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A framework for measuring physical garment durability

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ABSTRACT

Measuring the physical durability of garments is difficult and current assessment methods lack objectivity and reliability or don't reflect the complex nature of durability for different garment categories. This study presents a novel and reproducible methodology for testing and ranking the absolute durability of commercially available t-shirts and denim jeans. Multiple durability factors were used to modulate the ranking as opposed to previous studies which only reported on single factor tests to evaluate durability. This new ranking methodology was used to explore the relationship between garment durability and retail price, consumers commonly use price to evaluate whether a garment is of good quality and durable, however, results indicate that retail price cannot be used to predict the durability of garments. The methodology developed during this study is now being used to assess garment durability for the Waste Action Resource Programme's (WRAP) Textile 2030 initiative as part of their strategy to reduce the environmental impact of UK fashion. Multiple UK fashion brands are signed up to this initiative and this method will provide a way of measuring and benchmarking different garment types as a step towards improving the durability of garments on the market.

1. Introduction

The important role garment durability can play in circular strategies to minimise the huge environmental impacts of the fashion industry is being recognised by academics, brands, NGOs and governments. Studies have shown that extending the lifetime of garments can positively impact sustainability and that improving the physical durability of garments can support extended lifetimes, garment utilisation, and reduce overconsumption (Klepp et al., 2020; Benkirane et al., 2022; Cooper and Claxton, 2022). Policymakers and industry initiatives are now exploring how durability can be incorporated into future legislation and business models.

The fashion industry is associated with a wide range of significant negative environmental and social impacts with the vast bulk of these impacts linked to the pre-production and production stages of the product lifecycle. These stages include fibre production, yarn and fabric production and garment manufacturing (Berg et al., 2020; United Nations Environment Programme, 2023). The scale of these impacts is directly related to the scale of global clothing consumption, which has doubled since 2000 (Ellen MacArthur Foundation, 2017). Much of this growth in consumption has been attributed to the fast fashion phenomena. Fast fashion has been characterised as a form of fashion where there is a rapid turnover in the fashion trends and garment quality is considered worse than contemporary products (Brewer, 2019; Centobelli et al., 2022), resulting in garments having short lifetimes and being underutilised (Niinimäki et al., 2020).

Poor garment utilisation (Smith, 2023) amplifies the environmental and social impacts of the industry, as it drives greater demand to produce new garments to feed accelerated consumption patterns, as well as significantly increasing clothing waste. Currently, the UK alone produces 336,000 tonnes of textile waste per year that is sent to landfill or incinerated (WRAP, 2022b), and it has been estimated that the global fashion industry will create 148 million tonnes of clothing waste by 2030 (Global Fashion Agenda, 2017).

The use of new circular business models has been proposed to reduce absolute consumption and minimise garment waste (Koszewska, 2019; Shirvanimoghaddam et al., 2020; Ruckdashel et al., 2021; Coscieme et al., 2022; Muthu, 2022). However, there is now an increased focus and recognition of the importance of garment durability to underpin circular business models such as garment reuse and leasing. Furthermore, improving physical garment durability to extend utilisation has been recognised as a significant factor for improving the sustainability of the clothing and fashion industry (Cooper and Claxton, 2022). Small improvements in utilisation, extending the active life of clothing by 3

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months, can lead to a “5–10% reduction in each of the carbon, water and waste footprints” (WRAP, 2012, p.1). Furthermore improved garment durability contributes to extended utilisation and the extension of garment lifespans (Laitala and Klepp, 2020) which is considered critical for circular economy strategies that rely on garments being used multiple times (Sun et al., 2021). Currently, cheaper garments are seen by consumers as dispensable and therefore are more likely to end up in the rubbish bin than a circular business stream compared with higher priced products (Degenstein et al., 2020).

Price has been used as a measure of quality and durability (Goworek et al., 2012; Degenstein et al., 2020) since the 1950s (Leavitt, 1954; Jacoby et al., 1971; Shapiro, 1973). Today the general perception is that cheap clothing is low quality, with poor durability and does not last (Gabrielli et al., 2013), whereas expensive clothing is perceived as better quality and longer lasting (Verma and Gupta; Barnes et al., 2013; Vanacker et al., 2022). In the absence of objective methods to measure durability, the price has become the default indicator for consumers and others to assess garment durability and therefore, utilisation (Shapiro, 1968). Although a cheaper product could potentially be more durable and have a longer potential lifespan than its more expensive counterpart.

The importance of durability for circularity is also recognised by policymakers, with the EU Circular Economy Action Plan requiring brands to improve the durability of their products and the proposed Ecodesign for Sustainable Products Regulation suggesting these requirements will become formalised, and as such access to the EU fashion market may require labelling to declare the durability credentials of garments. The EU Product Environmental Footprint (PEF) proposals imply product developers will need to achieve a minimum durability standard for consumer labelling (Zampori and Pant, 2019; Wojnarowska et al., 2021).

The UK’s Waste Prevention Programme for England states increasing product utilisation and improving the durability of clothing directly aligns with the UK government’s goals for the industry Climate Change Committee (2022); Furthermore, Textiles 2030, the UK’s voluntary textile initiative, aims to achieve significant reductions in the carbon and water footprints of UK fashion by improving garment durability using new durability standards (WRAP, 2017). The introduction of durability standards has also been cited as imperative for consumers to be able to identify garments with better durability (Vesterinen and Syrjälä, 2022) as opposed to using price as an indicator of durability.

To implement these legislative policies for improved durability a methodology for measuring garment durability is required. With such a methodology, the durability of garments can be measured and new standards for improving the durability can be created to enhance utilisation and improve the sustainability of products. However, at present there is no consistent or objective way to measure the durability of a garment (Cooper and Claxton, 2022).

Academic studies have explored garment durability, but no reliable and objective methods have been adopted by either industry or policy makers. This paper presents a novel methodology for the objective measurement of physical durability that can be applied to different garment types or categories. This method can be used to measure and compare the durability for different types of garments.

This paper first presents the literature to explore different approaches to measuring durability used in previous studies. It will analyse the different factors and approaches to validate the proposed methodology. Physical test results from T-shirts and Jeans will be used to present the method while exploring the relationship between durability and retail price. Subsequently, the methodology will be explained, and the results will be analysed. Conclusions will be presented along with limitations and future work.

2. Literature review

Durability is a measure of the reasonable wear life of a product and how its functionality degrades during use by repeated abrasion, stretching, and laundering (Hunter, 2009). The ability of a garment to remain functional is referred to as its physical durability (Ellen MacArthur Foundation, 2021). There are four groups of variables that influence garment durability (Klepp et al., 2020):

- Garment variables, such as its type, composition, construction, and components (zips, buttons, and interlining), with the least durable component defining the overall durability of the garment (Fletcher, 2012, p.226).
- User characteristics, such as gender, age and working status.
- Garment use profile, such as wearing and washing frequency.
- User’s clothing practices, such as the ability to repair garments.

Garment type directly impacts the factors that influence durability (Niinimäki and Armstrong, 2013; Cooper et al., 2013; Cooper and Claxton, 2022). The durability of a T-shirt is determined by its ability to resist the formation of holes in the fabric or shrinkage (Cooper et al., 2013; Benkirane et al., 2019), while the durability of jeans is determined by its ability to resist abrasion (Cooper et al., 2013). Garments can also exhibit multiple modes of functional failure, such as colour loss, loss of shape and pilling simultaneously, which all contribute to a reduction in durability (Cooper and Claxton, 2022). Garment type also influences the disposal behaviours of consumers suggesting consumers do not expect the same level of durability for all garment types (Degenstein et al., 2020).

How garments are used and how often they are worn (garment use profile) directly impacts the rate of functional degradation and the type of durability failure that can lead to garment disposal (WRAP, 2022a; Cooper and Claxton, 2022). Jeans worn in an office environment will have a different rate of functional degradation compared to the same pair of jeans being worn in an industrial environment such as a building site or factory.

Domestic laundry negatively impacts garment function, with high wash temperatures and the abrasive action of the drum and detergents degrading the fabric (Chiweshe and Crews, 2000; Annis, 2012; McQueen et al., 2017; Cotton et al., 2020). Using tumble dryers, with the combination of agitation, heat, and humidity, accelerates the degradation process (Wei et al., 2018). Washing frequencies vary significantly by consumer and product type (Klepp et al., 2020; Wiedemann et al., 2021), and garments washed more frequently deteriorate faster in terms of colour fading, abrasion, and pilling (McQueen et al., 2017).

As physical durability is dependent on multiple variables, (garment, user characteristics, use profile and clothing practices) developing an objective measurement method is challenging (Vanacker et al., 2022; Cooper and Claxton, 2022). Many studies have explored durability measurement methods and some of these are shown in Table 1. There are several studies which do not test a single garment but use other techniques to assess durability such as investigating clothes at the end of life (Cooper and Claxton, 2022). These have been included in the table despite not using physical test methods as it is important to highlight all past research in this area.

Generally, t-shirts and denim jeans were the focus of these studies, as these are readily accessible to all consumers regardless of price point (Badgett, 2019; Wakes et al., 2020). Apart from this, there was little consistency in the methods used to measure durability.

The type and scope of testing carried out by studies varied hugely, with some studies using many tests (Chowdhary, 2002) whilst some did no testing at all. Where garment testing was used, different test methods were employed to assess dimensional stability, pilling, fabric abrasion, fabric tensile and bursting strength, and seam strength, making comparisons between results very difficult. Colour change and colour fastness were assessed in some of the studies, but fabric spirality was considered in just two studies.

Despite the degradation caused by washing, many studies did not incorporate laundering into their assessment of durability (Chowdhary,

Table 1
Summary of past research papers examining different factors of garment durability.

Publication	Sample category	No of garments	Washing Protocol	Durability Test	Durability Ranking
Wakes et al. (2020)	T-shirts	5	30 wash/tumble dry cycles	Dimensional stability Spirality Colour change	Single test ranking
Badgett (2019)	T-shirts	3	20 wash/tumble dry cycles	Dimensional stability Bursting strength Colourfastness Pilling Skewness	Single test ranking
Ghaani Farashahi et al. (2018)	Jeans	3	5 wash/tumble dry cycles	Dimensional stability Tensile strength Colour difference Colour fastness Smoothness retention Seam strength	Single test ranking
Chowdhary (2002)	Jeans	3	N/A	Dimensional stability Tensile strength Seam strength Elongation Tear strength Abrasion resistance Colourfastness Fabric resistance to ravelling	Single test ranking
Kan and Yuen (2009)	Denim fabric	4	25 wash/tumble dry cycles	Dimensional stability Tensile Strength Stiffness of fabric Mass change Thickness change Stretch properties	No ranking
Card et al. (2006)	Jeans	9	25 wash/tumble dry cycles	Pilling Edge Abrasion	Single test ranking
Benkirane et al. (2019)	T-shirts	29	50 wash/tumble dry cycles	Dimensional Stability Colourfastness Spirality Seam Strength Bursting Strength Pilling	Multi-testing weighted ranking
Hailemariam and Muhammed (2022)	Denim fabric	4	N/A	Tensile Strength Tear Strength Abrasion Resistance Pilling Air Permeability	Single test ranking
Degenstein et al. (2020)	Clothing	9	N/A	N/A	No ranking
Cooper and Claxton (2022)	Clothing	1476	N/A	N/A	No ranking
Vanacker et al. (2022)	Clothing	N/A	N/A	N/A	No ranking
McQueen et al. (2017)	Jeans	4	3 and 30 wash cycles	Fabric mass Tensile strength Colour change	No ranking
Laitala, K. et al. (2020)	N/A	N/A	N/A	N/A	No ranking

2002; Yuksekkaya et al., 2016; Eryuruk, 2019; Mandre et al., 2021; Hailemariam and Muhammed, 2022) despite several studies noting the significant effect laundering had on physical durability (Card et al., 2006; Kan and Yuen, 2009; McQueen et al., 2017). Where laundry was used as part of the assessment process, different wash temperatures and drying methods were used (Card et al., 2006; Ghaani Farashahi et al., 2018), and the number of wash cycles also varied from as low as 5 (Ghaani Farashahi et al., 2018) up to 50 (Benkirane et al., 2019). Most studies used only 5 or fewer garments for their sample set. Just two studies used more than 5 garments for their sample set (Benkirane et al., 2022; Cooper and Claxton, 2022).

In addition, there was little alignment on how the durability of the tested garments was compared and ranked. Some studies identified the most durable garments, but the process for analysing the test results to define the most durable was not clearly explained (Ghaani Farashahi et al., 2018; Badgett, 2019; Hailemariam and Muhammed, 2022). Benkirane et al. used a weighted score for the durability of the garments assessed in their study, however, this was based on a consumer perception rather than an objective analysis of the test results.

The wide range of different approaches to measuring garment durability demonstrates the process is complex and ambiguous. As a result, there is a lack of agreement on a standardised approach (Vanacker et al., 2022; Cooper and Claxton, 2022). However, it is clear that physical durability cannot be assessed via a single test method, and to have an objective and consistent assessment, a multitude of tests are needed to reflect the different factors that influence the durability of different garment types (Annis, 2012).

Finally, most studies aimed to replicate real-life garment ageing in a consistent and repeatable manner using a range of laboratory test methods. These methods can not reflect every aspect of real-life wear, including user characteristics, use profiles and clothing practice, but they can replicate years of wear in a matter of hours (Annis, 2012). Unlike wear trials which have been used to explore these variables and are known to be subjective due to their reliance on participants' perceptions (Klepp et al., 2020), laboratory testing focuses solely on the measurement of the absolute physical durability derived from the garment variables. This absolute durability focuses on the ability of the garment variables to retain functionality within a fixed or consistent profile of use which facilitates the opportunity to compare garment performance without the influence of user-based variables.

3. Methodology

This study aimed to establish a methodology to provide an objective method to assess and compare the absolute durability of different garments. This means assessing garment variables, such as fabric quality and seam performance against a consistent use profile. The use profile is established by using standard laboratory tests to replicate real life stresses in a controlled environment and using a consistent approach for washing. This ensures variables associated with the user and clothing practices are excluded, so as such this methodology can be used to assess and compare the absolute durability of different garments. Taking this approach facilitates the opportunity to rank garments in terms of their relative physical durability, irrespective of how a particular individual may use the garment in real life.

Physical durability must be assessed within the context of the garment category, and the type of fabric used in its construction, to reflect its real-life use (Hunter, 2009), as well as its intended use (Cooper et al., 2013; Niinimäki and Armstrong, 2013; Cooper and Claxton, 2022). Methods for testing durability must be developed with consideration of use and the most common mode(s) of failure that causes the garment to be no longer functional. By understanding these modes of failure, protocols assessing durability for specific garment types can be established.

This study focussed on two garment types, denim jeans and t-shirts. The most common causes of woven denim jeans failure are damage associated with abrasion, fabric ripping, colour fading and seam damage (Cooper et al., 2013; Cooper and Claxton, 2022). Many studies in Table 1 recognised the importance of these modes of failure for jeans (Chowdhary, 2002; McQueen et al., 2017; Ghaani Farashahi et al., 2018; Hailemariam and Muhammed, 2022).

T-shirts are generally constructed of cotton or cotton blended weft knitted fabrics which are much more fluid in terms of stretch and elongation characteristics and have yarns with lower twist and more open structures. As a result, a t-shirt's common modes of functional failure include poor fabric and garment stability, pilling, colour fading and surface disruption, or felting (Cooper and Claxton, 2022). Again, studies in Table 1 reflect these common modes of durability failure (Benkirane et al., 2019; Badgett, 2019; Wakes et al., 2020).

Based on these modes of failure, an assessment protocol was developed for each product type, with each protocol consisting of a range of appropriate laboratory test methods, repeated domestic laundry cycles, and a visual assessment. Where possible, recognised textile test methods were used to assess the different aspects of garment durability, with Table 2 listing the methods.

All laboratory testing was carried out to the prescribed methods for each standard and where appropriate in a temperature and humidity controlled environment.

3.1. Domestic laundry

To replicate the impact of domestic laundering on the functionality of the garments, whole garments were repeatedly washed and air dried. As there is no recognised method for assessing the durability of clothing to garment washing, a laundry test method was developed to reflect UK consumer washing.

Table 2
Summary of test methods used to assess garment durability.

Test	Standard	Jeans	T-shirts
Abrasion	BS EN ISO 12947–2:2016 (9kpa)	✓	–
Bursting Strength	ASTM D3787	–	✓
Pilling – Final Grade	BS EN ISO 12945–2:2020	–	✓
Seam Strength	BS EN 13935–2:2014	✓	–
Spirality	BSISO 16322–3:2021	–	✓
Stability	BS EN 5077:2007	✓	✓
Tensile Strength Weft	BS EN 13934–1:2013	✓	–
Tensile Strength Warp	BS EN 13934–1:2013	✓	–
Visual Assessment – Final Grade	Modified ISO 15487	–	✓

As washing time and temperature can have a significant effect on the durability of garments (Cotton et al., 2020) washing was carried out in identical Miele W 1724 front loading domestic washing machines, that had the fuzzy logic removed, using 50 g of commercially available non-biological washing powder. A cotton wash cycle at 30 °C was selected as consumers are being encouraged to wash at lower temperatures to prolong the longevity of their garments (Cooper et al., 2013).

Wash load weight affects the mechanical stress garments experience during the laundry process (Mac Namara et al., 2012), therefore, each wash loads was a consistent dry weight (approximately 4 kg). Jeans and t-shirt loads were washed separately to avoid colour staining from the denim (McQueen et al., 2017). All garments were air dried after each wash cycle, as air drying is a commonly used drying method (Laitala et al., 2020).

There is no industry standard for the minimum number of washing cycles for the lifetime of a garment, however, according to the WRAP Longevity Protocol, 30 washes for jeans and 56 washes for t-shirts were identified as the number of washes for an average garments lifetime (Cooper et al., 2014).

Garment samples from the domestic laundry cycles were used to assess garment stability and spirality. Two critical measurements were used to assess garment stability:

- **Jeans:** Leg Length, Waist width.
- **T-shirts:** Body Length, Chest Width.

The percentage change in these dimensions was compared to common UK industry standards and clothing brand protocols for the maximum acceptable change in dimensions for these product types as shown below:

- **Jeans**: ± 3% warp & weft.
- **T-shirts:** ± 5% length,±7 width.

T-shirt stability was recorded for the 5th, 10th, 15th, 20th, 30th, 40th, 50th, and 56th wash/dry cycles, and jeans up to the 30th cycle interval.

Spirality measures the tendency of weft knitted garments to twist during washing. The washing action releases rotational tensions in the yarns and the fabric (Khan et al., 2019) causing the garment to twist which consequently affects the fit of the garment. The spirality of the t-shirts was assessed at the 5th wash only as no further twisting would occur after this (Kothari et al., 2011).

3.2. Visual assessment

Repeated laundry cycles were used to quantify changes in the visual appearance of the garments as these changes reflect changes in the durability of a garment (Hunter, 2009). A modified version of the visual assessment standard ISO 15487 (British Standards Institution, 2018) was used to assess changes in garment appearance. This method was modified as there are factors included which do not relate to durability such as creasing through wash.

Fashion has dictated that well-worn denim is still deemed to be functional despite a high level of fading and abrasive damage that would be unacceptable in other garments (Cooper et al., 2013). However, excessively fast fading and extensive abrasive damage would lead to a loss of garment function. Abrasion contributes to the impression of colour fading for denim products, as abrasion disproportionately damages the dyed warp yarns which reveal more of the undyed, 'white' weft yarns (Hatch, 1993). Visual assessment of jeans was designed to assess the level of fading that occurred over time.

Pilling, colour fading, and surface disruption or felting have been identified as the most common reasons for the disposal of T-shirts (Cooper and Claxton, 2022), so these aspects were assessed as part of the visual assessment. Each characteristic was assessed on a scale of 0–3, where 0 indicated no visual change, and 3 indicated a significant change to the washed garment compared to a reference sample. The sum of the visual assessment scores provided an overall measure, 0 indicating no change, and 9 indicating extreme pilling, fading, and felting after washing.

The visual assessment evaluated the degree of fabric pilling developed due to wet abrasion associated with garment washing. The pilling standard (British Standards Institution, 2020) assesses the propensity of fabrics to pill in dry abrasion conditions. Both pilling mechanisms were used to evaluate t-shirt durability.

Washed t-shirts were visually assessed at wash/dry cycles 5, 10, 15, 20, 30, 40, 50 and 56, and jeans were assessed up to interval 30. Two independent assessors completed visual assessment and dimensional measurements of garments to reduce subjective bias.

3.3. Garment samples

The study tested 50 garments across two garment types (17 jeans & 33 T-shirts) and a mix of menswear and womenswear styles sourced from UK high street and online brands during 2022. Colour can influence the visual assessment of pilling and felting (Badgett, 2019; Barakzehi et al., 2016; Wakes et al., 2020), so only dark coloured T-shirts were selected. The selection of garments represented a wide range of recommended retail prices.

4. Results

The durability assessment results for each product type and gender are presented in Tables 3–6. Each sample displayed in the table has been coded to protect the brand's identity, the first letter referring to gender, M for men and W for women. The following two letters refer to the garment category, DJ for denim jeans and TS for T-shirt.

Where appropriate, the mean average of each test is included, excluding spirality which uses a known industry standard of±5%. The mean average is used to define the test threshold. Results below the mean average or threshold are shaded on the following tables for ease of reading.

Due to the large number of measurements for the dimensional stability assessment, these have been summarised into a single-dimensional stability value, which is the total number of in-tolerance measurements. An in-tolerance measurement is a result that is no more than the 3% maximum acceptable change for jeans and 5/7% for T-shirts. As dimensional stability measurements for the two measurement points were taken at 8 different wash intervals for T-shirts a result of 16, indicates all measurements are in tolerance. For denim jeans, the two dimensional stability measurements were taken at 5 different wash intervals, therefore a result of 10 indicates all measurements are in tolerance. A result of 0 indicates all measurements were out of tolerance and the garment suffered from repeated shrinkage at each of the wash cycle intervals.

4.1. Jeans

Tables 3 and 4 show test results for Womenswear and Menswear jeans and are ordered by price from the lowest to highest price.

There is wide variation in the abrasion performance across both women's and men's jeans. MDJ6 had the poorest abrasion results at 15,000 rubs, while WDJ1 was best with 105,000 rubs. Seam strength also exhibited a high degree of variability across the samples, ranging from 73N (WDJ2) to 550N (MDJ7), as did weft tensile strength; 120N (WDJ2) up to 1300N (MDJ1). Low seam and weft strength results indicate a higher likelihood of seam or fabric ripping, which would result in a loss of function and directly impact the garment's durability. Several garments had excellent stability, with all measurements within tolerance, but there were two garments with half or more measurements outside the industry tolerance (WDJ4 & MDJ2).

Overall, many products performed very well for one or more tests, but poorly for other assessment points. For example, WDJ1 had the best abrasion results, but some of the worst seam and weft strength results. Conversely, MDJ1 had poor results for most of the tests but had the best weft tensile results.

4.2. T-shirts

Tables 5 and 6 show the durability results for women's and men's t-shirts. The visual assessment results are the final appearance score for each garment after the last wash cycle, with 0 indicating no change in visual appearance and 9 indicating the maximum degradation in appearance.

As with the denim garments, the t-shirts demonstrated a very wide range of test results. For visual appearance WTS15 and WTS9, two of the more expensive garments had poor appearance scores of 8, while WTS6 achieved a score of 5, despite being one of the cheaper garments.

The pilling is graded on a scale of 1–5 after 7000 rubs, which is the maximum extent of the employed test method. 5 indicates no pilling, and 1 is the worst score denoting very significant pilling. Most t-shirts demonstrated relatively good pilling, with all but four garments achieving a 3–4 grade.

T-shirts displayed widely variable stability results, ranging from 7 to 16 across the category. WTS5 and WTS2 achieved the worst results of 7 and 8 indicating that half of the measurements recorded were not in tolerance. This suggests these garments would no longer fit the consumer leading to disposal and therefore, are less durable. 8 garments, in total, achieved 16 in-tolerance measurements, suggesting these garments had a very good stability performance.

Spirality also varied widely, with WTS13 & MTS6 being very stable with 0% spirality, while WTS5 & MTS2 demonstrated significant twisting above 12% spirality. This level of twisting would badly affect the fit of the garment and would negatively affect the functionality of the garment.

Table 3
Womenswear denim test results in price order (low to high).

Women's Denim	Price	Abrasion (revs)	Seam Strength (N)	Tensile Weft (N)	Tensile Warp (N)	Dimensional Stability
WDJ1	£13.00	105,000	260	260	1600	10
WDJ2	£17.00	90,000	73	120	1100	8
WDJ3	£20.00	30,000	270	470	450	8
WDJ4	£22.50	70,000	320	340	1100	10
WDJ5	£39.50	45,000	370	450	1500	10
WDJ6	£45.99	80,000	260	530	1100	10
WDJ7	£75.00	45,000	300	800	1200	10
WDJ8	£110.00	25,000	410	470	1000	4
WDJ9	£140.00	65,000	310	470	1300	10
Threshold		**60,000**	**290**	**430**	**1200**	**8**

Table 4
Menswear denim test results in price order (low to high).

Men's Denim	Price	Abrasion (revs)	Seam Strength (N)	Tensile Weft (N)	Tensile Warp (N)	Dimensional Stability
MDJ1	£7.00	45,000	170	1300	590	8
MDJ2	£10.00	30,000	190	270	630	5
MDJ3	£19.00	40,000	340	260	1400	8
MDJ4	£20.00	90,000	250	230	1300	8
MDJ5	£24.99	60,000	260	270	890	9
MDJ6	£32.99	15,000	390	380	1000	7
MDJ7	£64.99	100,000	550	950	1500	7
MDJ8	£90.00	70,000	370	540	1400	10
Threshold		**55,000**	**320**	**530**	**1100**	**7**

Table 5
Womenswear t-shirt test results in price order (low to high).

Women's T-Shirts	Price	Visual assessment	Pilling	Dimensional Stability	Spirality (%)	Bursting Strength (N)
WTS1	£2.50	7	4	13	5.3	259
WTS2	£3.99	7	3–4	8	11.6	214
WTS3	£4.50	7	4	10	1.5	204
WTS4	£5.00	6	4	9	4.0	297
WTS5	£5.99	7	4	7	15.4	188
WTS6	£6.00	5	4	11	1.5	287
WTS7	£6.00	7	4	11	1.2	255
WTS8	£7.50	7	4	16	5.5	266
WTS9	£14.95	8	3	9	2.7	276
WTS10	£17.50	7	4	16	5.3	220
WTS11	£19.00	7	2	14	0.7	250
WTS12	£19.99	7	4	11	2.0	386
WTS13	£20.00	6	4–5	12	0.0	258
WTS14	£20.00	6	3–4	13	4.2	241
WTS15	£22.00	8	3	16	11.6	274
WTS16	£40.00	7	4	12	2.8	291
Threshold		**6**	**3–4**	**11**	**5**	**260**

Table 6
Menswear t-shirt test results in price order (low to high).

Men's T-Shirts	Price	Visual assessment	Pilling	Dimensional Stability	Spirality (%)	Bursting Strength (N)
MTS1	£2.00	7	3	10	6.4	284
MTS2	£3.99	7	4–5	10	12.9	241
MTS3	£4.00	5	3–4	14	0.8	336
MTS4	£5.00	7	4	11	9.6	207
MTS5	£6.00	7	3–4	10	5.2	317
MTS6	£6.50	6	4	15	0	295
MTS7	£8.00	7	4–5	16	8.7	265
MTS8	£12.99	7	3–4	10	6.4	240
MTS9	£14.95	8	4	16	11.1	348
MTS10	£14.99	6	4–5	9	3.5	187
MTS11	£16.00	7	4	15	2.5	303
MTS12	£18.00	9	3–4	16	4.4	437
MTS13	£20.00	6	4–5	9	6.1	217
MTS14	£21.00	7	4–5	11	0.4	246
MTS15	£25.00	7	4–5	16	2.3	331
MTS16	£25.00	7	4–5	16	2.1	245
MTS17	£39.00	6	4–5	10	0.7	193
Thresholds		**6**	**4**	**12**	**5**	**276**

Finally, bursting strength showed variability ranging from 187N (MTS10) to 437N (MTS12). Those garments with very low bursting strength results are more likely to suffer fabric rips during wear than others, with a rip critically impacting the functionality of the garment.

Similarly, to the jeans, a few T-shirts scored well on all the tests, such as WTS6, WTS13, WTS14, MTS6, MTS3 and MTS15. But again, garments tended to perform well for some tests but poorly for others. For example, MTS13 performed well for visual appearance and pilling but stability, spirality and bursting strength were below the threshold.

5. Durability assessment and ranking

Using multiple tests to assess the overall durability of a garment is the most comprehensive approach as this reflects the different functional modes of garment use. However, when some garments performed well across several tests, but not all, and others were best in class for one measure of durability but failed to reach the threshold for many others, to determine which products had the best overall durability ranking requires test scores to be combined.

Other studies have attempted to apply a ranking process to identify garments with the best and worst durability (Jin et al., 2018; Troynikov et al., 2018; Benkirane et al., 2019) however, there is limited information on how to do this and no agreed method for such ranking. Therefore, this study developed an iterative ranking process that assessed overall durability based on the combined test results.

As each test assesses a different aspect of durability and uses a different scale for quantifying the durability, results from different tests cannot simply be added together to create an overall durability ranking. Furthermore, some tests are more important than others when assessing the durability of different garment types. For example, abrasion is an important measure of denim durability but is not important for t-shirts. However, pilling is important for t-shirts, but not for denim. Therefore, test results must be weighted to reflect the relative importance of the most common causes of durability failure.

Based on the studies reviewed in Table 1, other literature, and industry feedback, the most important or higher weighted tests for denim are: abrasion, seam strength, weft tensile strength, warp tensile strength and stability. Similarly, for t-shirts, the test weighting is visual assessment, pilling, stability, spirality and bursting strength. Poor results for abrasion are a more important durability measure than poor stability results for denim, while poor bursting strength results are less important than visual assessment scores for determining t-shirt durability.

However, the application of these weightings is not linear, as the degree failure for lower weight tests can have a disproportionate impact on the overall durability of the garment. For example, a very poor weft tensile strength result for denim jeans, such as WDJ2 (120N), would suggest the garment is more likely to lose functional integrity due to a fabric tear, before it fails due to abrasion. Even though WDJ2 had an excellent abrasion performance (90,000 revs) the durability of the garment is compromised by the very poor result for a lower weighted aspect of durability. To determine whether results from less important tests override the more important tests the thresholds, or mean averages, are used. Test results that are below the threshold have increased importance and become more influential in determining the overall durability of the garment.

A process for ranking results using weighting and thresholds was developed to determine the overall durability and is explained using the Women's denim sample set as an example. Results are arranged based on the most important durability test, abrasion, with the best result in 1st position and the worst in last. Products below the abrasion threshold are highlighted.

The ranking is then adjusted based on the next most important factor, which is seam strength. Those garments with abrasion result above the threshold are ordered by the seam strength results. Garments with a seam strength below the seam strength threshold are moved down the ranking, as the poor seam strength results become more important than abrasion. Despite WDJ1 having the best abrasion results, it must move down the ranking due to its poor seam strength. Denim garments below the abrasion threshold, are then re-ordered based on the seam strength results, with strength results below the seam threshold moved down in the ranking.

The weft tensile strength results are then used to re-order the garments using the same application of thresholds. For WDJ9 & 4, abrasion and seam strength results are above the threshold, so they are ranked above all the other garments as the rest of the sample set have results below the threshold for abrasion and seam strength. As WDJ9 has the best abrasion performance, this is ranked higher than WDJ4, even though WDJ4 has a marginally higher strength result. However, the tensile strength of WDJ4 is below the threshold, so this becomes a more important result, and its ranking drops below WDJ9. Similarly, WDJ1 has a superior abrasion result to WDJ6, so would be ranked above WDJ6, but below WDJ4 & 9 due to a below threshold result for seam strength. However, although WDJ1 & 6 have the same below threshold result for seam strength, WDJ1 has a below threshold result for tensile strength, so it is ranked below WDJ 6.

This process of re-ordering the garment durability ranking continues across the remaining set of results. By using this iterative process, the overall garment durability ranking can be established. The ranking process was automated using the process explain above using the Excel 'Custom Sort' function by adding levels of rules. Fig. 1 provides the framework for the ranking process which can be used for all garment categories regardless of the durability factors that need to be considered in the ranking process.

5.1. Jeans durability ranking

Tables 7 and 8 show the durability results after the denim garments have been ranked, with the most durable products at the top, and the poorest at the bottom of the table.

The value of the iterative ranking process can be seen by considering the Women's denim results. WDJ2 has the second best performance for the most important test for denim, abrasion. However, its seam and weft tensile strength are well below the threshold, so these results have a greater influence on the ranking than the primary abrasion result. This reflects the likelihood of this product failing due to a rip or burst seam. Products with lower abrasion results are ranked above WDJ2 because these samples have results that meet the threshold for abrasion and seam and weft tensile strength. The abrasion results for WDJ8 & WDJ3 are below the threshold, so despite their superior tensile strength compared to WDJ2, they are ranked below and are considered less durable.

Similarly, WJD1 has the best abrasion results and would be ranked the most durable, however, poor seam and weft tensile strength results reduce its overall durability ranking, with WDJ9, WDJ4 and WDJ6

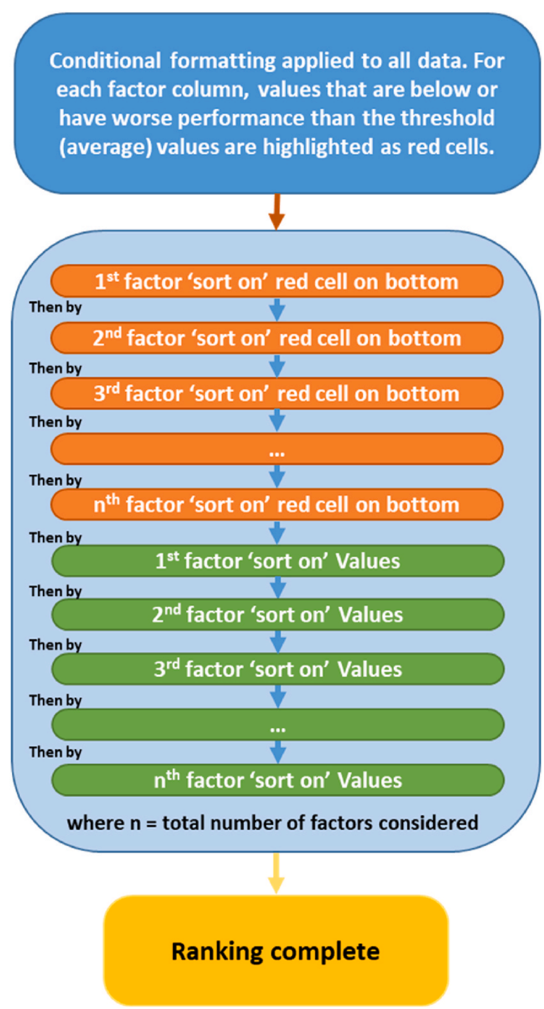

Fig. 1. Framework for the ranking process.

Table 7
Ranked womenswear denim test results (most durable to least durable).

Women's Denim	Price	Abrasion (revs)	Seam Strength (N)	Tensile Weft (N)	Tensile Warp (N)	Dimensional Stability
WDJ9	£140.00	65,000	310	470	1300	10
WDJ4	£22.50	70,000	320	340	1100	10
WDJ6	£45.99	80,000	260	530	1100	10
WDJ1	£13.00	105,000	260	260	1600	10
WDJ2	£17.00	90,000	73	120	1100	8
WDJ5	£39.50	45,000	370	450	1500	10
WDJ7	£75.00	45,000	300	800	1200	10
WDJ8	£110.00	25,000	410	470	1000	4
WDJ3	£20.00	30,000	270	470	450	8
Average		**60,000**	**290**	**430**	**1200**	**8**
Weighting		**1**	**2**	**3**	**4**	**5**

Table 8
Ranked menswear denim test results (most durable to least durable).

Men's Denim	Price	Abrasion (revs)	Seam Strength (N)	Tensile Weft (N)	Tensile Warp (N)	Dimensional Stability
MDJ7	£64.99	100,000	550	950	1500	7
MDJ8	£90.00	70,000	370	540	1400	10
MDJ4	£20.00	90,000	250	230	1300	8
MDJ5	£24.99	60,000	260	270	890	9
MDJ3	£19.00	40,000	340	260	1400	8
MDJ6	£32.99	15,000	390	380	1000	7
MDJ1	£7.00	45,000	170	1300	590	8
MDJ2	£10.00	30,000	190	270	630	5
Average		**55,000**	**320**	**530**	**1100**	**7**
Weighting		**1**	**2**	**3**	**4**	**5**

moving above despite their lower abrasion performance.

It is important to note the top two ranked products for Women's denim have very similar results despite a price difference of over £115. WDJ8 and WDJ3 also have similarly poor results but have a price difference of £90.

5.2. T-shirts durability ranking

Tables 9 and 10 show the t-shirt ranking based on the weighted iterative process, with the most durable products at the top, and the poorest at the bottom of the table.

For t-shirts, the most important durability factor, the final visual assessment grade, has determined the primary ranking. WTS6 has the best result of 5, followed closely by WST13 with a grade of 6. WTS6 achieved results above the threshold in all tests, making it the most durable garment overall.

For the Men's t-shirts, stability and bursting strength results have had more impact on the overall ranking. Several garments that have good visual appearance and/or pilling results (MTS7, MTS9, & MTS13) have been ranked lower than other products because their stability and bursting strength results are below the threshold, so these garments move down in the ranking.

5.3. Garment price and durability

For the denim garments, two of the most expensive products (WDJ9 & MDJ7) are ranked best, however, some of the other most expensive garments (WDJ8 & MDJ6) are ranked as one of the worst. Equally, some of the top performing garments are also some of the lowest priced garments (WDJ4 & WDJ4).

Detailed analysis of the results shows there are only marginal differences between the performance of the top two products for Women's jeans, despite a price difference of over £115. Furthermore, four garments (WDJ6, WDJ5, WDJ7 & WDJ8) are more expensive than the 2nd

Table 9
Ranked womenswear t-shirt test results (most durable to least durable).

Women's T-Shirts	Price	Visual assessment (Final Grade @ 56 washes)	Pilling (Final Grade @ 7000 revs)	Dimensional Stability	Spirality (%)	Bursting Strength (N)
WTS6	£6.00	5	4	11	1.5	287
WTS13	£20.00	6	4–5	12	0.0	258
WTS14	£20.00	6	3–4	13	4.2	241
WTS4	£5.00	6	4	9	4.0	297
WTS12	£19.99	7	4	11	2.0	386
WTS16	£40.00	7	4	12	2.8	291
WTS7	£6.00	7	4	11	1.2	255
WTS8	£7.50	7	4	16	5.5	266
WTS10	£17.50	7	4	16	5.3	220
WTS1	£2.50	7	4	13	5.3	259
WTS3	£4.50	7	4	10	1.5	204
WTS5	£5.99	7	4	7	15.4	188
WTS2	£3.99	7	3–4	8	11.6	214
WTS11	£19.00	7	2	14	0.7	250
WTS15	£22.00	8	3	16	11.6	274
WTS9	£14.95	8	3	9	2.7	276
Thresholds		**6**	**3–4**	**11**	**5**	**260**
Weighting		**1**	**2**	**3**	**4**	**5**

Table 10
Ranked menswear t-shirt test results (most durable to least durable).

Men's T-shirts	Price	Visual assessment	Pilling	Dimensional Stability	Spirality (%)	Bursting Strength (N)
MTS6	£6.50	6	4	15	0.0	295
MTS17	£39.00	6	4–5	10	0.7	193
MTS10	£14.99	6	4–5	9	3.5	187
MTS13	£20.00	6	4–5	9	6.1	217
MTS3	£4.00	5	3–4	14	0.8	336
MTS15	£25.00	7	4–5	16	2.3	331
MTS11	£16.00	7	4	15	2.5	303
MTS16	£25.00	7	4–5	16	2.1	245
MTS9	£14.95	8	4	16	11.1	348
MTS7	£8.00	7	4–5	16	8.7	265
MTS14	£21.00	7	4–5	11	0.4	246
MTS2	£3.99	7	4–5	10	12.9	241
MTS4	£5.00	7	4	11	9.6	207
MTS12	£18.00	9	3–4	16	4.4	437
MTS5	£6.00	7	3–4	10	5.2	317
MTS1	£2.00	7	3	10	6.4	284
MTS8	£12.99	7	3–4	10	6.4	240
Average		**6**	**4**	**12**	**5**	**276**
Weighting		**1**	**2**	**3**	**4**	**5**

and 3rd ranked garments but have worse durability results. For Men's jeans the 3rd most expensive product (MDJ6) ranked the 3rd worst, with three lower priced garments performing better.

Similarly, for women's t-shirts, WTS6 is ranked as the most durable. However, some of the most expensive women's garments received a poor durability ranking, such as WTS15 (£22) & WTS11 (£19), while WTS6 (£6) & WTS4 (£5) performed better than WTS16 (£40) which is more than 6 times more expensive. WTS1, the cheapest t-shirt (£2.50) is ranked better than six more expensive garments, one of which is almost 9 times more expensive (WTS15).

The most durable Men's t-shirts priced at £6.50 (MTS6), performed significantly better than garments priced at £25 (MTS15), £25 (MTS16), and even £39 (MTS17). At the bottom of the ranking, the three worst performing were priced at £6 (MTS5), £2 (MTS1), and £12.99 (MTS8).

6. Implications

6.1. Academic contributions

Assessing and ranking the durability of garments is a complex process. A multitude of tests are needed to measure the durability performance across a range of different physical parameters. The tests used must reflect the various modes of functional failure that a garment would suffer in typical wear and washing, and these functional failures are specific to the garment type. For example, jeans are expected to fade and abrade, whereas t-shirts would be disposed of if they faded and aged in the same way that denim does. Garment type also determines the relative importance, or weighting, of the different tests used, with some tests being more important than others. However, the weighting of a particular test is modulated by the extent of failure to that test, with thresholds playing an important role when determining the overall durability ranking.

The methodology was used to assess and rank the absolute durability of 50 garments, the largest study to date of this kind. For each garment type, the ranking evaluated the ability of garment characteristics to retain functionality while under the influence of the same use profile, to allow a direct comparison of durability performance between sample garments. This paper has outlined the process for testing and ranking demonstrating how the method can be replicated. Further work can be done to build on the test data provided for t-shirts and denim jeans as well as across more garment categories. Furthermore, there are limitations around real life wear versus laboratory testing only, further work needs to be completed to understand the extent of laboratory methods mimicking real life wear to make a comparison between product lifespans and durability.

6.2. Practical implications

The ranking process presented can be used to inform consumers and policymakers about the relative durability performance of different garments when worn and used in the same way.

Using this methodology, the relationship between garment durability and garment price was explored. There is a general assumption that garment price can provide a measure for relative garment durability, with the implication that higher price point garments would last longer than cheaper garments. Across the four categories, it was clear that the highest-priced garment does not guarantee the most durable product, with some higher-priced products performing badly in the overall ranking. The durability of high-priced and low-priced garments ranged from excellent to very poor. Therefore, price cannot be used as a reliable metric to predict the physical durability of garments, as corroborated by Ghaani Farashahi et al. (2018).

Furthermore, the retail price cannot be used to quantify the relative difference in durability performance between garments. We cannot assume a garment that is 5 or 10 times more expensive than another like for like garment will be 5 or 10 times more durable. Some low-priced garments demonstrated excellent value for money and outperformed expensive garments in terms of pound for pound durability performance. These findings indicate that some cheaper 'fast fashion' products have the potential for utilisation that exceeds much higher-priced garments.

With UK and EU legislation for circularity developing, there is a greater focus on how the physical durability of garments can be assessed and compared. The methodology presented in this paper provides policymakers with the tools needed to complete this assessment through an objective and robust process. Without this type of methodology, approaches to label garments with a durability ranking, or the implementation of the PEFCR regulations or the use of EPR policies that are based on durability cannot be delivered.

7. Conclusion

This study presents a method for testing and ranking the durability of 50 garments across two garment categories, t-shirts, and denim jeans. Multiple different physical factors have been evaluated to create a novel and reproducible method that considers various durability factors as opposed to single aspects only. Findings indicate that price cannot be used as an indicator of durability which corroborates the conclusions of other scholars (Ghaani Farashahi et al., 2018; Badgett, 2019) who explored the relationship between price and durability on a smaller scale.

The methodology and results presented in this paper have been validated through engagement with the Textiles 2030 initiative, the UK's government, and industry sustainability and circular fashion initiative, and with a wide range of industry experts. Based on the positive feedback from this engagement, the research has been extended to assess other garment types.

This second phase will use the same process of identifying functional modes of durability failure, to inform the testing required for each garment type. The process of weighting and thresholds will be applied to create the overall ranking of durability. This phase of research will involve testing over 200 garments across 10 different garment types.

Finally, it is hoped that the findings from this study can contribute to the wider policy discussion about durability, how it is assessed, and how durability can be used to support strategies for improving the sustainability of the clothing industry. However, it is recognised that assessing the physical durability of garments provides only one component of understanding garment utilisation and lifetimes. Psychological factors such as sentiment, individual expression, status, and vanity (Norman, 2004; Niinimäki and Koskinen, 2011; Niinimäki and Armstrong, 2013) play a powerful role in how consumers use clothes. These psychological factors influence the user's connection with the product, and its ability to remain relevant and desirable to the wearer (Ellen MacArthur Foundation, 2021); this is referred to as emotional durability (Chapman, 2005), and it is vital that the role of emotional durability is also considered as part of a wider and more in-depth analysis of clothing durability.

CRediT authorship contribution statement

Yue Guo: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Kate E. Morris:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Mark Sumner:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Mark Taylor:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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