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A material flow analysis of the UK clothing economy

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ABSTRACT

Historically, clothing accounted for a significant proportion of annual income for most UK citizens, so items were carefully preserved and often passed down through generations. In the 21st century, however, just 40 min of work at minimum wage is sufficient to purchase a dress, shirt, or pair of trousers that may be discarded after a handful of uses. UK per-capita clothing consumption is 2–3 times the global average, reliant on international supply chains associated with many environmental and social issues. Steering the clothing system towards ecological sustainability requires wide-ranging strategies, but the lack of data on flows of clothing makes it difficult to quantify the impacts of current production and consumption, let alone design and evaluate sustainability interventions. Here we use material flow analysis to track clothing flows through the UK economy as a prelude to considering embodied carbon and changes in economic value across the system. Our results show the system is characterised by relatively high rates of reuse but very low rates of recycling. More clothing is destroyed (via landfill and incineration) than is reused and recycled. Consequently, reducing consumption of new clothing by just ~4% would be as effective for reducing waste as doubling current recycling activity. The UK also imports eight times more clothing than it produces, but offshores over half of the associated textile waste. In our carbon analysis, uncertainty is the key theme – estimates put the cradle-to-consumer emissions associated with 2018 UK clothing consumption anywhere from 9 $Mt.CO_2e$ to over 30 $Mt.CO_2e$. Our economic analysis shows substantial, but unsurprising losses in economic value of clothing as it flows through the economy, with some unexpected nuances. Improving the accuracy of current flow and impact data is critical for understanding how the clothing system can be most effectively moved towards circularity.

1. Introduction

In the Middle Ages and early Renaissance, clothing was among the most significant of household expenditures and was passed down through generations (Lemire, 2012). A basic shirt could cost a labourer in Western Europe a full week of wages[1] and clothing was so expensive that executioners often claimed the clothes the convicted wore to their execution.[2] In the 21st century, however, just 40 min of work at the legal minimum wage is sufficient for a UK employee to purchase a £5 fast fashion shirt or dress; which may be discarded after a handful of uses (Niinimäki et al., 2020). And despite these low costs, an average UK household has accumulated in their wardrobes £4000 worth of clothes (WRAP, 2012).

The dramatic fall in the cost of clothing in affluent countries such as the UK is to some degree a story of global inequality (Mair et al., 2016). Low Global South labour costs are exploited to provide cheap imported consumer goods – an arrangement that fosters forced labour, child labour, and dangerous working conditions (Better Work, 2016). But it is also a story of industrialisation of enormous scale. Globally, the textile industry is now associated with nearly 100 Mt of fibre production per year, an equal amount of waste materials, 6% of global CO_2 emissions, and disproportionate amounts of micro-plastic and chemical pollution (Niinimäki et al., 2020; Shirvanimoghaddam et al., 2020).

In the UK and the EU, annual textiles consumption is over 25 kg per person – 2–3 times the global average (Niinimäki et al., 2020) – and over 60% of this is clothing (EEA, 2019; WRAP, 2019b). Further, ~90% of UK clothing is imported, meaning the supply chain emissions escape the UK government's progressive climate goals (DEFRA, 2020). Similarly, considerable water consumption, chemical pollution, and other impacts are largely borne by key suppliers like India, China and South Africa

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[1] Historians estimates vary; a week may be conservative (www.bookandsword.com/2017/12/09/how-much-did-a-shirt-really-cost-in-the-middle-ages/).

[2] For other anecdotes, see: www.bookandsword.com/2021/05/08/how-much-did-a-tunic-cost-in-the-roman-empire/.

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(Niinimäki et al., 2020). This is not to say the UK has offshored all the negative impacts of clothing production. Investigations into UK sweatshops, most famously in Leicester, show that exploitative labour conditions are common within the industry due to widespread weak enforcement of (and thus non-compliance with) minimum wages and worker safety regulations (EAC, 2019).

Moving the clothing economy towards ecological sustainability and away from these social injustices will involve a multiplicity of strategies and interventions. For sustainability, much of this sits within the concept of Circular Economy (Ellen MacArthur Foundation, 2017; EEA, 2019; Shirvanimoghaddam et al., 2020; Jia et al., 2020; Bartl and Ipsmiller, 2023). Propositions range from incremental changes to production (e.g. more use of renewable energy in production; reductions in cutting waste), through improved management and recovery of resources (e.g. increased reuse and recycling of used clothing), to the curtailing of the economic and cultural imperatives that underpin the fundamentally unsustainable phenomenon of fast fashion (e.g. clothing lifetime extension and new business models). In countries such as Sweden and The Netherlands, industry has made significant, albeit limited, progress towards circularity (Brydges, 2021; Reike et al., 2022).

However, despite the long lists of purportedly attractive solutions in the literature, action continues to be insufficient (Leal Filho et al., 2022). The carbon emissions of the global fashion industry increased 30% from 2000 to 2015 and fibre consumption doubled (Peters et al., 2021). Efficiency improvements thus remain a long way from offsetting consumption growth, and even an enormous scaling-up of recycling activity would be unlikely to change this (Bartl and Ipsmiller, 2023). Indeed, it has been argued that the fashion system is locked into an uncontrolled state of extraction and disposal (Buchel et al., 2022). In wealthier regions such as the EU (EEA, 2019) and UK (WRAP, 2019b), consumption has flattened out, but at a level above the global average (Niinimäki et al., 2020). Where progress towards circularity has been made, there remain serious issues with scaling up recycling capacity (Reike et al., 2022) and developing solutions that extend beyond waste to the full supply chain (Brydges, 2021).

One major barrier to improved sustainability is the low quality of available data. This makes it difficult to estimate the current impacts of textile and clothing supply chains, and even more difficult to quantify the benefits of sustainability interventions. The accuracy of available assessment data suffers from the messy and globalised structure of supply chains, which are formed by complex networks of industrial processes and dominated by small and medium enterprises (Luo et al., 2021). While various reviews of the ecological impacts of textile and clothing production exist (Munasinghe et al., 2021; Niinimäki et al., 2020; Sandin and Peters, 2018), the numbers reported for indicators such as carbon, energy or water footprints vary considerably even for the same key materials (e.g. CO_2/kg of cotton clothing). Researchers have thus questioned whether shifts to supposably lower-impact fibres do in fact deliver environmental benefits (Ivanović et al., 2021), especially when wider market changes are considered (Hurmekoski et al., 2022).

Moreover, in the UK, many of the basic details about how clothing flows through the economy remain unknown. There are substantial uncertainties regarding how much clothing is recycled or reused and via what channels, and how much is wasted or disposed and via what methods. Material flow analysis is key technique for such analysis. Recent work has considered material flows of clothing in Europe at an aggregate level, finding that only ~35% of disposed clothing is separately collected for reuse or recycling, with a similar amount being incinerated and slightly less landfilled (Amicarelli and Bux, 2022). More granular material flow analysis at the level of recycling plants suggested that nearly 80% of collected textiles in Europe are reusable, however, quality was found to have decreased over the past decade (Nørup et al., 2019). Other researchers have suggested that material flow analysis can be a useful corporate tool in the textiles sector (Silva et al., 2021).

Here we thus present a preliminary material flow analysis of clothing through the UK economy, from imports and UK production through consumption, reuse, downcycling,[3] disposal, exports and beyond. To our knowledge, such analysis does not currently exist for the UK textiles economy. However, it is highly valuable, as it can support broader, fully integrated sustainability analysis (Millward-Hopkins et al., 2018) of environmental, social, economic and technical values (Iacovidou et al., 2017; Iacovidou et al., 2017). We probe the beginnings of such wider analysis, by considering the embodied carbon emissions flowing through the UK clothing economy, and changes in the economic value of various flows. Understanding material flows of textiles through the economy is also invaluable for both highlighting the points in the system where interventions may be most effective, and understanding the implications of uncertainties in impact per-unit data (e.g. water use per kg of clothing) for whole-system analysis.

2. Background and methods

2.1. The clothing supply chain

Clothing supply chains are disperse and complex and include sectors from agriculture, forestry and petrochemicals; numerous manufacturing processes; retail, distribution and consumption; and, finally, various treatment, reuse and recovery pathways (Sandin and Peters, 2018; Niinimäki et al., 2020; Moazzem et al., 2022). Putting aside circular strategies, the starting point is the extraction and production of.

- natural fibres such as cotton or wool more-or-less directly from agricultural products;
- semi-synthetic cellulose fibres such as viscose and rayon by intensive chemical processing of woody pulp;
- man-made fibres such as polyester or nylon, produced from petroleum-derived chemicals.

Yarn is then produced from these fibres – typically via spinning – before being woven or knitted into fabrics, which are themselves used to manufacture items of clothing. These are then transported to retailers – often internationally, from countries with cheap labour to those with higher purchasing power – before being sold to consumers. Then, after what has been observed to be an increasingly short period of time (Ellen MacArthur Foundation, 2017), clothes are discarded by consumers, and may either be resold, recycled, downcycled, incinerated, or landfilled (Shirvanimoghaddam et al., 2020; Amicarelli et al., 2022).

Many strategies have been suggested to reduce the environmental impacts of clothing production. The simplest of these include shifting to cleaner production, for example, using more renewable energy, less and/or fewer chemicals in processes such as dying (Shirvanimoghaddam et al., 2020), and lower-impact fibres. Also on the production-side are design-related changes, such as improving communication between designers and manufacturers in order to reduce pre-consumer waste (Niinimäki et al., 2020), or moving to fabrics that do not release micro-plastics (Laitala and Henry, 2018). Downstream of the consumer are a multiplicity of proposed strategies to increase recycling of materials – targeting fabrics and fibres, or just monomers and polymers – or to downcycle clothing into rags, blankets or insulation (Sandin and Peters, 2018). To these ends, mechanical, chemical or bio-based methods can be used (Ribul et al., 2021), although (low) quality and mixed materials present challenges for any recycling approach (Amicarelli et al., 2022; Nørup et al., 2019). Finally, there are consumer-focused strategies, which include reducing clothing disposals by increasing items' lifespans, expanding rental-based business models, and growing clothing resale markets (WRAP, 2017). As described below, due to the predominately linear nature of the UK clothing economy, not

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[3] Downcycling refers to when clothing items are recycled into lower-value products such as industrial rags, blankets, mats, or insulation materials (Sandin and Peters, 2018).

all of these pathways are included in our material flow analysis.

2.2. Material flow analysis

The basic principle of material flow analysis (MFA) is conservation of mass (Cencic and Rechberger, 2008). MFA conceptualises systems as flows of materials between processes, which themselves may contain 'stocks' – material that accumulates within a process, rather than continuing on to another process. In the absence of a stock change, the inflows entering and outflows leaving each process should balance. The key equation underpinning MFA is thus:

$$\sum_{1}^{n} inflow_i - \sum_{1}^{m} outflow_j = stock\ change,$$

where, i indexes all n inflows into a given process, and j indexes all m outflows.

The boundary of the system being considered is defined by the modeller after considering the research question and available data. This system may be linear – where material enters the system boundary, passes through the various process, before exiting the boundary – or circular such that flows recirculate material between processes. The analysis may be either static, so only a single point in time is modelled (or the system is assumed to be stable through time), or dynamic, so the evolution of the system over time is modelled. Flows themselves may be specified as having a particular composition. For example, a flow of clothing could be specified as a composition of different fibres, which in turn may comprise flows of homogenous (e.g. cotton shirts) or mixed materials (polyester-cotton blends). A broader sustainability analysis may add layers of value to material flows, some of which may (like mass) be conserved, while others may be created or destroyed, or endogenously or exogenously determined (Millward-Hopkins et al., 2018).

The system we develop here is simple, being both linear and static. Consequently the calculations are implemented in a simple spreadsheet model. This linear assumption is appropriate as the UK clothing economy – and indeed the global clothing economy – remains predominantly linear, with closed-loop recycling at under 1% of the mass of total global production (Niinimäki et al., 2020). Our static approach is appropriate for our aim of offering the first MFA of the UK clothing economy and, moreover, there is evidence that key parts of the system – such as clothing consumption – have been relatively stable over the 2010–2018 period, with annual consumption hovering at 1.0–1.1 Mt (WRAP, 2019b). We provide analysis for 2018, prior to the COVID19 pandemic. This snapshot is a necessary first step towards a holistic, dynamic sustainability analysis, which considers multiple dimensions of value and alternative future pathways (Iacovidou et al., 2017; Iacovidou et al., 2017). The latter could include scenarios assuming different mixes of fibre that allows for higher material recycling; different treatment of the clothing arising in residual waste; and lower consumption of new clothing – either through conscious changes in consumer culture or unintentionally due to economic decline in the wake of Brexit and other factors.

Nonetheless, we must note the limitations of our approach. For example, while closed-loop recycling in the textiles sector is minimal, clothing reuse via second-hand markets is far more significant. We include reuse flows in our MFA, but the question of how much increasing this flow might reduce consumption of new clothing is not something we currently address (not least because it is poorly understood in a quantitative sense, and rebound effects are potentially present; Campos and Paola (2022)). Our static approach also ignores stocks, in the sense that releases from stocks to reuse or disposal and their relations to time lags between purchases and discards of new clothing are not directly considered, but the annual release rate is assumed to be static. However, we do calculate potential annual additions to the UK wardrobe. Finally, we consider material flows of clothing as a whole, but – due to a lack of data – not their composition in terms of fibre mixes (polyester-cotton blends) and clothing type (shirts, trousers, etc.). Analysis along these lines would allow detailed assessment of things like the recyclability of disposals and low-quality exports, and hence would be a valuable direction for future work.

The various data sources we use are described in the results section as we summarise the UK clothing MFA and included in Table 1. These vary from academic papers through government data sources to non-peer reviewed – and often opaque – grey literature. As a final point, we emphasise that we focus here only upon the total mass of clothing items (including associated pre-consumer textiles waste such as production material offcuts), and we do not consider other textiles such as shoes, bags, towels and bedding. Clothing accounts for ~60–65% of total textiles consumption in the UK (putting aside mattresses and carpets), but only 35% of textiles waste (WRAP, 2019b). Had we focused upon all textiles, therefore, the scale of our MFA would be on average ~60–65% larger, but with substantially more material being disposed than reused.

2.3. Carbon and cost analysis

For our carbon analysis we take a review-based approach, rather than undertaking a detailed life-cycle analysis (LCA) or similar ourselves. Primarily, we use embodied emissions data from the recent review of the environmental impact of clothing production by Munasinghe et al. (2021). They summarise recently published LCA data for a range of materials, and for different stages of the clothing supply chain including

Table 1
Data underpinning Fig. 1, with main data sources indicated. Where data has been calculated entirely by balancing other mass flows, the source is simply recorded as *[calculated]*.

Flow source	Flow destination	Mass (kt)	Data sources
Imports	Arisings	1169	UK trade data (www.uktradeinfo.com/trade-data/)
UK Production	Arisings	142	UK Fashion and Textile Association (www.ukft.org)
Arisings	Consumption	1063	*[calculated]*
Arisings	New exports	249	UK trade data (www.uktradeinfo.com/trade-data/)
Consumption	Charity shops	285	WRAP (2019a) & WRAP (2019b)
Consumption	Textile banks	220	
Consumption	Other collection	89	
Charity shops	Collected	285	*[calculated]*
Textile banks	Collected	220	*[calculated]*
Other collection	Collected	89	*[calculated]*
Consumption	Reused UK	72	eBay (2021)
Consumption	Kerbside waste	245	WRAP (2019b)
Consumption	HWRC	91	
Consumption	Unaccounted	61	*[calculated]*
Kerbside waste	Residual waste	245	*[calculated]*
HWRC	Residual waste	91	*[calculated]*
UK Production	Residual waste	35	Reverse Resources, 2017, EAC (2019) & Niinimäki et al. (2020)
Collected	Reused UK	190	WRAP (2019b)
Collected	Used exports	356	UK trade data & WRAP (2019b)
Collected	Downcycled	18	WRAP (2019b)
Collected	Residual waste	30	
Residual waste	Incineration	307	DEFRA (2021)
Residual waste	Landfill	75	
Residual waste	Other treatment	19	
Used exports	Reused non-UK	214	Manieson and Ferrero-Regis (2022) & Greenpeace (2022)
Used exports	Disposed non-UK	143	
Imports	Disposed non-UK	292	Reverse Resources, 2017, EAC (2019) & Niinimäki et al. (2020)

fibre production, yarn spinning and dying, fabric knitting/weaving and dying, and garment manufacture & retailing. We extract average, minimum and maximum embodied carbon values from the data for cotton, polyester, viscose and polyamide; the former three materials dominate UK clothing at 48%, 26% and 10% of consumption, and polyamides (of which nylon is the best-known) are the largest contributor to the remaining 16% (WRAP, 2020). We sum the carbon values from fibre production to retail, thus ignoring emissions related to use and end-of-life. This gives what we refer to as 'cradle-to-consumer' emissions. Beyond fibre production, however – for yarn spinning & dying, fabric knitting/weaving & dying, and garment manufacture & retailing – Munasinghe et al. only report data for cotton and polyester. We thus use the average of these to estimate post-fibre production emissions for viscose and polyamide.

Finally, we cross-check these data with values from the widely cited review of Niinimäki et al. (2020), before making a broader comparison with LCA data from the Waste and Resources Action Programme (WRAP) and the UK carbon footprint accounts of DEFRA (2020). WRAP is an independent charity, partly funded by the UK Government, whose research is central in informing government strategies addressing the impacts of the UK clothing economy. In contrast, the UK carbon footprint accounts are official national statistics (and no longer considered *experimental statistics*).

Underpinning the UK carbon footprint is an Environmentally Extended Input-Output (IO) model. This estimates embodied carbon emissions associated with UK consumption of goods and services for various household (and non-household) final demand sectors, including *clothing* (note, *footwear* and *household textiles* are recorded separately). IO analysis is the principal methodology used for producing carbon footprints at national and regional levels. While the categories IO models consider are relatively aggregated – they struggle to estimate the carbon impacts of, say, shifting between different fibre types – generally they outperform LCA for more aggregate footprint assessments, such as for cities (Fry et al., 2018), or, of more relevance to the current work, whole industrial sectors such as textiles. IO models are fundamentally based upon information describing financial transactions and emissions *only*, so they are not linked in any way to mass flows. But total clothing emissions can be divided by the mass of clothing consumed by UK households, for any given year, to obtain kg of CO_2e per kg of clothing. We use these data in our later discussion (see section 3.2).

Finally, we undertake a basic cost analysis to build a picture of where economic value is being created and lost across the system. For this we use a range of sources, which we summarise in the results. Some of these sources are the same as that used for the mass flow data and are likely to be quite robust; others are more speculative and variable. As such, our carbon and cost analyses alike are intended to demonstrate the large uncertainties, and lack of consensus, in the existing literature.

3. Results

3.1. Material flows through the UK

Our estimate of the material flows of clothing through the UK economy are presented in Fig. 1 and Table 1 in kilotonnes of clothing. Herein we describe the system from left-to-right, considering three groups of flows. We summarise calculations, data sources, uncertainties, and open questions as these issues arise.

3.1.1. New clothing arising in the UK economy

The first group of flows includes all new clothing arising within the UK, which in turn includes that purchased by UK consumers and exported for sale elsewhere (dark blue and purple on the MFA). The mass of clothing **imports** is available from UK trade data (www.uktradeinfo.com/trade-data/), described precisely in mass terms as **1169 kt** in 2018, one quarter of which are from the EU. **Exports** are available from the same source and are given as **249 kt** in 2018, 86% of which are destined for the EU. Uncertainties in these data are likely to be relatively small. Note that the imports figure on the MFA of 1461 kt includes pre-consumer waste; we describe this estimation later in this section.

Data on the mass of clothing produced by UK manufactures couldn't be found. Eurostat offer detailed production data for highly disaggregate industrial sectors, but for clothing sectors much of the data is in 'number

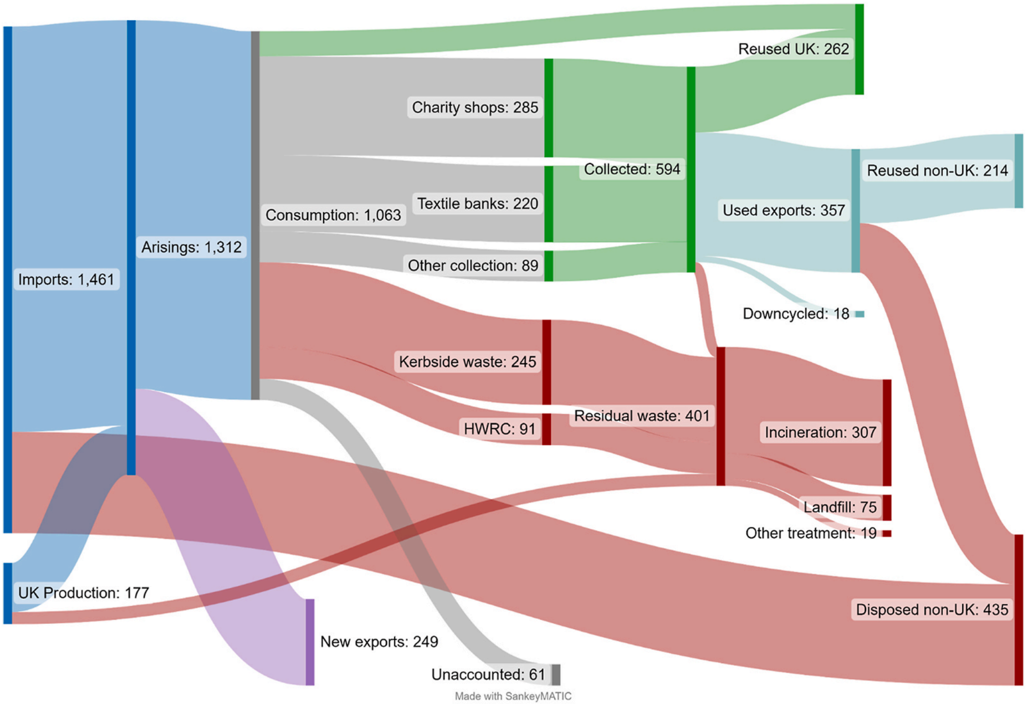

Fig. 1. Mass flow analysis of the UK clothing economy in 2018 (with flows originating on the left), from imports and UK production (dark blue) through to UK reuse (green), non-UK reuse (light blue) and disposals (red). Numbers indicate the size of the mass flows, in kilotonnes, at each point of the system. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of items' rather than production mass. We thus use the economic value of **UK production** as a basis for estimation. Industry statistics from the *UK Fashion and Textile Association* (www.ukft.org) provide 2017 data for the cash-value of UK clothing imports (£19 billion), exports (£7 billion), and production (£2.9 billion) – the final thus value fills the gap left by the UK Trade data. Assuming the value per tonne of clothing produced in the UK is the same as that of imports leads to UK production being estimated at 180 kt (1169 × 2.9/19). Assuming, perhaps more reasonably, that the value per tonne of UK production is the same as the (higher) value of exports leads to an estimate of 103 kt (249 × 2.9/7). Nonetheless, we take UK production to be the average of these at **142 kt**. UK **consumption** is now easily calculated as:

$$\text{Consumption} = \text{UK production} + \text{Imports} - \text{Exports},$$

which gives **1063 kt**, closely matching the 1070 kt reported by WRAP for 2018 (WRAP, 2019b).

An interesting observation here is that exports of clothing exceed UK production. This implies a substantial amount of clothing is imported and then re-exported. Even taking the higher, and less-likely, import-based estimate for UK production from above (180 kt), there remains 69 kt (249–180) of clothing that appears to be re-exported, even under the unreasonable assumption that all UK production were exported. We could not, however, find data to estimate the share of UK production purchased by UK consumers.

3.1.2. Post-consumer collections, reuse, and recycling

The second group of flows includes clothing collected for reuse and recycling and its destinations (grey, green and light blue on the MFA). WRAP (2019b) report the total amount of textiles collected in 2017 and 2018 at 600 and 620 kt, respectively, but they do not report how much of this is clothing. Other sources suggest 650 kt of clothing is collected annually (EAC, 2019), but inconsistent wording suggests this may refer to all textiles. We thus move forward with the WRAP estimate.

We use two calculations to estimate how much of these collected textiles are clothing. The first uses data from the same WRAP (2019b) report. Specifically, in 2017, consumption of textiles and clothing were 1665 kt and 1040 kt, respectively, while waste disposals were 920 kt and 336 kt (clothing dominates consumption; non-clothing textiles dominate waste). Non-clothing textile consumption and waste were thus 625 kt and 584 kt, respectively. Within any given year, it is reasonable to assume that:

$$\text{Consumption} - \text{Collections} = \text{Waste},$$

which implies non-textile collections are small at 41 kt (625–584). This, in turn, implies that at least 93% of collected textiles are clothing ((600-41)/600 = 93%). Our second estimate uses UK household waste compositional data from WRAP (2019a). This reports the amount of household textiles in local authority recycling streams in 2017, and provides disaggregate estimates for clothing, shoes, bags & belts, carpets & underlay, and other non-clothing textiles. It shows that 98% of the household textiles collected for recycling are clothing – putting aside carpets & underlay, which is outside the scope of textiles as defined by (WRAP, 2019b). Together, then, these two estimates suggest that 93–98% of the 620 kt of textiles collected for recycling in 2018 is clothing. We take the middle of this range for our MFA, thus estimating total clothing **collections** to be **594 kt**, so 56% of clothing consumption. This collection rate compares to the European average of 15–20% (Sandin and Peters, 2018) and best-practice rate of 75% found in Germany (Watson et al., 2018).

WRAP (2019b) also report the split of clothing collections via different routes – charity shops (48%), textiles banks (37%), and various more minor routes (15%). We use these shares directly in our MFA, making the associated values **285 kt**, **220 kt**, and **89 kt**, respectively. WRAP (2019b) then report the destination of these collections – used exports (60%), UK reuse (32%), downcycling (5%) and waste (3%) – and we also use these shares directly. In addition, we consider the destination of exported clothing. Research suggests that only 60% of the used clothing exported to East Africa is reused, with the remainder disposed (Manieson and Ferrero-Regis, 2022; Greenpeace, 2022). We thus estimate **used exports** of clothing at **357 kt** (594 × 60%) and **non-UK reuse** at **214 kt** (357 × 60%).

Cross-checking of data here unearths some discrepancies, however, as the clothing collected for via minor collection routes appears too small compared to data in WRAP (2019a). Specifically, among the minor textile collection routes reported by WRAP (2019b), local authority kerbside and in-store bring-backs are each reported as accounting for 1% of the 600 kt total. This implies around 6 kt each, but WRAP (2019a) report 15 kt and 47 kt for the same collection routes, and an additional 53 kt of clothing collections at household waste recycling centres. Indeed these three routes alone (115 kt) are larger than our estimate for all minor collection routes (89 kt). We do not resolve this issue here, but simply highlight it as a point of uncertainty.

Our total used export flow can be sense-checked with more success. UK trade data reports the mass of exported used textiles as 373 kt – a value that comes from drilling down into HS Commodity Code sector 63 to extract used textiles, which come under category 6309. Scaling down to estimate just used clothing can be done via the fractions above (i.e. 93-98%). This suggests 347–366 kt of used clothing exports – our value falls in the middle of this range. Note also that the same UK trade data shows 14 kt of used textiles imported into the UK economy – we consider this small enough to omit from the MFA.

Finally, we estimate how much used clothing is reused in the UK due to direct resale by consumers – in other words, what flows directly from consumption to UK reuse on the MFA. Our estimate for this flow is particularly uncertain: the most appropriate data we found comes from an in-house *eBay* study of used clothing sold on the website in the UK in 2021, reported in a blog post (eBay, 2021). They suggested that 17.8 kt of used clothing were diverted from landfill through the auction site between January and August 2021, and that this was a 12% increase on the sales volume of 2018. Scaling this up to an annual value and back-casting to 2018 (17.8/112% × 12/8) gives an estimate of 23.8 kt of used clothing resale through eBay alone. We multiply this by a factor of three, to account for the key platform of Facebook Marketplace as well as smaller platforms, thus estimating direct clothing resale in the UK at **72 kt**. This is a crude estimate that should be refined in future work.

We then carry out a final sense check. Subtracting direct resale, all collections, and household waste from total clothing consumption leaves **61 kt** of clothing – recorded as **unaccounted** on the MFA. One explanation for this is it represents an annual stock increase of clothing in UK wardrobes. And this can be checked. WRAP (2017) estimated clothing in UK wardrobes at 3.1 Mt in 2012 and 3.6 Mt in 2016. The stock increase can thus be estimated as:

$$\text{Stock change} = \left(\text{Stock}_{t\text{end}} - \text{Stock}_{t\text{start}}\right) \ / \ \left(t_{\text{end}} - t_{\text{start}}\right),$$

where, t_{end} and t_{start} are the final and initial years over which the change in stock occurs. This gives 125 kt per year, i.e. (3.6-3.1)/(2016-2012). This is double our 61 kt unaccounted flow, which could be explained in various ways. For example, the stock increase may be smaller than the rough above calculation suggests; purchases of used clothing (not just new clothing) may be adding to the UK's wardrobe; and/or direct resale may be lower than our crude estimate suggests. Again, this serves to highlight the uncertainties in current data.

3.1.3. Waste disposals, in the UK and beyond

The third group of flows includes all post-consumer clothing that is disposed of by households, and the pre-consumer waste associated with production (red flows on the MFA). We consider waste occurring within the UK, and that outside the UK that's associated with the UK clothing economy.

UK waste (**residual waste** on the MFA), has four inflows. Two are directly from households, and include disposals into black bins that are collected at the kerbside, and household waste recycling centres (HWRC) where people typically dispose of larger amounts of waste. WRAP (2019b) report the amount of clothing disposed to kerbside collection and HWRC as **245 kt** and **91 kt**, respectively. Clothing waste generation has been relatively stable over the 2010s (WRAP, 2012, 2017, 2019b, so we assume 2017 values are a reasonable estimate for 2018. The third is another flow of household clothing waste that has already been mentioned, namely, the small share (5%) of clothing collected for reuse and recycling that is instead diverted into the waste stream – this adds another **30 kt**. The fourth is pre-consumer waste from UK production. Studies estimate that 10–30% of fabric used in clothes manufacturing is wasted as offcuts, or due to production errors (Reverse Resources, 2017; EAC, 2019; Niinimäki et al., 2020). We take the middle of this range for our calculations, thus assuming pre-consumer waste is 20% of production. This adds **35 kt** to UK residual waste, making the total **401 kt**. However, regarding pre-consumer waste, two things should be borne in mind. On the one hand, while much pre-consumer waste is currently disposed, much is also utilised in reuse or down-cycling markets (Reverse Resources, 2017). On the other, pre-consumer manufacturing waste is compounded by the issue of unsold clothing, or 'deadstock', which may contribute an equal volume of waste and is often incinerated (Niinimäki et al., 2020). These issues pull in both directions, so our central pre-consumer waste estimate of 20% may be reasonable. But these complicating factors must be noted.

We assume the destination of clothing arising in the UK residual waste stream is the same treatment methods as residual waste more broadly. Incineration and landfill dominate, at 76% and 19% of the residual, and energy recovery is used for 98% of the former (DEFRA, 2021). This means **307 t** and **75 kt** of clothing are treated by incineration and landfill, and **19 kt** via other treatment methods.

Finally there is non-UK waste, which has two inflows. The first is the clothing that has been collected for reuse and recycling, leaves the UK on the exports market, but then, for quality-related reasons or otherwise, is disposed once abroad. Using the 60% reuse fraction from Greenpeace (2022) as reported above, non-UK disposals of exported clothing thus total **143 kt** (357 × 40%). The second includes the pre-consumer waste associated with UK clothing imports. Using the same 20% pre-consumer waste fraction from above leads to non-UK pre-consumer waste being estimated at **292 kt**. Summing these leads to an estimate that **435 kt** of non-UK clothing waste is associated with the UK clothing economy. It is important to note, however, that this non-UK pre-consumer waste is the only flow on our MFA that does not enter the UK economy. It is included for consistency nonetheless, as it is directly related to UK imports, and thus as closely related to the UK clothes economy as the clothing that leaves our borders after consumption.

3.2. *Imports and exports of embodied carbon*

Before discussing total carbon emissions related to the UK clothing economy, we consider the carbon intensities of producing clothing of different fibres – i.e. the embodied emissions per unit weight (kg.CO_2e/kg). Our summary of the data of Munasinghe et al. (2021) indicates how widely these intensities vary even for the same materials (Fig. 2). The intensities reported for fibre production vary an order of magnitude for cotton (0.6–9.5 kg.CO_2e/kg) and even more so for viscose fibre (0.3–9 kg.CO_2e/kg). In relative terms, these ranges are much smaller when total cradle-to-consumer embodied carbon is considered, but estimates for cotton still vary by more than a factor of three (12–42 kg.CO_2e/kg) and polyester by a factor of two (15–30 kg.CO_2e/kg). Fibre production is 12% of total cradle-consumer embodied carbon for cotton and 16% for polyester.

Niinimäki et al. (2020) also summarise embodied impacts of clothing production. Their review is less detailed than Munasinghe et al. in terms of specific numbers: they report only single values, which are limited to fibre production. These are, however, reasonably close to the averages we calculate from Munasinghe et al., considering the ranges of the latter. Niinimäki et al. report intensities of fibre production 13–30% lower, except for polyamide (nylon) for which it is 25% higher.

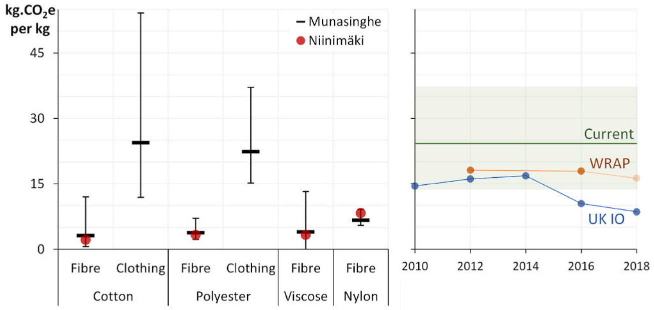

Fig. 2. The carbon intensity of producing cotton, polyester, viscose and polyamide (nylon) fibres and clothing derived from the former two (*left*), and the aggregate cradle-to-consumer intensity of producing UK clothing (*right*). On the left, the error bars indicate ranges obtained from the review of Munasinghe et al. (2021). On the right, data from *WRAP* (2017) is shown for 2012 and 2016. The estimated reduction between 2016 and 2018 from WRAP (2020) is used to approximate the 2018 data point (displayed as transparent to reflect its approximate nature). The *UK IO (input-output)* data is from DEFRA (2020), and is divided by annual consumption in mass to obtain these intensities. The *current* data is an average of the Munasinghe et al. ranges shown on the left, weighted by the fibre mix in UK consumption.

Taking a weighted average of the Munasinghe et al. intensities – with the weighting based upon the mix of materials in 2018 UK clothing consumption – we estimate a cradle-consumer carbon intensity of UK clothing of 24.2 kg.CO_2e/kg, with a min-max range of 14–37 kg.CO_2e/kg (Fig. 2, right). WRAP data for 2012 to 2018 comes in at the lower-middle end of this range – it starts at ~18 kg.CO_2e/kg in 2012 (WRAP, 2017) and falls ~10% by 2018 (WRAP, 2020). However, the IO-based data from DEFRA (2020) shows substantial discrepancies. Specifically, while DEFRA (2020) and WRAP (2017) data are reasonably consistent up to 2014, the former shows a 38% reduction from 2014 to 2016, increasing to a 50% reduction by 2018. These reductions far outpace those reported by WRAP (2020) over the 2012–2020 period for UK retailers covering nearly half of the UK market. Further, the IO data in 2016 and 2018 falls below even our lowest estimated carbon intensity from the Munasinghe et al. data.

What can explain these considerable differences? The reason our own range of estimates are mostly higher than WRAP and DEFRA may be due to the simple fact that, despite the review of Munasinghe et al. being very recent, some of the data they report dates back to circa 2010, when supply chains may have been more carbon intensive. On the other hand, the UK IO data in 2010 suggests the carbon intensity per kg of clothing purchased was *increasing* – and even this 2010 data is at the low end of our estimate. One may then look to changes in the mix of fibres in UK consumption for explanation (our estimate uses the mix in 2018). However, the UK fibre mix did not change significantly over the 2012–2020 period (WRAP, 2020), so this is unlikely to be playing a role. Finally, then, one may look to the source regions underpinning the UK's clothing consumption. The UK IO data shows these in detail (Fig. 3, left): The proportion of the carbon footprint of UK clothing originating in China has decreased considerably, from ~45% in 2009/10 down to 30% in 2019; a decrease that has been countered mostly by increases in Africa and mainland Europe, alongside minor increases in the America's and Australia (i.e. the *rest of OECD*). In absolute terms, the contribution of emissions located in China to the UK clothing footprint decreased by a factor of three during the 2010s; those from the Middle East have been volatile, but decreasing overall; those from India have halved; and those from mainland Europe and Africa have increased ~20% (Fig. 3, right). To reiterate, all this has occurred while UK clothing consumption has remained close to 1 Mt/year.

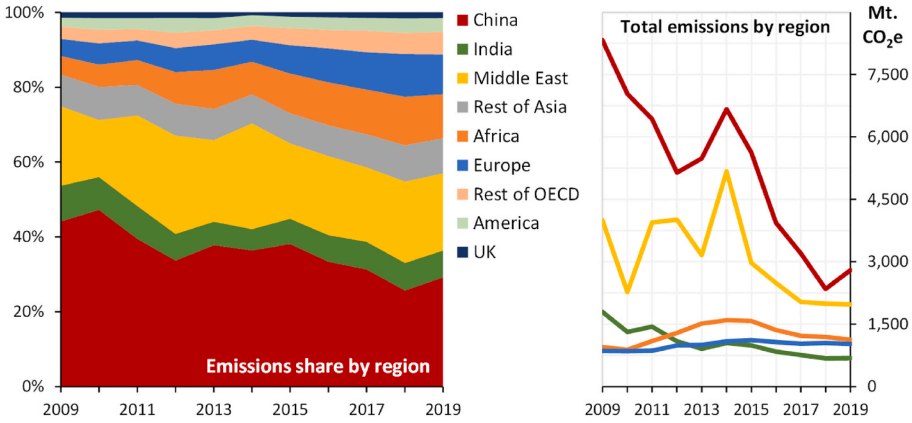

Fig. 3. A regional breakdown of the carbon emissions embodied in UK clothing consumption (left), and the corresponding emissions in absolute terms for key regions (right). All data is straight from DEFRA (2020).

These regional changes may partially explain why our central estimate is much higher than WRAP and DEFRA. The Munasinghe et al. data shows differences between regions that we did not consider. For example, for cotton, the intensity of African production (0.9 kg.CO_2e/kg) is at the lower end of the range (0.6–9.5 kg.CO_2e/kg). So if the countries supplying UK clothing have moved towards those associated with generally lower emissions intensities, then our high values are incorrect and an estimate towards the lower end of our range is more appropriate, which would be more consistent with WRAP and DEFRA. However, the wide range of our estimates must still be borne in mind, as it indicates that the uncertainties in the WRAP and DEFRA data may also be large. Furthermore, the discrepancy between WRAP and IO data beyond 2016 – i.e. the sharp reduction found only in the latter – remains a mystery worthy of further investigation.

Finally, we highlight the considerable implications of these uncertainties for absolute carbon emissions. Scaled up to 2018 UK clothing consumption (1063 kt), our carbon intensities from Fig. 2 (right) imply the emissions embodied in UK clothing in 2018 are 26 Mt.CO_2e, with a range from 15 to 40 Mt.CO_2e (Fig. 4). In comparison, WRAP data suggests 17 Mt.CO_2e, while DEFRA suggests only 9 Mt.CO_2e. Ignoring the upper half of our range – in case it tends towards overestimation – this implies that, in 2018, cradle-to-consumer emissions of UK clothing consumption were between 1.5% and 4.2% of the UK's total carbon footprint. Given these already considerable uncertainties, for the present work we leave emissions related to use and end-of-life out of scope. As a first estimate, though, 2016 data from WRAP (2017) suggests these would together add a further 6 Mt, making UK clothing consumption, use, and disposal total 2.5%–5.2% of the UK's total carbon footprint.

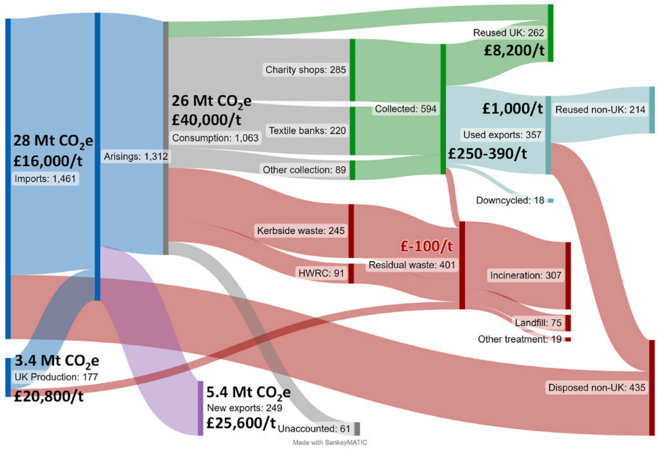

Fig. 4. Mass flow analysis of the UK clothing economy in 2018 from Fig. 1 (with the same colour scheme), where numbers refer to the size of the mass flows in kilotonnes. Here, key values of embodied carbon and economic value are overlaid. The former are total emissions associated with the material flows; the latter are normalised by the size of the flows to give a value (£) per tonne. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3. Changes in economic value across the system

Our high-level analysis of the value of clothing as it flows through the UK system shows some surprising changes, and that most of its economic value is lost even in those cases where much of its functional value remains.

UK trade data reports the economic value of clothing imported into the UK to be £18.8 billion, which converts to **£16,000/t** after considering the mass of imports. Per tonne, EU imports (£21,300/t) are of significantly higher value than non-EU imports (£14,300/t), but the much larger mass of the latter means they dominate the total import value (at £12.6 billion). UK trade data also reports the economic value of UK clothing exports to be £6.4 billion, which converts to **£25,600/t**. In contrast to imports, exports to the EU (£23,700/t) are of significantly lower value per tonne than non-EU exports (£37,600/t), and the far greater mass of the former means they dominate the total export value (at £5.1 billion). By definition, we estimate the value of UK clothing production to be halfway between the import and export values at **£20,800/t**.

The above data are likely to be robust, given the detailed accounting underpinning the UK trade data. However, some discrepancies are found when looking to UK consumption. WRAP (2019b) report UK household spending on clothing at £60.5 billion in 2018 (up 2% on 2017 spending), based upon the *Consumer Trends* data of the ONS (2022). The latest data from the same source revises down this estimate to £56.5 billion. But this remains extremely high given that, when divided by the associated mass flow, it implies a value of £53,200/t – double that of UK exports. Moreover, ONS data on UK clothing retailers reports their total sales were £43.5 billion in 2018, implying that at least 25% of the £56.5 billion spent on clothing by UK households must have occurred through non-UK retailers. However, other ONS data on clothing expenditure exists. ONS (2020) *Household Expenditure* data suggests total UK household spending on clothing was much lower, at £28.5 billion in 2018. This implies a value of £26,900/t, which is very close to the value of UK exports. We thus take a value halfway between these two as our central estimate for the economic value of new clothing purchased by UK consumers (**£40,000/t**).

The value of used clothing varies considerably depending upon the pathway it takes. For reuse and recycling, four pathways are most common. First, there is the clothing collected and sold by charity shops –

we estimate the 2018 value of this to be **£8200/t** (with a range of £4000/t to £16,600/t), based upon data from the *Charity Retail Association*'s *Average Selling Prices report* (CRA, 2019) – see the Supplementary Information for details on our calculations. Second, there is the material rejected by charity shops that is purchased by clothing exporters – data from letsrecycle (2018b) indicates the 2018 prices of these rejects was low at **£393/t** .[4] Similarly, there is the clothing collected in textiles banks, also largely sold to exporters, but at an even lower price of **£250/t** (according to the same *letsrecycle* data). Finally, there is the clothing sold directly by consumers via markets such as *eBay* – we are not able to estimate an average value per-tonne for clothing reused through this pathway, but *eBay* data suggests that typical items of clothing may sell for prices at least two or three times higher than in charity shops (again, see the Supplementary Information for details).

The remaining two economic values we estimate are that for exports of used clothing, and for clothing disposed to the residual waste stream. The former can – as for imports and exports of new clothing – be estimated directly from the UK trade data, which gives a value of **£1000/t** (and doesn't vary significantly for EU and non-EU exports). The latter can be estimated as **−£100/t**, which is a weighted average of the energy-from-waste and landfill gate fees in the UK in 2018 (*letsrecycle, 2018a*).

4. Discussion and conclusions

Stepping back to look at the MFA as a whole, we can make a number of interesting observations. First, in contrast to the case of something like plastic packaging, the clothing system is characterised by a very low amount of material recycling (and downcycling), but a high degree of reuse. By mass, consumption of used clothing in the UK is 25% of the total consumption of new clothing, and if reuse outside of the UK is also considered then this rises to 45%. This is much higher than in, for example, the USA, where only 15% of textile waste is collected for reuse and recycling combined (Shirvanimoghaddam et al., 2020). While this trend is positive, the minimal amount of recycling ensures that more clothing is landfilled, incinerated, and otherwise wasted than is reused. This is true when considering clothing within the UK only, and also when considering all clothing related to UK new clothing consumption, irrespective of whether reuse and disposal occurs within the UK or abroad. This also means that, for reducing the amount of clothing currently wasted, reducing UK consumption of new clothing by just 4% would be as effective as a doubling of the current recycling rate. Exploring how much reuse and recycling could be scaled-up would require analysis of the composition of material flows in terms of clothing type, fibre blends, and remaining lifetimes – this goes beyond what we offered here and would be a valuable direction for future research. Finally, when we aggregate (i) the pre-consumer clothing & textile waste associated with clothing imported into the UK and (ii) the post-consumer waste associated with UK exports of low-quality clothing, we find that UK clothing consumption generates slightly more waste outside of the UK than within it. So while the UK imports eight times more clothing, in mass, than it produces – making it a significant net importer of both economic and technical value – it still manages to offshore over half of the associated waste.

There are, of course, uncertainties in our MFA data, which occur throughout the system. But moving on to our carbon analysis, uncertainties and disparities in existing data is perhaps the key theme. LCA estimates of the embodied carbon of fibre production vary an order of magnitude or more for the same material, and a factor of 2–3 for cradle-to-consumer clothing production. This implies there is considerable overlap between the embodied carbon of different materials, suggesting that mitigation strategies based upon substitution of higher-impact materials with lower-impact ones may not always have the desired effect. Given that much of the industry relies on volume sales, and the uncertainty in embodied emissions are hardly a secret, these strategies are as likely to be driven by commercial desires to increase market share of purportedly low-carbon fibres as they are driven by any meaningful commitment to reduce carbon emissions.

Further, estimates of the total embodied carbon associated with UK clothing consumption from key UK institutions and our own estimate vary considerably, perhaps due to different methodologies (LCA vs. IO analysis). The cradle-to-consumer emissions associated with UK clothing consumption in 2018 may thus be anything from 9 $Mt.CO_2e$ to over 30 $Mt.CO_2e$. Interestingly, official UK government carbon footprint statistics indicate a 50% reduction in emissions associated with clothing consumption between 2014 and 2018, despite consumption in mass terms remaining almost flat over the same period. Yet these considerable reductions don't appear in the various documents guiding UK clothing retailers' ambitions for emissions reductions over the coming decade, laid out, for example, in the WRAP (2021) Textiles 2030 Roadmap. All these uncertainties are perhaps unsurprising, considering the quality of available evidence. As an anecdote, even the comprehensive, widely cited *Nature* review of the environmental impacts of the global clothing system by Niinimäki et al. (2020) references a considerable amount of grey literature, which itself is often underpinned by opaque methods and occasionally contradictory estimations. Improving this data is critical for understanding how the system can be most effectively moved towards circularity.

Finally, the large loss in economic value of clothing as it flows through the UK economy is also unsurprising. Per tonne, the value of clothing passing from, say, charity shops and textiles banks to UK used clothing exporters, is under 1% of the value of new clothing. Interestingly, used clothing exporters themselves manage to triple of the value of this flow, despite rejecting very little material. Used clothing sold within charity shops is of much higher value still, at around 20% of the value of new clothing (although the uncertainties here are large). Other markets for second hand clothing potentially generate even higher value. There are thus important questions regarding how these reuse markets can be expanded in a way that substitutes consumption of new clothing – rather than catalysing rebound effects – and how differences in prices and policies can help or hinder this goal.

All of this serves to underline two important aspects of a practical, sustainable circular economy. The first is that the only sure way to reduce the carbon emissions associated with clothing – or indeed any good – is to reduce both consumption and primary production. Effective strategies must first focus upon reducing the extraction and processing of raw materials into clothing. And they should only substitute one material for a purportedly lower-impact alternative when the emissions associated with both are significantly different. The second is that understanding the combination of technical and cultural factors that determine why the economic value of clothing plummets after first use, and intervening to preserve this value, is essential to promote reuse to replace virgin consumption. The 80%–99% drop in the value of clothing is not accompanied by a comparable deterioration in its technical properties, so these factors must be cultural. Indeed, fieldwork in African markets evidences this, where traders frequently spoil and conceal cheap (new) imported Asian shoes among used imports from the global North, which allows them to fetch a *higher* price for the former due to the perceived (or actual) superior quality of the latter – their second hand nature notwithstanding (Brooks and Simon, 2012). The environmental burden of the UK clothing economy could thus be considerably reduced by importing cultural norms from the very same places it currently exports its clothing 'waste'.

CRediT authorship contribution statement

Joel Millward-Hopkins: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Phil Purnell:**

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[4] Note that WRAP (2019b) report the prices of textiles from charity shops at ~£330/t, and given the above we assume they are referring to rejected textiles, rather than those sold within charity shops.

Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Sharon Baurley:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Phil Purnell reports financial support was provided by UK Research and Innovation.

Data availability

Data is in the Supplementary file

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Appendix A. Supplementary data

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