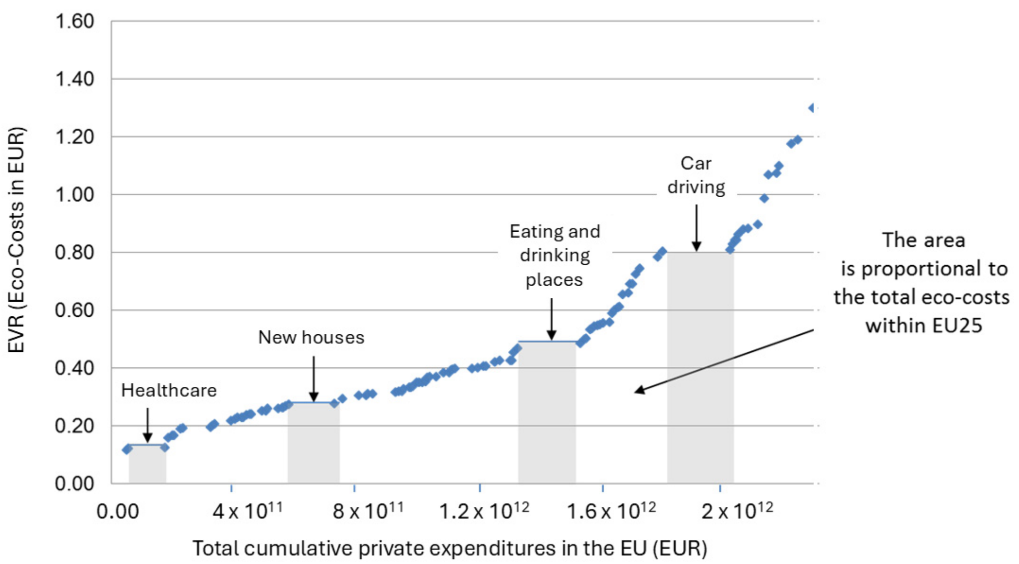

Figure 6. The EVR as a function of the total expenditures of all consumers in the EU.

The area underneath the curve is proportional to the total eco-costs at the EU level. Basically, there are two sustainable strategies:

1. Forcing the industry to make products with lower eco-costs, which would shift the curve downward.
2. Encouraging consumers at the high end of the curve to reduce their expenditures, while letting consumers at the low end spend their money as they desire, which would shift the middle part of the curve to the right (note that the total expenditures are not likely to reduce since people would not accept that they are forced to spend less than they earn).

The key to improvement is the innovation of products and services that fulfil the following dual objectives: (1) adding more value for buyers so that they are prepared to pay more, while at the same time (2) reducing the environmental burden (eco-costs); see Figure 7.

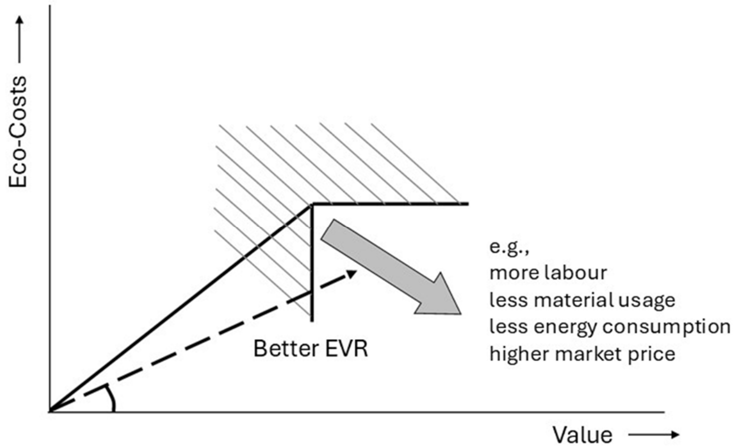

Figure 7. The dual objectives of innovation. The arrows represent the shift towards products or services with a better EVR. The more the striped arrow moves into the direction of the big grey arrow, the lower the eco-costs and the higher the value will be. For a better EVR a position in the right lower corner of the figure is the best, following the movement of the stripes and the fat arrow.

The reader may have a first impression that such dual objectives are not feasible ("making products greener will cost more money"), but it should be noted that costs and value are not the same. Value is highly determined by product quality and image (influenced by marketing). In fashion, production costs are small in comparison with distribution and marketing costs. The authors of Eco-efficient Value Creation [23] illustrate the techniques and give examples of how to create value with lower eco-costs. The N.I.O. project is another example, which will be discussed in the next section.

6. Results of EVR Calculations

The Dual Objectives of the N.I.O. Model with Knitting on Demand

The aim of this new business model is to avoid overproduction, which is the result of a mismatch between supply and demand. This mismatch is caused by challenges in forecasting and market dynamics. In the end, every company wants to reduce the high costs of overproduction. In mass production systems, however, overproduction is increasing due to the ever higher agility in markets, partly caused by increasing temperature fluctuations from global warming [24].

It is well known that on-demand knitting can eliminate this overproduction. A disadvantage of on-demand knitting is that it is slightly more expensive (mainly because of the costs of labour in the EU). However, with the added value (see the discussion in Section 6), it is likely that these extra costs can be tackled with a well-designed marketing strategy.

Data on overproduction in the literature show big differences between brands (see Appendix A). In this study, we used a reasonable estimate that has been given in the Global Fashion Agenda 2023 [25] (p. 19): as a rule of thumb, 30% is unsold and 30% is sold at a discount, and thus 40% is sold at full price. It should be noted that this document was published under the supervision of Bestseller, the H&M Group, Kering, Nike, the Ralph Lauren Corporation, and Target.

Let us assume that the retail price of a jumper (300 g) is EUR 300 (EUR 1000 per kg), the discount price is EUR 150, the overstock rate of mass-produced unsold products is 10% (i.e., never sold by the brand), and the rate is 20% for obsolete inventory (i.e., inventory never sold to consumers). For mass production, there is a high percentage of obsolete items in the form of returns, especially for purchases made over the internet. For on-demand production, there is no overstock because the on-demand system allows the customer to digitally view and fit what has been ordered beforehand and so the customer will not have ordered what is not satisfactory. What is not ordered will not be made. However, there is a small percentage (1.5%) of obsolete items because of discrepancies and a small number of returns. The value of overstock and obsolete (discarded) jumpers is set to zero.

With these assumptions (see Appendix A and Table A2), we conducted an EVR calculation of the eco-costs of a company that has a turnover of EUR 165,000 in jumpers (400 × EUR 300 + 300 × EUR 150); see Figure 8 for the results. The claim that mass production of virgin woollen jumpers has 44% higher eco-costs than on-demand knitting can be explained as following: The eco-costs per jumper are EUR 3.53. For 1000 mass-produced jumpers (100 overstock + 400 full price + 300 discount + 200 obsolete), the cost is EUR 3530. For 560 on-demand knitted jumpers (400 full price + 150 full price + 10 obsolete), this is EUR 1977 in total, which represents a revenue-normalized reduction of 44% in eco-costs for on-demand versus mass-produced jumpers.

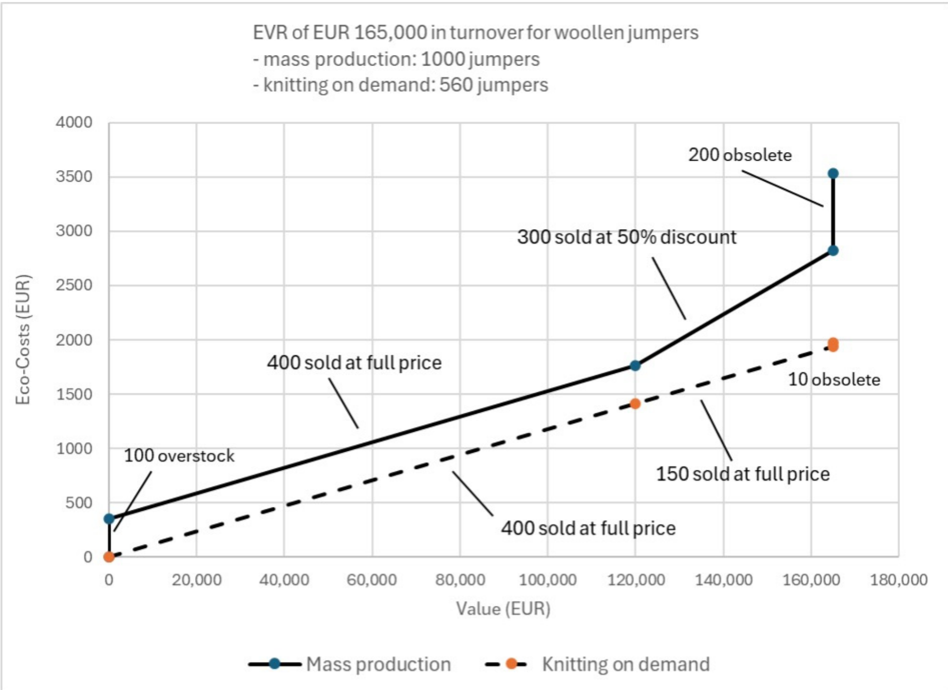

Figure 8. The eco-costs of a company with a turnover of EUR 165,000 for virgin Merino wool jumpers of 300 g each. The eco-costs of mass production are 44% higher, nearly double the eco-costs of on-demand knitting, based on this "revenue-normalized comparison" (EUR 1977 and EUR 3530 at equal turnover).

7. Discussion

7.1. The Extra Value of Knitting on Demand for Consumers

As explained in Table A1 of Appendix A, there are several ways for on-demand knitted products to reach consumers, and each route has its specific advantages and value. Via the B2C route, the consumer will receive the exact product as purchased, including in terms of the colour of the jumper; its shape with respect to width, length, and form; and details such as cuffs and collar. It is assumed, but has not been extensively tested yet, that the consumer is willing to pay a premium price for this on-demand service. In addition, the high quality of the garment and the sustainable image of no waste and local production could justify the higher retail price. Because the software employed for whole-garment knitting is very flexible, it is feasible that in the future not only jumpers could be knitted on-demand, but other kinds of products could also be made.

7.2. The Advantage of Unravelling and Re-Knitting for Consumers

While unravelling is an existing economic solution to resolve production errors during the manufacturing phase (see Appendix C), this technique also entails an opportunity to add value for consumers: a circular on-demand knitting system can offer the service of re-knitting a jumper when there are fitting issues or when it has gone out of fashion. The use of recycled yarn can be perceived as an advantage by consumers who, for example, cherish the environment or may have an emotional value attached to the jumper. However, consumer surveys have noted that the value of recycled textile products is poorly received, as the quality is perceived to be low and the fibres are seen as unclean and unhygienic [13]. These aspects could be less important when pre-consumer unravelled yarn is used.

7.3. Nuances in Wool LCA Data

Virgin wool production is known to score high on greenhouse gas (GHG) impacts in the raw material phase due to the emissions of methane (NH_4) and nitrous oxide (N_2O) from sheep farming. There are strong local differences, depending on the breed, feed, and soil conditions. Furthermore, LCA scores depend significantly on the allocation of co-products in the system, in combination with the yield of scouring [26]. Recent studies suggest that the impact of wool production may have been misrepresented in many LCA databases due to the generalization of impact data by using global averages instead of geographically specific data, as well as a lack of consideration of wool's biogenic system. For example, Nautiyal et al. (2025) and Roberts et al. (2023) indicated a possible 30% overestimation of the GHG impact of New Zealand wool [27,28]. In general, Australian Merino wool cannot be compared directly to wool from New Zealand, the USA, or England.

The Idemat data used in this study are based on the data of Wiedemann et al. [13] on Merino wool with economic allocation, combined with recent scouring yields for 2022–2024 and the most recent data on energy from 2024. Although the details and background of the GHG calculations described in the publication are not entirely clear, we trust in the expertise of the authors.

8. Conclusions

The environmental burden of a circular knitting on-demand system and recycling for woollen jumpers is quite significant. To summarize, we refer back to the research questions outlined in Section 1.2:

(a) What is the environmental impact of producing a virgin wool jumper?

The cradle-to-grave environmental burden of a virgin Merino wool knitted jumper amounted to EUR 3.53 in eco-costs and a carbon footprint of 21.93 kg CO_2-e.

(b) What is the environmental impact of producing a recycled wool jumper?

The environmental burden of a recycled wool (shredded) knitted jumper from cradle to grave amounted to EUR 0.31 in eco-costs and a carbon footprint of 1.56 kg CO_2-e. The environmental burden of a reknitted jumper made of unravelled wool amounted to EUR 0.19 in eco-costs and a carbon footprint of 0.89 kg CO_2-e.

(c) Which recycling strategy (shredding or unravelling wool) is the best choice?

Depending on the yarn quality of the feedstock, a recycling strategy can be chosen. When yarn quality is maintained, unravelling and reknitting offer very low environmental costs due to being higher up the R-ladder, the lack of virgin material input and needing less extensive processing. However, when yarn quality is low it is unlikely that unravelling and reknitting will offer a suitable solution, and shredding will be more applicable. Both recycling strategies have low environmental costs compared to using virgin wool to make a jumper.

(d) What are the hotspots (most critical activities) of the new systems?

In Scenario 1 (virgin wool), the raw material stage has the highest environmental impact due to the use of virgin material. In Scenario 2 (recycled wool), the manufacturing stage is the hotspot, mainly due to the spinning, dyeing, and knitting processes. In Scenario 3, the knitting process is the main driver of environmental impact. A sensitivity analysis shows variations in the following parameters: (a) virgin material input, (b) yarn count in the spinning process and (c) the wears per wash ratio, combined in worst- and best-case scenarios. The variations affected Scenario 1 the most, mainly due to changes in the raw material category, which is impact-heavy. Additionally, to check the effect of garment lifetime variations per scenario, the "impact per wear" was also calculated. The results show a similar outcome pattern, with S1 having the highest environmental impact, followed by S2 and S3.

(e) What is the environmental gain of knitting on demand versus mass production?

The environmental gain of a knitting on-demand system is the avoidance of (1) overstocking of jumpers after production, (2) a surplus of obsolete jumpers that are not sold by retailers in shops or online, and (3) discounted sales to get rid of unsold products. An example of these three effects is shown in Figure 6: for a company with a turnover of EUR 165.000, for virgin Merino wool jumpers weighing 300 g each, the eco-costs of mass production are 44% higher than on-demand knitting (revenue-normalized).

Supplementary Materials: The following supporting information can be downloaded from https://www.mdpi.com/article/10.3390/textiles6010019/s1: Inventory Data Scenario 1: Tables S1–S6; Inventory Data Scenario 2: Tables S7–S9; Inventory Data Scenario 3: Tables S10–S12; Detailed Results: Tables S13–S16; Sensitivity Analysis Results: Tables S17–S21; Limitations of Textile LCAs: Table S22.

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Idemat database is openly available at https://www.ecocostsvalue.com/data-tools-books/ (accessed on 23 October 2024).

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Appendix A. The Literature on Overproduction

According to several references [9,24,29], "overstock" exists when products are produced but are not sold. These products come directly from the production line and remain in the warehouse. E-commerce and in-store returns are not covered by overstock because products are sold to consumers and then returned to the store or to the warehouse of the retailer. The aforementioned references note that for fashion, the average return rate of online purchases in Europe is 20–30%, while for brick-and-mortar stores, it is around 10%. However, some industry experts suggest that more than half of the fashion items bought online are returned. In general, higher-priced items tend to have higher return rates, and 70% of fashion returns are related to poor fit or style rather than defects.

In addition to overstock and returns, there are other categories of unsold goods, namely, "obsolete products" (products for which there is no longer any demand in retail shops) and "damaged products" (products that have been damaged in transit or storage). Overstock and obsolete products are the result of a mismatch between supply and demand, which can occur due to forecasting difficulties, market dynamics, economies of scale, or business strategy [26].

Niu et al. [29], referred to in the ETC CE Report 2024/4 [5], estimated that fashion brands hold 25–40% of products unsold at the end of a selling season. The same report refers to the following numbers from the ReHubs study: 60–80% of goods sold through core channels, meaning that 20–40% of goods go through alternative channels or remain unsold. The available data generally combine (i) products that never left warehouses/distribution centres, (ii) products that were sent to stores but never sold, and (iii) products returned from stores to warehouses.

By averaging the data across the abovementioned literature sources, it can be estimated that 21% of textile products remain unsold. These goods can follow multiple pathways, but in general they are sent (i) to external outlets/jobbers, (ii) as donations, and (iii) for destruction (incl. recycling). When donated to Africa, 46% of EU textile exports end up in landfills or are burned, and 41% of textiles exported to Asia mostly become rags or industrial wipes.

While the exact figures vary by region and the methodology applied, 20–50% of the 21% of unsold textiles ultimately end up being destroyed (by direct incineration or in landfill; failed exports become waste or are recycled, which destroys the original product form) rather than being used by consumers.

The recent literature on prices and markdowns of unsold goods reveals the following percentages: approximately 30% of clothing made is not sold and 30% is sold at discount [28]; a large sports brand stated that, on average, around 44% of its assortment was marked down in 2024 and that this number was higher than in the years before [5].

Based on the above definitions and percentages, which are often not straightforward, we decided upon the descriptions and data presented in Tables A1 and A2 to perform the calculations for this research.

Table A1. Terminology used for brand and retailer and explanations of sales routes.

Term	B2B Sales Route	B2C Sales Route
Brand—company that designs and sells the product...	...to a retailer	...directly to the consumer (brick-and-mortar or online)
Retailer—company that sells the product...	-	...directly to the consumer (brick-and-mortar or online)

B2B—business to business; B2C—business to consumer.

Table A2. Terminology used, explanations, and quantities applied.

Term	Explanation	Quantity Applied
Full price	Retail price for the consumer = 100%	40%
Obsolete	Products brought to the market but never sold to the consumer	20%
Overstock	Products never sold by the brand which stay in the warehouse	10%
Unsold products (mass)	Obsolete + overstock	30%
Unsold products (on demand)	Obsolete	1.5%

Appendix B. Yarn Specifications

Wool is known as a high-quality, durable, natural fibre with a well-established recycling history and infrastructure. For this study, the following three types of wool yarns were selected: 100% virgin Merino wool, 100% recycled wool, and unravelled Merino wool (Figure A1).

Scenario 1 is based on the Cashwool/SWE from Zegna Baruffa Lane Borgosesia S.p.A. (VALDILANA, Biella, Italy), which has a 2/48 Nm, or 416 dtex, and is 100% virgin Merino wool yarn used regularly by N.I.O in its operations.

Scenario 2 is based on the JFK from Filpucci S.p.A. (Campi Bisenzio, Italy), which has a 2/14 Nm, or 1429 dtex, and is 100% recycled wool yarn made from a mixture of pre- and post-consumer fibres. The manufacturer could not give a specific percentage of the mix of pre- and post-consumer recycled yarn; however, Bianco et al. [16] states a 15% pre-consumer, 85% post-consumer mix for their 100% recycled wool yarn. The Supervisor of the Digital/Physical Textiles Lab MSc. at Amsterdam University of Applied Sciences, Tanya Yeromina, performed a series of durability tests (Martindale pilling and abrasion resistance methods, evaluated against the European TCG recommendations for knitwear) on JFK Filpucci. The outcomes showed acceptable surface stability and a high level of durability and resistance to wear, confirming that the 100% recycled material performs well under intensive use.

Scenario 3 is based on a concept of unravelled yarn, assuming that a virgin wool sweater retrieved through a take-back system has been unravelled. Studies, as well as Table A3, have indicated that the quality of unravelled yarn is insufficient based on post-consumer feedstock and too damaged to be reknitted into a new garment [30,31]. However, pre-consumer unravelled yarn and post-consumer yarn with minimum-use deterioration show a significantly better level of yarn tenacity; therefore, the study assumed that the feedstock for S3 consisted of yarn within this range of quality in order to be reknitted. The yarn count has been estimated to be around 600 dtex, based on the range of the two pre-consumer unravelled yarns from Razipour's study, 670 dtex and 468 dtex [30].

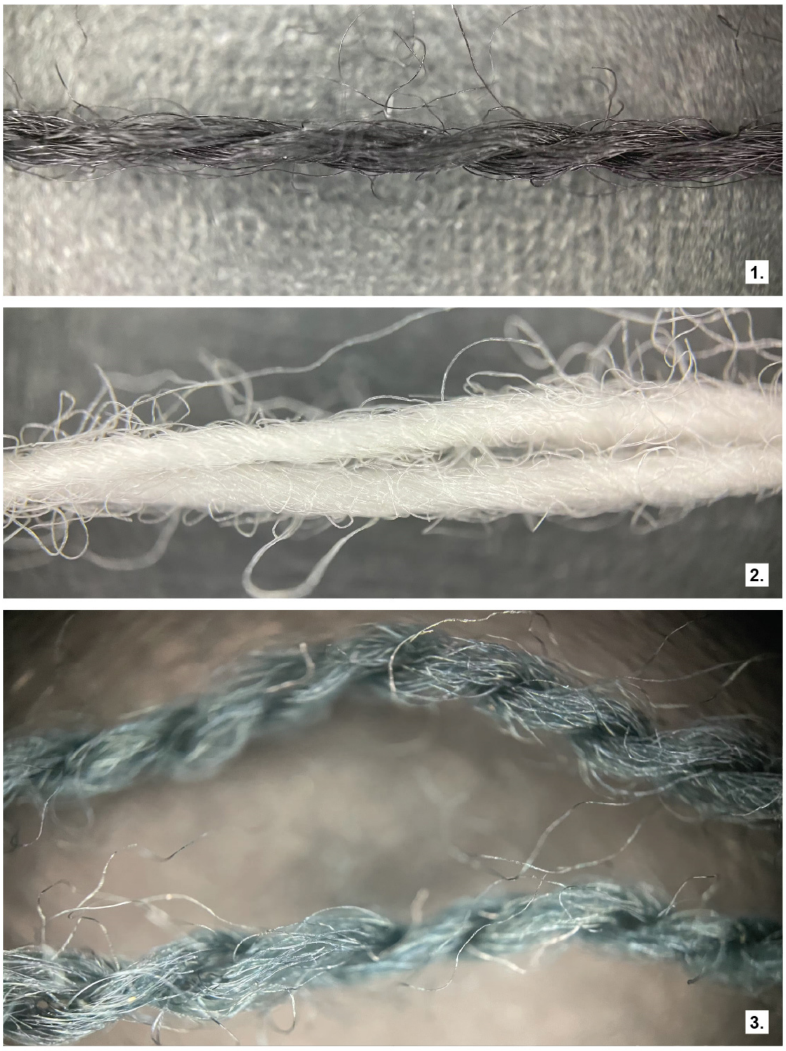

Figure A1. Overview of selected yarns: (**1**) 100% virgin wool yarn; (**2**) 100% recycled wool yarn; (**3**) 100% unravelled Merino wool. Photos by New Industrial Order.

Appendix C. Unravelling

Unlike traditional mechanical recycling that shortens fibres through shredding, unravelling (or de-knitting) recovers continuous yarn lengths by undoing knitted loops, preserving yarn quality and enabling reuse. The method of unravelling is not a new phenomenon; it has been practised by hand-knitting communities for decades. Additionally, modern automated unravelling systems have transformed this manual process into industrial-scale operations. These machines feature tension control mechanisms, automated break detection, and multi-head capabilities, allowing them to process up to 12 garments simultaneously [30]. The technology is particularly compatible with seamless knitting, where garments consist of continuous yarn without seams. Industrial unravelling is a common practice applied in factories to pre-consumer textiles that have failures, but it is less frequently applied to post-consumer textiles. One of the main reasons that prevents the adoption of post-consumer knitwear for reknitting is a steep decrease in yarn tenacity, as shown in the yarn testing results obtained from Razipour [30] and the yarn manufacturer information [32] in Table A3. Bukhonka and Kyzmchuk [31] reached similar conclusions and indicated the lack of standardization of "knittable" mechanical properties of yarn. However, hand-knitters are currently buying up high-quality, second-hand knitted garments to unravel and reuse these "thrifted" yarns to make new garments, indicating a potential for this feedstock once sorted and assessed for quality [33].

Table A3. Yarn testing results regarding tensile strength (cN/Tex), obtained from the Mesdan reports in Razipour, 2024 [30], and yarn manufacturer information [32].

Material	Ply	cN/Tex
Virgin wool yarn (pre-knitting)	2-ply	13.84
Recycled wool yarn, black (pre-knitting)	1-ply	3.78
Recycled wool yarn, beige (pre-knitting)	1-ply	3.24
Unravelled virgin wool yarn (pre-consumer knitwear)	2-ply	6.36
Unravelled virgin wool yarn (post-consumer knitwear)	2-ply	1.57
Unravelled virgin wool yarn (N.I.O knitwear)	2-ply	5.99
Recycled wool yarn JFK (pre-knitting)	2-ply	3.25

The recycling technique of unravelling has a better position on the R-ladder than recycling by means of shredding, since unravelled yarn requires fewer operations than shredded fibres before being reused again. On the other hand, transport for collecting the feedstock (knitted items) and moving them to different industrial locations might increase the environmental impact. Case-specific measurements and analyses are needed to determine and compare the real impacts. Limited research has been performed on the unravelling process and yarn knittability after unravelling of pre- and post-consumer textiles, with various outcomes being reported [30,31], and economic aspects have been reviewed. To date, the environmental aspects of unravelling and reknitting have not been analysed.

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