Kaunas University of Technology
Institute of Environmental Engineering
Faculty of Mechanical Engineering and Design

The Significance of Digital Platform Energy Consumption in Assessing the Environmental Benefits of Clothing Lifespan Extension via Swapping

Master's Final Degree Project

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Supervisor

Kaunas, 2026

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Sustainable Management and Production (6213EX001)

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Task of the Bachelor's/Master's final degree project

Topic of the project	The Significance of Digital Platform Energy Consumption in Assessing the Environmental Benefits of Clothing Lifespan Extension via Swapping
Requirements and conditions	Review literature on the environmental impacts of clothing production, clothing lifespan extension, reuse practices, and circular economy strategies. Review literature on the environmental impacts of ICT systems and digital platforms facilitating clothing exchange and textile transfer. Perform mapping and characterisation of digital platforms used for clothing swapping and exchange. Develop and apply a model to estimate electricity consumption associated with platform use, including user devices, data transmission networks, and backend infrastructure. Construct a Life Cycle Assessment (LCA) model of a cotton T-shirt as the baseline scenario and develop an integrated model incorporating ICT-related energy consumption. Perform environmental impact assessment calculations, scenario modelling, sensitivity analysis, and break-even analysis. Evaluate the significance of digital platform energy consumption in relation to the environmental benefits achieved through clothing lifespan extension via swapping. Interpret and discuss the results in the context of circular economy, digital sustainability, and sustainable consumption.
Supervisor	Prof. Dr. Jolita Kruopienė

01.06.2026

Nazakat Mammadova. The Significance of Digital Platform Energy Consumption in Assessing the Environmental Benefits of Clothing Lifespan Extension via Swapping. Final Degree Project. Supervisor prof. dr. Jolita Kruopienė; Kaunas University of Technology, Institute of Environmental Engineering, Faculty of Mechanical Engineering and Design.

Study field and area (study field group): Environmental Engineering (E03) – main study field, Production and Manufacturing Engineering (E10), Business (L01), Engineering Sciences.

Keywords: Life Cycle Assessment (LCA), clothing swapping, digital platforms, Information and Communication Technologies (ICT), electricity consumption, garment lifespan extension.

Kaunas, 2026. 65 p.

Summary

This thesis evaluated the environmental significance of digital platform electricity consumption in clothing lifespan extension through swapping. The research used a Life Cycle Assessment (LCA) approach in OpenLCA. Two models were created: a baseline LCA model for a cotton T-shirt and an integrated LCA model that accounted for electricity demand from user devices, network activities, and backend server infrastructure. The findings indicated that including digital platform operations increased environmental impacts, especially regarding climate change and the scarcity of fossil resources.

Scenario analysis revealed that using the platform, extending the lifespan of garments, and behaviour around substitutions greatly affected the environmental results of the swapping system. When reuse periods were short and substitutions were low, the environmental savings from reducing garment production did not offset the extra burden related to ICT. However, longer reuse of garments, along with effectively replacing new garment production, resulted in lower overall environmental impacts compared to the baseline garment system. Overall, the study demonstrated that digital clothing swapping can offer environmental benefits when garments are actively used for long enough and effectively replace new clothing purchases.

Nazakat Mammadova. Skaitmeninių platformų energijos vartojimo reikšmė vertinant mainomų drabužių naudojimo pratęsimo naudą aplinkai. Magistro baigiamasis projektas / vadovė prof. dr. Jolita Kruopienė; Kauno technologijos universitetas, Aplinkos inžinerijos institutas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Aplinkos inžinerija (E03) – pagrindinė, Gamybos inžinerija (E10), Verslas (L01), Inžinerijos mokslai.

Reikšminiai žodžiai: Gyvavimo ciklo vertinimas (LCA), drabužių apsikeitimas, skaitmeninės platformos, IRT elektros energijos vartojimas, drabužių naudojimo trukmės pratęsimas.

Kaunas, 2026. 65 p.

Santrauka

Šiame tyrime vertinama skaitmeninių platformų elektros energijos vartojimo reikšmė vertinant drabužių naudojimo trukmės pratęsimo per apsikeitimą (angl. clothing swapping) naudą aplinkai. Tyrime taikytas gyvavimo ciklo vertinimo (LCA) metodas naudojant OpenLCA programinę įrangą. Buvo sukurti du modeliai: bazinis medvilninių marškinėlių LCA modelis ir integruotas LCA modelis, kuriame papildomai įvertintas elektros energijos vartojimas naudotojų įrenginiuose, tinklo infrastruktūroje ir serveriuose. Rezultatai rodo, kad skaitmeninių platformų veikla padidina poveikį aplinkai, ypač klimato kaitos ir iškastinių išteklių naudojimo kategorijose.

Scenarijų analizė parodė, kad platformos naudojimo intensyvumas, drabužių naudojimo trukmės pratęsimas ir pakeitimo koeficientas reikšmingai veikia sistemos aplinkosauginį efektyvumą. Kai drabužiai po apsikeitimo naudojami trumpai ir pakeičia tik nedidelę naujų pirkimų dalį, papildoma skaitmeninės platformos energijos sąnauda nekompensuojama. Tačiau ilgesnis drabužių naudojimas ir didesnis naujų pirkimų pakeitimas lemia didesnę išvengtos gamybos naudą ir mažesnį bendrą poveikį aplinkai. Tyrimo rezultatai rodo, kad skaitmeninės drabužių apsikeitimo platformos gali teikti naudą aplinkai, jei drabužiai po apsikeitimo naudojami pakankamai ilgai ir veiksmingai pakeičia naujų drabužių įsigijimą.

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Abbreviations:
CDN – Content Delivery Network
CO_2 eq – Carbon dioxide equivalent
EEA – European Environment Agency
EoL – End-of-Life
EU – European Union
GB – Gigabyte
ICT – Information and Communication Technology
IEA – International Energy Agency
ITU – International Telecommunication Union
kWh – Kilowatt-hour
LCA – Life Cycle Assessment
LCI – Life Cycle Inventory
LCIA – Life Cycle Impact Assessment
PEF – Product Environmental Footprint
PEFCR – Product Environmental Footprint Category Rules
tkm – Tonne-kilometre

Introduction

The global clothing sector has experienced significant growth in production and consumption in recent decades. The pace of textile production is unsustainable, and the environment faces great challenges due to fast fashion. These challenges include overexploitation of resources, water use, energy use, chemical waste, and the generation of textile waste. In particular, the high turnover rate of clothing means that many products are still discarded even before they reach the end of their useful life, compounding the problem of increasing textile waste in landfills. Since the textile industry is considered a major source of global carbon (around 10 percent) and the second-largest industrial water polluter, it is important to find ways of extending the life of clothes and minimising environmental effects [15,32].

A potentially valuable measure to reduce the environmental impact of clothing is the development of a circular economy system in which products are reused, recycled, and valued over the long term. Clothing reuse has been considered one of the effective strategies that can be used among various circular strategies. Digital systems that enable clothing swapping allow consumers to change their clothes instead of buying new ones, extending the life of existing clothes and minimising the need to create new ones. Although the environmental benefits of reuse are widely accepted, there is limited analysis of the environmental impact of the energy use associated with the digital platforms on which exchanges are made. These platforms rely on significant infrastructure, such as user devices, cloud servers, and data transmission networks, all of which consume energy and contribute to greenhouse gas emissions.

The study aimed to fill this gap by analysing the environmental impacts of extending the lifespan via swapping, with a particular focus on the energy consumption of digital platforms that facilitate these processes. By using software, the reference research modelled the life cycle of a T-shirt made of cotton and explored how the swapping of this garment impacted the overall environmental footprint of the item, considering both the entire life cycle of clothing and the energy demands of the digital service.

Problem Statement

Despite the idea of clothing swapping having gained significant popularity as a proven approach to circularity, the energy consumption of digital tools applied to this solution has not been calculated. While swapping may reduce the need for new garment production, it needs to assess whether the energy required by digital platforms offsets the environmental benefits of prolonging clothing use.

Digital platforms can promote sustainability, whereas they are also the source of increased energy footprint of the ICT sector. This energy consumption is mainly linked to the user devices, transmission of data, cloud-based infrastructure, including data centres, which are critical to operating digital services. Therefore, while the direct environmental impact of clothing swapping via digital platforms has the potential to reduce carbon emissions and textile waste, it is equally important to assess the energy consumption of these platforms and how it influences the overall environmental balance.

Project aim

To assess the significance of the environmental impact of energy consumption required for operating digital platforms used to prolong clothing lifespan via swapping.
Project object: energy consumption by digital platforms for clothing swapping.

Project Objective

1. Review literature on environmental impacts of clothing production and benefits of prolonging clothing lifespan.
2. Review literature on environmental impacts of digital platforms that assist product, in particular textiles, transfer to secondary users.
3. Perform mapping and characterisation of digital platforms used for clothing exchange.
4. Model the energy consumption of the selected platform use.
5. Construct lifecycle model of the selected garment baseline scenario and the selected scenarios with clothing transfer. Perform impact calculations, sensitivity analysis, break-even analysis.
6. Present insights from the performed calculations.

Research hypothesis:

The environmental benefits of digital platform-mediated clothing exchange depend on key conditions, such as ICT energy efficiency, substitution rate, lifespan extension, and may only remain positive above a defined break-even threshold.

Use of Artificial Intelligence Tools

ChatGPT (OpenAI) was used during preparation of this thesis for language editing, grammar correction, and improvement of text readability. The scientific content, research design, data collection, modelling, analysis, interpretation of results, and conclusions were developed and verified by the author.

1. Literature Review

1.1.Clothing Lifespan, Reuse, and Circular Economy Strategies

Recent research on clothing sustainability highlights the environmental problems caused by fast fashion, shorter garment lifespans, and rising clothing consumption. Studies show that using garments for longer through reuse and circular economy strategies can help lower the environmental impact of making and disposing of clothes. However, the actual benefits of reuse depend on how consumers behave and how often they replace items. This section reviews important studies on clothing production impacts, ways to extend garment lifespan, reuse systems, and circular economy strategies in the clothing sector.

1.1.1. Environmental impacts of clothing production

The textile and clothing industry is widely recognised as one of the most resource-intensive and environmentally sensitive consumer sectors, facing significant pressures throughout the product life cycle. These pressures occur from raw material production through disposal and involve greenhouse gas emissions, water use, chemical pollution, and waste generation. The fast-fashion model, which encourages regular, low-priced clothing purchases and reduces product lifespans, is one of the drivers of this trend [32,29,24].

Environmental impacts arise from both resource extraction and industrial processing. Fibre production, especially conventional cotton, requires significant water, fertilisers, and pesticides, leading to water shortages and ecosystem harm. Fibre production can account for up to 60% of total environmental impact due to intensive agricultural inputs [24]. Subsequent stages, such as spinning, dyeing, and finishing, consume substantial amounts of energy and chemicals, contributing to air and water pollution [29]. Wet processing generates high chemical oxygen demand and considerable wastewater pollution. Life cycle assessments consistently identify impacts related to climate change, water use, and human health.

The European Parliamentary Research Service reports that textiles account for a substantial share of household consumption-related environmental pressures, particularly greenhouse gas emissions, land use, and water consumption [14]. These impacts are driven by globalised supply chains, with production frequently concentrated in regions with weaker environmental regulations, increasing the risk of inefficient resource use and pollution.

From a life cycle perspective, environmental impacts are distributed across all stages but are not equally significant. Raw material production and textile processing typically account for a large share of energy and water use, while garment manufacturing adds additional emissions and waste [29]. Distribution and retail stages add further impacts through transportation and logistics, while the use phase, comprising washing, drying, and ironing, requires ongoing energy and water inputs. The use phase can account for approximately 20–30% of total energy and water use, depending on user behaviour and garment type [24]. Additionally, washing synthetic textiles releases microplastics into water systems and is recognised as an important source of microplastic pollution [13]. These environmental pressures are further intensified by the fast-fashion model, which increases the speed and volume of clothing production. Rapidly changing collections and low-cost garments encourage consumers to purchase more frequently and use garments for shorter periods [32]. EU-level evidence also suggests that some cheap garments may be discarded after only seven or eight wears, while the number of collections released annually by major fashion companies increased substantially during the 2000s [14]. This is important from an environmental perspective, as the impacts of production are spread across fewer uses, increasing the environmental impact with each wear.

1.1.2. Importance of clothing lifespan in environmental impact

The lifespan of clothing plays a key role in determining its overall environmental performance. When garments are used for longer periods, the environmental impacts generated during production are spread across more uses. In contrast, when garments are discarded after a short period, the environmental impacts of production are associated with fewer wear events.

Fast fashion has shortened clothing lifespans. People now buy new clothes more often and replace them quickly because of changing trends, low prices, and easy availability [32].

Life cycle assessment (LCA) studies consistently show that production and use phases are among the main contributors to environmental impacts in clothing systems [29,24]. Also, research confirms that early disposal leads to inefficient resource use.

Short clothing lifespans increase environmental pressures by driving demand for continuous production. In contrast, extending garment lifetimes reduces the frequency of replacement purchases, thereby lowering total production volumes and associated impacts. Niinimäki et al. (2020) highlight that even moderate increases in clothing lifespan can provide meaningful environmental benefits when applied across large populations.

Studies show that if clothing is used for an additional 9 months, carbon, water, and waste footprints can drop by about 20–30% [40,24]. Doubling the number of times a garment is worn also decreases greenhouse gas emissions. Reviews agree that making clothes last longer is one of the best ways to reduce environmental impact. Research on life cycle assessments finds that using clothes for longer has a greater impact than recycling, which still requires additional processing [1].

1.1.3. Consumer behaviour and clothing disposal

Consumer behaviour strongly influences how long clothing remains in use. Garments are often discarded for reasons that are not directly related to physical damage. According to research on clothing disposal behaviour, consumers may stop wearing garments due to changes in fashion preferences, poor fit, boredom, or a lack of interest in certain items [27].

In addition to early disposal, a considerable proportion of clothing remains unworn for extended periods before being discarded. Prolonged storage of garments in wardrobes constitutes the underutilisation of household resources. This underuse is environmentally consequential, as it lowers the number of wears per garment and increases the environmental impact associated with each use [11].

Literature explains that clothing disposal behaviour affects both the lifespan of garments and their potential for reuse or recycling. In some cases, garments are stored in wardrobes for long periods of time without being used and are eventually discarded. When consumers decide to dispose of garments, they use different methods. These include donating garments, giving them to friends or family, selling them in second-hand markets, or discarding them as waste. Reuse methods, such as donating and reselling, are considered more environmentally friendly because they allow garments to remain in use for longer [27].

Ekström and Salomonson (2014) found that clothing is closely tied to identity, social comparison, and fashion trends. This helps explain why people might throw away clothes, even if they are still usable, instead of keeping or passing them on. Social and psychological factors like changing trends, personal taste, and how people value items all affect these decisions.

As demonstrated by European Parliamentary Research Service (2019), people in the EU now buy around 40% more clothes compared to previous decades. At the same time, more than 30% of clothes in wardrobes have not been worn for at least one year. When these clothes are discarded, more than half end up in mixed household waste instead of separate collection systems. The report also indicates that only about 1% of used clothing is recycled into new garments. These findings show that environmental impacts are influenced not only by clothing production, but also by consumption patterns, clothing use, and disposal practices.

1.1.4. Environmental benefits of clothing reuse

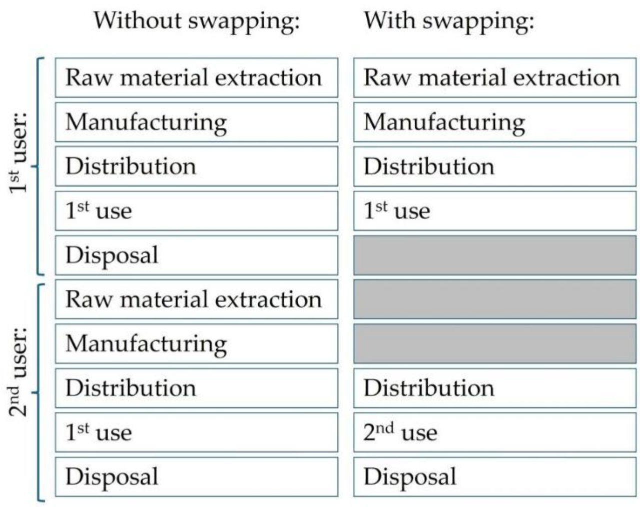
Clothing reuse is one of the most effective strategies for reducing environmental impacts in the textile sector, primarily because it can offset the need for new production. When a garment is reused, it can displace the production of a new item, thereby avoiding the associated environmental burdens [15].

The environmental benefit of reuse depends on the substitution rate**,** which represents the extent to which reused garments replace new purchases. Higher substitution rates lead to greater avoided impacts, while lower rates reduce the overall net environmental benefit. This relationship is supported by recent research on substitution effects in textile systems, which shows that substitution between alternative products is often incomplete. Empirical evidence indicates that new textile materials or alternatives do not fully replace existing production, but instead may only substitute a portion of it while the remaining share contributes to overall market growth [20]. This highlights that the environmental benefits of reuse are highly sensitive to the degree of actual displacement of new production, rather than the mere circulation of garments.

LCA studies show that the avoided impacts of production outweigh the additional impacts associated with the collection, sorting, and transportation of reused clothing [15,24]. As a result, reuse is generally considered more environmentally beneficial than recycling. Research on LCA analysed 45 LCA studies on textile waste management and circular practices and found that separate collection followed by reuse and recycling made significant environmental benefits, but the impacts associated with reuse were typically lower than those of recycling. The same research also emphasises that extending textile service life before the need for waste treatment produces the most significant environmental benefits. This highlights the importance of models focused on reuse, such as swapping, which can postpone replacement and extend the life of the current garment [1].

Other life cycle assessment research examines the environmental benefits of clothing reuse. For example, a study by Farrant et al. (2010) evaluate the environmental impacts of reusing clothing compared with direct disposal. The study assesses scenarios in which used garments are collected, sorted, and resold as second-hand clothing. The results indicate that reuse can significantly reduce environmental impacts because it avoids the production of new garments. According to same research, purchasing 100 second-hand garments could replace approximately 60 new garments in

Sweden and 75 in Estonia. These results demonstrate that the environmental benefits of reuse depend largely on whether reused garments actually substitute new purchases [15].



	Without swapping:	With swapping:
1st user:	Raw material extraction	Raw material extraction
	Manufacturing	Manufacturing
	Distribution	Distribution
	1st use	1st use
	Disposal	
2nd user:	Raw material extraction	
	Manufacturing	
	Distribution	Distribution
	1st use	2nd use
	Disposal	Disposal

Fig. 1. Comparison of clothing life cycle stages with and without swapping, illustrating avoided production and extended garment use

The principle of product displacement can be used to understand clothing reuse, in which reusing a garment reduces the need for new production. As illustrated in Fig.1.[24] the conventional consumption model involves each user purchasing a new garment, resulting in repeated production processes. In contrast, a garment is used by multiple users in a swapping system, thereby avoiding additional production stages and extending the use phase. This significantly reduces environmental impact, as the most resource-intensive stages of the clothing life cycle, raw material extraction and manufacturing, are avoided entirely or partially.

1.1.5. Circular Economy Strategies in the Clothing Sector

In response to the growing environmental pressures in the fashion industry, the circular economy has gained attention as a framework for improving sustainability. The circular economy aims to reduce resource use. Consumption and waste generation by maintaining the value of products, materials, and resources within the system for as long as possible [32,11].

Within the clothing sector, circular strategies encompass a range of approaches, including designing for durability, enabling repair and maintenance, promoting reuse and resale, improving recycling processes, and supporting alternative consumption models such as rental and sharing systems [31]. These strategies aim to extend the functional lifespan of garments and reduce the need for new production.

Among these approaches, product longevity plays a key role. Sustainable design practices emphasise the importance of creating garments that are physically durable, adaptable, and suitable for prolonged use. This includes considerations such as material quality, modular design, and ease of repair, which facilitate reuse and recycling at later stages ([31].

Ramírez-Escamilla et al. (2024) discuss that circular economy strategies in the clothing sector primarily focus on recycling, reuse, and repair. Their study indicates that recycling remains the most frequently addressed strategy in the literature, although its implementation is often limited by the need for advanced technologies, infrastructure, and financial investment. Reuse is identified as a key strategy because it enables garments to be used again without requiring complex processing; however, its effectiveness depends on consumer participation and acceptance of second-hand practices. Repair, while less frequently discussed, contributes to extending the lifespan of garments, although challenges such as limited access to repair services and a lack of awareness remain. These findings suggest that improving sustainability in the textile sector requires a combination of technological development and changes in consumer behaviour.

The transformation to circular clothing systems requires coordinated action among multiple stakeholders, including consumers, manufacturers, retailers, and waste management actors. Consumer behaviour influences garment use duration and disposal pathways, while producers and retailers shape product design, quality, and business models. In addition, the development of infrastructure such as textile collection systems, sorting facilities, and second-hand markets plays an important role in enabling reuse and recycling activities [9].

However, the circular economy should not automatically be considered sustainable. The research shows that while reuse and recycling can reduce some environmental impacts, they do not always lead to an overall reduction in material consumption. In the textile sector, recycling is limited by factors such as material complexity, fibre fragmentation, and the continued need for virgin material inputs. Therefore, circular strategies should be evaluated using a full life cycle assessment rather than assumed to be environmentally beneficial [25].

These limitations are particularly evident in the case of recycling. Sandin et al. (2025) support these claims, stating that technical limitations related to fibre composition, material degradation, and quality loss limit the effectiveness of textile recycling systems. Furthermore, empirical studies show that while textile-to-textile recycling can help reduce climate and water-related impacts, the overall environmental benefits remain relatively limited compared to the overall impacts associated with clothing consumption [35]. These findings highlight that upstream strategies, particularly reducing consumption and extending garment lifespans, are important for achieving substantial environmental improvements. As a result, circular economy approaches in the clothing sector increasingly prioritise reuse and longer use phases instead of downstream solutions such as recycling, consistent with the waste hierarchy.

1.2. Environmental Impacts of ICT and Digital Platforms

The environmental impacts of information and communication technologies (ICT) and digital platforms have become increasingly significant as economic and social activities rely more heavily on digital services. Although digitalisation is often presented as a cleaner and more efficient alternative to traditional systems, the literature consistently shows that digital technologies are not immaterial. Their operation depends on physical infrastructure, including user devices, communication networks, data centres, and cloud-based systems, all of which require energy and resources throughout their life cycles [7,39].

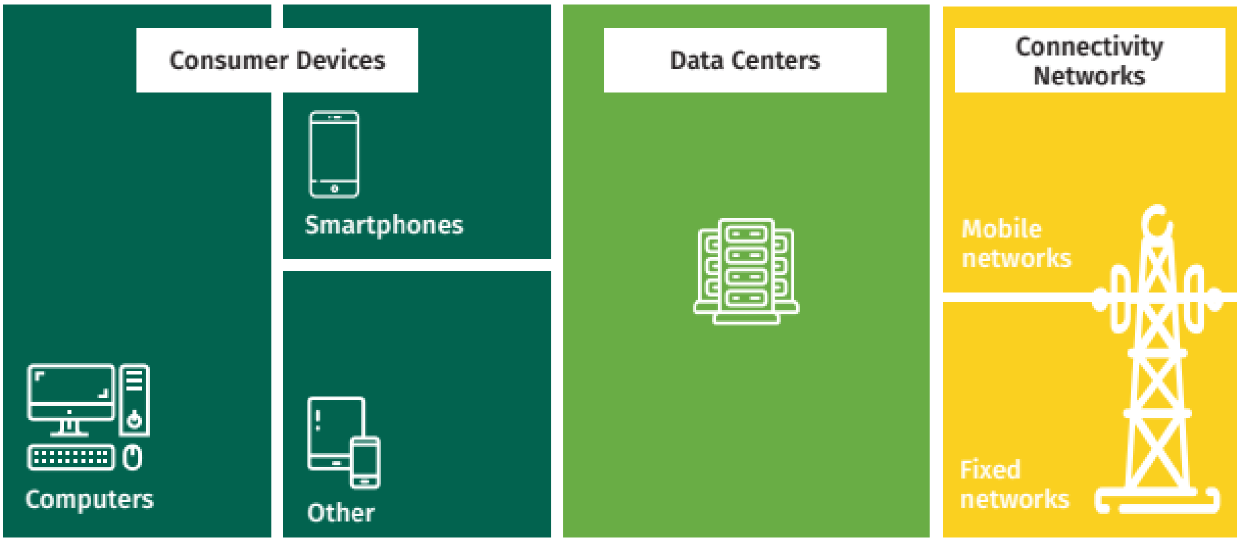


Fig. 2. Main sources of emissions in the ICT sector

Fig. 2. [23] shows the main components of the ICT system that contribute to environmental impacts, including consumer devices, data centres, and connectivity networks. Consumer devices include smartphones, computers, and other electronic equipment used by individuals, while connectivity networks refer to both mobile and fixed infrastructures that enable data transmission. Data centres represent the backend systems responsible for storing and processing data. Together, these components form an interconnected system, where each part contributes to overall energy use and emissions. In this sense, ICT should not automatically be considered environmentally beneficial simply because it replaces certain physical activities. Instead, it represents a complex system in which environmental benefits and burdens occur simultaneously.

A further important point from ICT literature is that digitalisation often shifts rather than removes environmental burdens. Digital services may reduce the need for some physical activities, but they also transfer environmental pressure toward less visible infrastructures such as servers, communication equipment, and end-user hardware. Life cycle assessment research highlights that digital transformation should be assessed across both direct and indirect effects, including rebound effects, increased demand for data processing, and the growing number of connected devices [18,22]. This is particularly relevant for platform-enabled clothing exchange, where the environmental benefits of avoided production need to be considered together with the additional impacts created by digital infrastructure.

Direct impacts include emissions from raw material extraction, manufacturing, transport, electricity use during operation, and end-of-life treatment of ICT equipment. Indirect impacts include changes in production systems, transport, trade, and consumer behaviour resulting from digitalisation [7]. Also, several studies highlight that ICT already represents a measurable share of global emissions. Estimates suggest that the sector accounts for approximately 1.8% to 3.9% of global greenhouse gas emissions, depending on system boundaries and methodological approaches [7,39]. In absolute terms, ICT emissions were estimated at approximately 1.2–2.2 Gt CO_2 in 2020 [39]. These findings indicate that digital infrastructures are environmentally relevant at the global scale.

1.2.1. Energy use in user devices

One of the most consistent findings in the literature is that the environmental burden of digital services is strongly linked to end-user devices. These include smartphones, laptops, desktops, televisions, and other connected equipment. Their impact arises not only from electricity consumption during use but also from embodied emissions associated with manufacturing [39].

Device production can represent a significant share of total environmental impact. For example, estimated cradle-to-gate carbon footprints include approximately 33 kg CO_2 eq. for a smartphone, 156 kg CO_2 eq. for a laptop, 169 kg CO_2 eq. for a desktop, and up to 340–500 kg CO_2 eq. for televisions, depending on size [39]. These values indicate that device manufacturing is a major contributor to overall digital environmental impacts, particularly when devices are replaced frequently. Also, the same study proves that operational energy use also varies significantly between devices. Larger and more powerful devices consume more electricity than smaller ones. For instance, approximate hourly electricity consumption values include 0.027 kWh for laptops, 0.13 kWh for desktops, and between 0.14 and 0.18 kWh for televisions, depending on size [39]. As a result, the same digital activity may have different environmental impacts depending on the device used.

User devices represent a foundational component of the energy footprint of digital platforms, as they constitute one of the four major categories of electricity use within communication technologies. The study by Andrae & Edler (2015) shows that devices such as desktops, laptops, smartphones, tablets, and monitors collectively consume several hundred terawatt-hours annually, with usage patterns influenced by device lifetimes, production volumes, and efficiency improvements. The authors estimate annual efficiency gains of around 1–5%, which gradually reduce per-device electricity consumption; however, the rapid global increase in the number of smartphones and tablets offsets much of these savings. For example, smartphone production is projected to rise from 350 million units in 2010 to 3 billion units by 2030, while tablets increase from 50 million to 560 million units. Although televisions dominate total consumer-device electricity use, the study indicates that personal computing and mobile devices remain a substantial and growing source of energy demand, particularly because their relatively short lifetimes (1–3 years) lead to frequent replacement cycles.

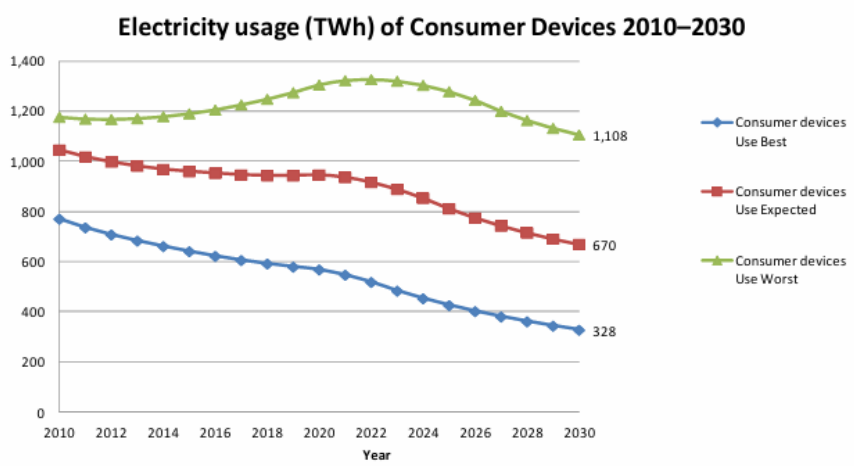


Fig. 3. Global electricity demand of consumer devices from 2010 to 2030

As shown in Fig. 3. [3] the projected trajectories of electricity consumption by consumer devices depend on efficiency improvements and growth in device numbers. While the best-case scenario suggests a decline in electricity use, the expected and worst-case scenarios both indicate increasing demand. This suggests that efficiency improvements alone may not be enough to offset the rapid growth in the number of connected devices. Similarly, Malmodin & Lundén (2018) estimate that end-user equipment accounts for approximately 50–60% of the total electricity consumption of the ICT sector, making it the largest single contributor. Even though individual devices such as smartphones and laptops consume relatively small amounts of electricity every year, the combined effect of billions of devices results in a substantial total electricity demand, estimated at around 400–700 TWh annually. In addition, short device lifetimes and frequent replacement cycles further increase the overall energy footprint, particularly because manufacturing energy can exceed energy use during operation.

From a consumer perspective, end-user devices are often the main contributors to the environmental impact of digital services. Research shows that the production and ownership of devices account for a larger share of impacts than electricity use during operation or data transmission. This means that digital impacts cannot be evaluated only based on app-level energy use, but must also include device lifetimes and replacement cycles [25].

1.2.2. Data transmission and network energy use

Data transmission through communication networks is another important component of ICT-related environmental impacts. Digital platforms rely on network infrastructures to transfer data between users, servers, and storage systems. Understanding the relationship between data transmission and network energy use requires moving beyond the simple idea that more data automatically leads to higher energy consumption. Recent studies show that many telecommunication networks have a high baseload power demand, meaning that a large share of electricity is consumed even when traffic levels are low [6,36]. Because of this, sending additional data through an already operating network may have only a limited short-term effect on electricity use.

This also means that common allocation metrics such as kWh/GB should be used carefully, because they do not always reflect how network equipment actually consumes energy [19,36]. In the longer term, however, data traffic still matters because sustained growth in peak demand can require additional network capacity. This can increase baseload electricity use and add further impacts through new infrastructure and equipment [26,36]. Therefore, the timing and pattern of data transmission, such as video-on-demand peaks or other high-throughput events, may be more important than total data volume alone. Overall, data transmission influences network energy use mainly through its role in long-term capacity requirements rather than through immediate changes in operational electricity use. While these studies highlight the structural characteristics of network energy use, other research provides quantitative estimates of energy intensity and emissions associated with different types of data transmission. Energy intensity varies significantly depending on network type and efficiency. For example, fixed networks may have energy intensities ranging from 0.0065 to 0.29 kWh per GB, while mobile networks may range from 0.01 to 7.53 kWh per GB under different performance conditions [39]. These variations indicate that mobile networks can be considerably more energy-intensive than fixed networks.

Network impacts are also influenced by geographic location and electricity mix. For example, one hour of video streaming can result in emissions ranging from 200 g CO_2 eq. to 3900 g CO_2 eq.

depending on network efficiency and electricity carbon intensity [39]. This demonstrates that digital impacts are highly context-dependent. Data-intensive activities, particularly video streaming, are identified as major drivers of network energy consumption. Data transfer volumes may range from approximately 0.3 GB per hour for low-quality streaming to up to 7 GB per hour for ultra-high-definition content. Video-related activities can account for between 28% and 68% of total digital environmental impacts, depending on user behaviour [39].

1.2.3. Cloud infrastructure, data centres, and digital storage

Cloud infrastructure and data centres represent a third major component of ICT environmental impact. These systems are responsible for processing, storing, and delivering digital content.

Data centres operate continuously and require electricity for both computation and cooling. Although often less visible to users, they are essential for digital platform functionality [7]. Energy intensity values for data centre operations are estimated to range between 0.01 and 0.072 kWh per GB, depending on system efficiency [39]. While these values may be lower than some network intensities, their cumulative impact becomes significant because of large data volumes and repeated access.

Moreover, digital infrastructure impacts are closely linked to platform growth. Increased demand for data processing, storage, and digital services leads to higher overall energy consumption, even when efficiency improves [2]. Recent industry analyses further support the observation that data centre energy demand continues to grow despite efficiency improvements. Reports indicate that increasing demand for cloud services, data storage, and emerging technologies such as artificial intelligence is driving higher energy consumption in data centres. Although technological advances have improved energy efficiency, these gains are often offset by rapid growth in digital services and data processing requirements, reinforcing the broader digitalisation paradox [12]

1.2.4. Digital platforms as both enablers and sources of impact

Digital platforms have a two-fold role in sustainability. On the one hand, they promote the principles of a circular economy, namely, resale, sharing, and even clothing exchange, which can prolong product life cycles and decrease the need to produce new products [37]. On the other hand, the operations of platforms demand continuous digital activity, including user interactions, data transmission, and backend processing. Search tools, uploading images, messaging, recommendation systems, and notifications are all energy-consuming functions.

Environmental impact is also related to platform design. Such functions like autoplay, high-resolution photos, and infinite scroll can raise the requirements and expenditures of data. Thus, depending on their design and usage, digital platforms can reduce or increase environmental impacts [39]. So, it will be needed to compare the environmental benefits and environmental burdens within the same system. Digital platforms can be seen as enablers, as they facilitate substitution and optimisation that can lead to reduced material use, transport, and energy demand. Meanwhile, they also cause environmental impact, in the sense that they are based on energy-intensive systems like devices, communication networks, and data centres. Moreover, the digital services can cause rebound and induction effects when efficiency is increased or more accessible, then higher levels of consumption will be observed. Research based on LCA demonstrates that such effects may partially or entirely offset the expected environmental benefits of the digital systems, and thus digital platforms should be considered sources of environmental impact and as potential contributors to environmental improvements [33].

1.3. Life Cycle Assessment (LCA) Approaches Relevant to the Study

1.3.1. LCA as a framework for clothing lifespan extension and reuse

In the clothing literature, most LCA studies show that the environmental benefits of reuse depend on how the functional unit, system boundaries, and substitution logic are defined. For example, Farrant et al. (2010) model reuse through a service-based functional unit and apply a system extension so that reused clothing can potentially be credited for the new clothing that it replaces.

Although different from charity-based second-hand systems, it is based on the same idea of keeping clothing in use for longer and reducing the need for new production. If recycled clothing is worn instead of new clothing, some of the production impacts can be avoided. If it is purchased in addition to new purchases or only slightly delays them, the environmental benefits may be reduced or even eliminated. This highlights the difference between reuse as circulation and reuse as substitution. Circulation describes the movement of clothing from one user to another, while substitution describes the extent to which this movement reduces the demand for newly produced clothing. Many studies consider this distinction to be important. The concept of substitution rate is particularly relevant because it clearly shows that the benefits of reuse are conditional, not automatic. Analytically, production avoidance does not occur automatically because reuse is available; rather, it depends on behavioural assumptions about what would otherwise happen [15,33].

Research by Abagnato et al. (2024) also shows that LCA results are very sensitive to assumptions. Factors such as substitution rates, transportation distances, and user behaviour can significantly influence the results. This means that the results can vary depending on how the system is modelled.

It also depends on how many additional uses are achieved. Clothing that is transferred but worn only a few times produces a different outcome than clothing that enters a longer second-use cycle [41]. Therefore, LCA is relevant not only because it allows for comparisons between reuse and replacement, but also because it requires the specification of the service provided, for example, ownership of a newly manufactured product, continued use of an existing item, or access to clothing through shared or platform-based systems [33,16].

Moazzem et al. (2020) report that many LCA studies identify the consumer use stage as a significant contributor to environmental impacts in textile supply chains. This stage includes washing, drying, ironing, and other care activities. The review also notes that technologies or product features that reduce the frequency of washing or extend the life of a garment can reduce overall impacts. Furthermore, this article states that a 50% reduction in washing frequency over the life of a garment can reduce overall environmental impacts by 15–30%. This is important because it shows that the use stage is not only related to the duration of ownership, but also how the garment is cared for during that time. The environmental impact of long-term use of garments depends on whether the garment remains in active use, how often it is worn, and whether care practices vary between users. Itten et al. (2020) think that use-phase assumptions should be considered as important modelling choices rather than fixed background conditions. For example, differences in washing frequency, drying methods, or transportation patterns can affect the overall environmental outcome of reuse systems.

1.3.2. Modelling the use phase in clothing LCA

Traditional product-based LCA is usually based on linear systems, in which a single product follows a single use trajectory and a single end-of-life pathway. However, circular and shared-use systems challenge these assumptions because the same garment may serve multiple users over time. This is common in reuse, rental, swapping, and other shared-use models. This raises important questions about the appropriate functional unit, the treatment of allocation, and the representation of avoided burdens [33]. Therefore, for shared-use systems, the functional unit becomes specially important. Pohl et al. (2019) explain that comparative LCA requires functional equivalence, meaning that what is compared should be the same type of service they provide, rather than how that service is delivered.

Another important point related to circular economy assessment is the distinction between different circular loops. The literature on the circular economy increasingly emphasises that LCA is not only essential in this context but also that circular strategies can lead to unexpected burdens in other areas. LCA can be used to support circular assessment, specifically by identifying the environmental hotspots and comparing alternative pathways, while also warning that circularity cannot be assumed to be environmentally beneficial in itself. This is particularly relevant to clothing swapping, which is often considered a circular practice because it keeps garments in use for longer and delays disposal [40]. Another important point in the same literature is the distinction between different circular loops. Additionally, digital technologies in LCA studies are mainly used to close and narrow loops, while slowing loops are discussed less frequently. Clothing swapping mainly belongs to the slow-loop category because its main purpose is to extend the use phase of existing garments rather than focus on recycling materials or improving production efficiency [38].

Evidence from studies on collaborative consumption in fashion supports the need to compare systems based on the service they provide rather than simple ownership. Zamani et al. (2017) show that using a functional unit such as "one average use" makes it possible to compare clothing-library models directly with traditional ownership-based consumption. This approach is important because it focuses on what the user actually receives, namely, access to clothing for a certain number of uses, rather than whether the garment is owned or shared. Their study demonstrates that shared-use systems should not be evaluated only based on the existence of a platform or the circulation of garments between users. Instead, they should be assessed based on the amount of clothing service they provide, ensuring a fair comparison with conventional consumption models.

1.3.3. LCA modelling of shared-use and circular systems

Circular systems and shared use challenge some fundamental assumptions of traditional product-based LCA. Linear systems usually imply that a single product is related to only one use trajectory and one end-of-life pathway. For example, a single garment can provide service to more than one user over time in shared-use, reuse, rental, or swapping systems. This raises important questions about the appropriate functional unit, the treatment of allocation, and the representation of avoided burden [33]. Therefore, for shared-use systems, the functional unit becomes particularly important. Pohl et al. (2019) explain that comparative LCA requires functional equivalence, meaning that what is compared should be the same type of service they provide, rather than how that service is delivered. In clothing swapping, the relevant service is not the use of an app as such, but access to a garment for a certain period pr numbers of wears.

Another important contribution of the recent literature is the distinction between different circular loops. Toniolo et al. (2025) observe that digital technologies in LCA have mostly been used to support closing and narrowing loops, while slowing loops remain less studied. Clothing swapping belongs primarily to the slowing-loop category because its environmental rationale lies in extending the use phase of existing products rather than recycling materials or improving production efficiency.

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1.3.4. Methodological challenges in integrating digital components

Traditional apparel LCAs typically focus on fibre production, garment manufacturing, transportation, consumer care, and end-of-life. In comparison, a replacement platform system includes a digital layer that is not visible or tangible, but still uses physical infrastructure and energy. The literature on digital service LCAs shows that this additional layer cannot be limited to "application electricity use." It depends on the distributed chain of devices and infrastructure that collectively implement the digital service [16].

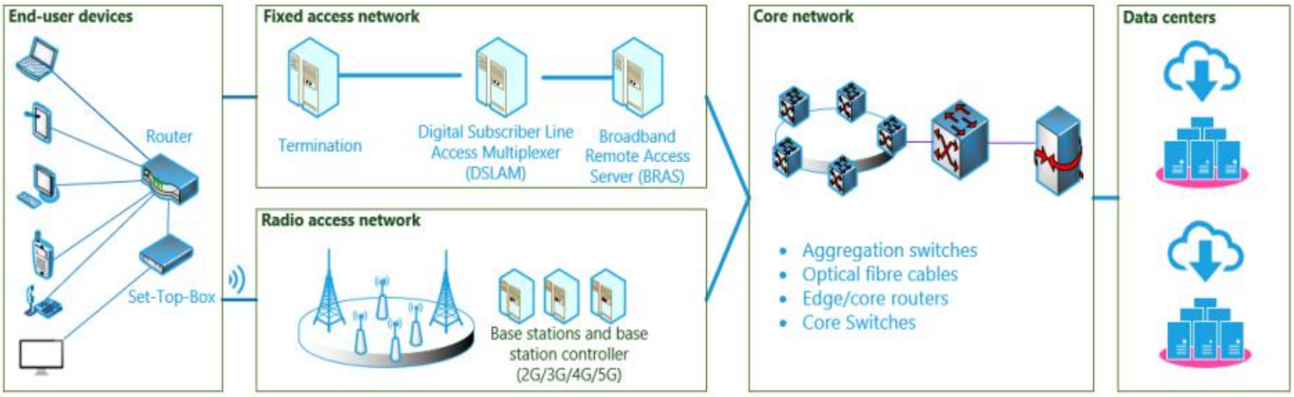

Fig. 4. Digital supply chain for the provision of digital services, including end-user devices, access networks, core networks, and data centres

The Fig.4. [16] illustrates the distributed infrastructure required to deliver digital services, highlighting that even simple user interactions depend on multiple interconnected technological layers. From an LCA perspective, this structure challenges the traditional product-based modelling approach, as environmental impacts cannot be attributed to a single device or process. Rather, there is a sharing of impacts between end-user devices, network components, and data centres, which are shared among two or more services and users.

A first challenge is multifunctionality Digital services are based on the use of shared terminals, routers, network equipment, servers, and storage systems that are shared across multiple services and users. The digital-service LCA is particularly challenging due to multi-actor, multi-product, and multifunctional features, when the allocation becomes unavoidable when a single device or network element supports multiple functions simultaneously. This has a direct effect on swapping systems. A user's smartphone is not dedicated to swapping activity, and network and data-centre resources are not reserved for that platform alone. For this reason, any LCA that includes digital components must adopt a defensible allocation logic [22].

The second challenge concerns inventory construction. As demonstrated by Toniolo et al. (2025), digital technologies can enhance the Life Cycle Inventory (LCI) by making it more automated, being traceable, and transparent. Meanwhile, they present trade-offs in terms of complexity, flexibility, and control over data collection and processing. This finding matters in two ways. First, digital tools may improve the traceability of circular systems and provide better data on material and information flows. Second, the same tools can make the inventory more difficult to interpret because data infrastructures, interfaces, and black-box calculations introduce new dependencies and skills requirements. For a study of clothing swapping, this suggests that digitalisation is not only an additional impact source but also a methodological source of both improved observability and increased modelling complexity.

The third issue is the difference between operational use and service development. Gröger et al. (2024) support that their digital supply chain concept covers the use phase of digital services, but software development may also need inclusion when it involves substantial digital infrastructure, such as high-performance training processes. Although a clothing-swapping platform is unlikely to resemble AI-intensive systems, the literature explains clearly that the exclusion of software-development burdens should be a justified modelling choice instead of an implicit omission.

1.3.5. Attributional, consequential, and scenario-based choices

Attributional LCA is typically used to describe the environmental burdens of a defined system under a given set of assumptions. This makes it suitable for comparing situations such as obtaining clothing through swapping versus purchasing new garments, while keeping behavioural conditions and system boundaries constant. In contrast, consequential LCA focuses on broader system-level changes, including market responses, shifts in demand, and indirect behavioural effects [10].

In the case of clothing swapping, this difference becomes important because both avoided production and digital platform use depend on user behaviour. ICT-related LCA studies often use comparative approaches to capture substitution and efficiency effects. However, they also note that wider effects, such as rebound or increased consumption, are more difficult to represent and are often addressed through scenarios or sensitivity analysis [33]. Similarly, Itten et al. (2020) highlight that ICT systems can influence production and consumption patterns in indirect ways, which makes their environmental assessment more complex and sometimes requires combining different methodological approaches. These indirect and behavioural effects are particularly important in clothing swapping systems. As a result, clothing swapping systems cannot be understood as a single fixed scenario. For this reason, scenario-based modelling is particularly useful. It allows different assumptions, like replacement rates, user behaviour, garment care practices, and digital use intensity, to be varied. This approach is supported by Hauschild et al. (2018), which is commonly used in LCA to address uncertainty and variability in system behaviour. It also helps to explain under which conditions exchanging leads to environmental advantages, rather than assuming a single result.

1.3.6. Uncertainty, data quality, and behavioural assumptions

Many studies have shown that uncertainty becomes more important when LCA attempts to reflect real-life behaviour and more complex systems. In clothing reuse studies, uncertainty often arises from assumptions about substitution, how often garments are used, transportation distances, and how long garments are stored [15,1]. In the digital service studies, uncertainty arises from distribution choices, differences in system usage, limited data, and the difficulty of tracking how shared infrastructure is used. When these two systems are combined, uncertainty does not decrease; on the contrary, it becomes more complex.

Toniolo et al. (2025) clearly explain this issue. Their review shows that digital technologies can improve data quality by providing more detailed and real-time information. However, they also make data systems more complex and difficult to manage. The authors note that the slowdown periods are still less studied, which is important for clothing replacement systems that rely on longer-term use rather than recycling. This means that better data does not eliminate uncertainty. It only changes the type of uncertainty, from missing data to the difficulties in managing and interpreting complex systems. Thus, while data from user devices is increasingly available, there is still a lack of quality data for networks and data centres [22]. They also note that modelling shared systems and use-phase data is difficult. Gröger et al. (2024) suggest how to organise digital impacts through ideas such as digital supply chains and digital master resources. However, their work also shows that many assumptions are important, especially regarding how systems are used and how impacts are shared.

Several behavioural assumptions are particularly important in clothing replacement systems. These include whether the user would otherwise buy new clothing, whether the platform changes shopping behaviour, how often the replaced clothing is worn, and how much digital activity is required for each exchange. Previous studies have shown that the environmental benefits of reuse are highly dependent on substitution behaviour and actual usage intensity [15,41]. Review studies also highlight that LCA results are highly sensitive to assumptions about user behaviour and system usage [1]. Similar challenges arise in ICT-related systems, as digital services can both substitute for and incentivise additional consumption, making it difficult to detect indirect effects [33,22].

1.4. Summary of Literature Review

The literature review demonstrates that environmental impacts in the clothing sector are closely associated with fast-fashion practices, shortened garment lifespans, and rising consumption patterns. Prior research indicates that extending garment use can reduce environmental burdens; however, the benefits of clothing reuse depend on specific conditions. Substitution rates, user behaviour, transport, and the duration of additional use all influence environmental outcomes, as these factors determine the actual savings.

Additionally, the review shows that digital platforms have a dual role. They can support circular practices such as clothing reuse and swapping, but they also depend on ICT infrastructure and users, for example, devices, communication networks, and data centres, which consume energy and create environmental impacts. Existing studies explain that digital services cannot be considered as impact-free, and their environmental effects depend on the way they are used and the system design. The literature further indicates that LCA offers a suitable framework for measuring clothing-swapping systems because it allows the study of physical and digital processes together. Various methodological issues, including functional units, system boundaries, substitution assumptions, allocation choices, and uncertainty, are highlighted by previous researchers. Additionally, many studies recommend using transparent assumptions, sensitivity analysis, and scenario-based modelling to better understand how results change under different conditions. Overall, the reviewed literature suggests that assessing clothing swapping systems requires an integrated perspective that considers both clothing-related and digital-service impacts. The findings in this chapter provide the basis for the following methodology chapter, which develops the analytical framework and modelling choices in order to assess clothing lifespan extension through platform-based swapping systems.

2. Research Methodology

2.1.Research Design Overview

Several stages were created for the methodological framework, beginning with the literature review and ending with the interpretation of the environmental results. The overall workflow of the study is presented in Fig. 5.

Fig. 5. Roadmap of research

The study began with a literature review and the development of the research design, followed by the definition of the assessment's goal, scope, and system boundaries. Then, platform mapping was conducted to identify digital platforms facilitating textile reuse in the Baltic Sea region. Later, detailed mapping of digital platforms was needed in order to identify the user interactions and system operations that contribute to energy consumption. ICT energy modelling was used to quantify and estimate the energy consumption of user devices, data transmission, and backend infrastructure based on this mapping.

Life cycle assessment modelling was performed in OpenLCA by comparing a baseline model of a cotton t-shirt with an integrated model that included ICT-related electricity consumption and the baseline model. Scenario analysis, sensitivity analysis, and break-even analysis were subsequently conducted to assess how different modelling assumptions affect the environmental performance of digital garment swapping. Finally, the results were interpreted and discussed in relation to avoided clothing production and ICT-related environmental burdens.

2.2. Goal and Scope Definition

The goal was to assess the environmental significance of energy consumption associated with digital platform operations relative to the environmental benefits generated by extending garment use and avoided production. The analysis focused on the role of ICT-related electricity consumption in clothing-swapping platforms and its contribution to overall environmental impacts.

In this study, garment lifespan extension was defined as the continued use of a garment after transfer to a secondary user following the initial ownership period. The baseline use period of the cotton T-shirt was defined as 12 months for the first user. After this period, the garment was assumed to still retain functional and aesthetic value and remain suitable for further use. The swapping scenarios, therefore, represented additional use periods by a secondary user rather than the creation of an entirely new physical lifespan for the garment.

The study evaluated these important points:

- the environmental impacts of the baseline cotton T-shirt life cycle;
- the contribution of user devices, data transmission, and backend operation to total digital energy demand in garment swapping via the platform;
- the environmental impacts of electricity source, device type, and platform usage intensity;
- the environmental effects of continued garment use under different additional use periods (+3, +6, and +12 months);
- whether the environmental benefits associated with garment reuse and avoided production were sufficient to offset additional ICT-related impacts generated by platform operation;
- the environmental performance of integrated scenarios combining garment reuse and digital platform operation.

The baseline cotton T-shirt model included transport associated with conventional distribution processes. However, transportation between users during the swapping process was excluded from the integrated model scenarios.

2.3.System Boundaries and Functional Unit

2.3.1. Functional Unit

The functional unit was defined as: One cotton T-shirt providing clothing functionality over a 12-month reference service life.

This functional unit was selected to ensure consistent comparison between the baseline garment system and the alternative swapping scenarios. Both systems therefore provide the same primary function: clothing use over a defined reference period. In the swapping scenarios, the garment may continue to be used beyond the 12-month reference period by being transferred to a secondary user. This additional use period is treated as garment lifespan extension rather than as a separate functional unit.

2.3.2. System Boundaries

Baseline LCA model was built for further analysis as a reference system and was visualized in Fig. 6. The system boundary of the baseline LCA covered from cradle to grave of life cyle of cotton t-shirt.

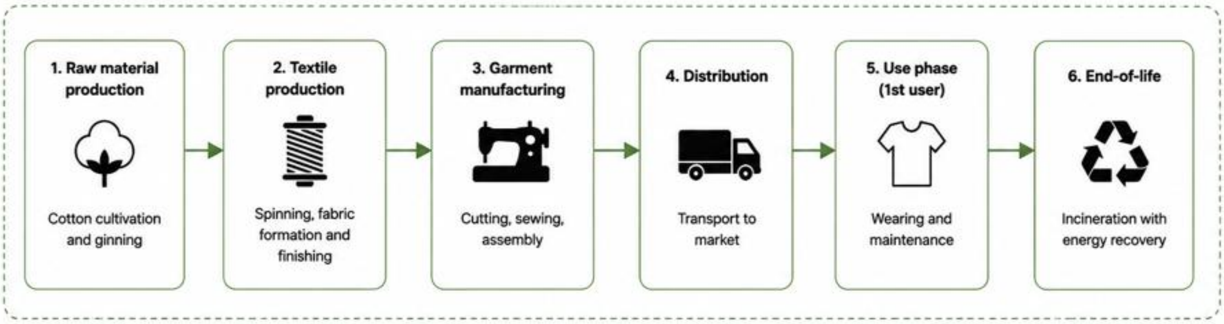

Fig. 6. Baseline LCA model

The integrated LCA model included a baseline model and garment swapping via a digital platform as a part of use phase (see Fig. 7). The swapping was supported by digital platform operations, which included three main components:

- User device energy consumption.
- Data transmission.
- Backend operations.

User device energy accounted for the electrical energy used by smartphones or laptops during platform interactions. Data transfer accounted for the electricity required to transmit data between user devices and the platform via internet infrastructure, such as Wi-Fi and mobile cellular networks. An average electricity intensity value (kWh/GB) from the literature was applied to represent overall network energy consumption. Additionally, backend processes included cloud hosting, data storage, and general platform operation.

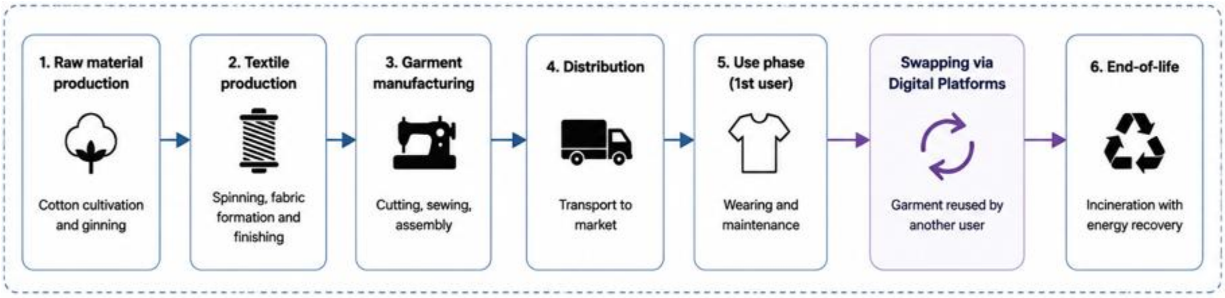

Fig. 7. Integrated LCA model

2.4. Digital Platform Mapping Procedure

Platform mapping was conducted in order to identify platforms which support resuse strategy. The geographical scope was focused on the countries in the Baltic Sea region, including Baltic and Scandinavian countries. In addition, some widely used European platforms operating in the region were also considered. Based on the identified criteria, the strengths and weaknesses of five platforms were analysed (see Table 4). Giver Tag was used as the reference platform to perform the digital platform mapping. This platform was selected, because it demonstrates the design and functionality of a clothing swapping application and provides real user activiy, meanwhile it was appropriate to modelling.

The mapping process has been implemented by integrating platform functionality with recorded user activity information. The process of actions that lead to a successful garment exchange was rebuilt using quantifiable indicators, including the duration of the session, the number of sessions, traffic of data, and user interactions. User interaction intensity was estimated based on session duration, number of sessions, and energy intensity. Backend system operations were analysed in the platform operation. The platform operates on a cloud-based virtual private server (VPS) infrastructure located in Lithuania. The server runs continuously and supports all user interactions, including data storage, request processing, and platform functionality. The average server utilisation rate was relatively low, estimated at around 8%, reflecting the scale of the platform. Annual electricity consumption of the server was approximated at 263 kWh, based on typical power usage server specifications.

The mapping process provided a link between user behaviour and the technical operation of the platform. Mapping made it possible to collect and aggregate data such as session time, data traffic, and server energy consumption, which were then used as inputs for the digital energy calculation.

2.4.1. ICT Energy Consumption Modelling

The estimation of ICT-related energy consumption was structured into three main components:

- user device energy
- data transmission energy
- backend energy

These elements represent the main sources through which digital activity was converted to electricity use. The total ICT-related energy was calculated as follows:

$$E_{ICT} = E_{device} + E_{network} + E_{backend} \tag{1}$$

Where;

- E_{ICT} - related energy consumption per functional unit (kWh)
- E_{device} – energy consumption of user devices (kWh)
- $E_{network}$ – energy consumption for data transmission (kWh)
- $E_{backend}$ – energy consumption of backend/cloud infrastructure (kWh)

Key platform activity parameters used for mapping and modelling of Integrated LCA model.

Table 1. Activity parameters

Parameter	Value
Average session duration	6 min 17 s
Average sessions per successful transfer	2.84
Data traffic per transfer	0.0887 GB
Total annual server electricity consumption (platform level)	263 kWh/year
Successful exchanged items in 2024	117

Parameters were determined according to provided data by GiverTag (see Table 1) The table includes platform-level operational data and transfer-level activity parameters that were later used to calculate ICT-related energy consumption per successful garment transfer.

2.4.2. User Device Energy

The energy of user devices consisted of all interactions that are performed on smartphones during the swapping process. This included photo taking and uploading of photos. It also involved activities of screen-on time, messaging that involves repetitive activation of devices. The initial calculation focused on the smartphone scenario, as it represented the reference for the Integrated LCA model.

The total duration of user interaction per functional unit was calculated using session-based data obtained from GiverTAG. First, the average session duration was converted into minutes with formula (2):

$$T_{session} = M + \frac{S}{60} \tag{2}$$

Where;

- $T_{session}$ – average session duration (minutes)
- M – minutes
- S – seconds

Then the total interaction time per successful exchange was calculated according to formula (3):

$$T_{exchange} = T_{session} \times N_{sessions} \tag{3}$$

Where:

- $N_{sessions}$ –average number of sessions per successful exchange.

Then, to calculate electricity demand, interaction time was converted into hours by dividing the total interaction time I minutes by 60 as indicated in formula (4):

$$T_h = \frac{T_{exchange}}{60} \tag{4}$$

User-device electricity demand was then estimated as:

$$E_{device} = P_{device} \times T_h \tag{5}$$

Where:

- E_{device}– user-device electricity demand (Wh)
- P_{device}– average device power demand (W)
- T_h– interaction time in hours

The energy consumption of the user device (smartphone) was then calculated by multiplying the total interaction time (in hours) by the assumed device power (2.5 W). Additionally, a laptop power demand of 30 W was assumed for the calculation of the laptop device scenario. The result was converted from watt-hours to kilowatt-hours to maintain consistency with the Integrated LCA model inputs.

All user-side activities, such as browsing, messaging, and interaction with others, were considered as total active usage time, instead of being modelled separately. This allowed the calculation to be consistent with the available platform data without having to make unnecessary assumptions about individual actions.

2.4.3. Data Transmission Energy

Data transmission energy was estimated based on the total data traffic with garment exchange activity on the platform. Instead of modelling individual activities separately, the calculation relied on aggregated platform-level data provided by GiverTAG.

The average data traffic per successful transfer was identified as 0.0887 GB. This value was derived from total platform data usage and the number of successful exchanges, to convert data traffic into electricity consumption, an average network electricity intensity factor of 0.06 kWh per GB was applied. This value was selected based on literature estimates for average internet data transmission energy intensity [4].

The energy consumption for data transmission was calculated as formula 6:

$$E_{network} = D_{transfer} \times EI_{network} \qquad (6)$$

Where;

- $D_{transfer}$– data volume per successful transfer (GB)
- $EI_{network}$– electricity intensity of data transmission (kWh/GB)

By applying this approach, network-related electricity demand was calculated directly from measured platform data and with a single conversion factor, ensuring consistency with the overall modelling framework. The specific detailed information was not available in the platform dataset regarding the difference between access technologies. Therefore, an average value was used to represent overall network energy demand per transfer during smartphone usage.

2.4.4. Backend / Cloud Energy

Backend energy consumption included computing, storage, and content delivery processes required to operate the platform.

The calculation formula followed 7:

$$E_{backend} = R \times E_{request} + S \times E_{store} + C \times E_{CDN} \qquad (7)$$

Where;

- R – number of server requests Application Programming Interface (API) calls, database queries
- S – storage demand over time (GBh)
- C – data transferred via content delivery networks (GB)
- $E_{request}$– energy per reques (Wh/request)
- E_{store} – energy per storage unit (Wh/GBh)
- E_{CDN} – energy intensity of content delivery (Wh/GB)

However, platform-specific data required to quantify these parameters, such as the number of API calls, database queries, storage usage, and Content Delivery Network (CDN) traffic, were not available for the selected case study. Due to the lack of specific information about each backend process, the total annual electricity usage of the servers was divided by the total number of successful garment exchanges recorded in 2024 in order to estimate backend electricity consumption per successful exchange, thus, simplified operational approach was adopted This method of allocation assumed that overall server electricity demand was equally shared among successful exchanges.

This is described as formula 8:

$$E_{backend} = \frac{E_{server_{annual}}}{E_{exchange_{annual}}} \tag{8}$$

Where;

- $E_{server_{annual}}$ – total electricity consumption of the platform server over one year,
- $E_{exchange_{annual}}$ – total number of successfully exchanged garment during the same period.

These values were used to estimate backend electricity demand associated with one garment exchange.

2.5.Baseline LCA Model Construction and Integrated LCA Model

The life cycle assessment of baseline model of a cotton T-shirt was developed in OpenLCA. The model was structured manually.

2.5.1. Baseline LCA Model

The baseline model included cotton production, yarn and fabric processing, dyeing and finishing, cutting and sewing, distribution, use phase, and end-of-life processes. This structure followed the general apparel life-cycle logic defined in the Product Environmental Footprint Category Rules (PEFCR) for apperal and footwear.

The stages were modelled seperately in OpenLCA, with inputs and outputs specified based on the literature and existing databases. In cases where direct data were not available, proxy datasets were used. Internal consistency and mass balance were modified in the model.

The inventory included key flows such as electricity, heat, water, chemicals, and waste outputs associated with each life cycle stage. Tranport was inluded in distibution stage from fabric to shop.

The transport demand is calculated based on the garment mass as shown in formula 9:

$$Transport = mass \times distance \tag{9}$$

The detailed LCI used for the baseline model was provided in Appendix 1. Following to the use phase, incineration method was chosen for disposed t-shirt as a last stage.

2.5.2. LCA model Integrated ICT Energy Burdens

The ICT-related energy consumption was converted using the European electricity grid mix based on smartphone usage. These impacts were then integrated into the LCA model as an additional process linked to the swapping scenarios.

The total digital electricity demand per exchange was used as input, which was derived from the user device, data transmission, and backend components. This energy demand was added into OpenLCA as an additional electricity-related process connected to garment exchange activity. The ICT energy values used in the model were based on the inventory and calculation procedure provided in Appendix 2. The integrated system model combines the baseline cotton T-shirt life cycle with the digital platform operation per exchange (see Fig. 3).

This integration ensured that digital platform activity was directly included in the environmental assessment and could be compared with physical life cycle impacts. Comparison provided increase rate with calculation of formula 10 between models.

$$Increase(\%) = \frac{I_{integrated} - I\_baseline}{I\_baseline} \times 100 \tag{10}$$

Where;

- $I_{integrated}$ -impact result of the integrated LCA model,
- $I_{baseline}$ - impact result of the baseline LCA model.

2.5.3. Impact Assessment

The environmental impacts were calculated in OpenLCA with the ReCiPe 2016 Midpoint (H) impact assessment method. A number of impact categories were chosen, namely;

- climate change;
- fossil resource scarcity;
- land use;
- water use.

The impacts of climate change were estimated in kg CO_2 equivalent; the scarcity of fossil resources in kg oil equivalent; land use in m^2a crop equivalent; and water use in m^3. During the assessment, the standard characterisation factors and the normalisation factor were applied according to the ReCiPe 2016 Midpoint (H) method. The normalised results were used to compare the relative importance of the various impact categories for the different analysed scenarios.

2.6.Scenario Development

Several scenarios were developed to evaluate how different ICT-related assumptions influence the environmental performance of the integrated garment reuse system see Table 2. The scenarios were implemented in OpenLCA by modifying selected digital electricity inventory inputs while maintaining the same baseline garment life cycle structure.

The scenario modelling focused on three main aspects:

- electricity source;
- user device type;
- platform usage intensity.

Electricity source scenarios were created by changing the electricity sources connected to ICT-related electricity consumption during smartphone usage. The specific sources indicated in Table 2. The renewable electricity scenario was modelled using photovoltaic (PV) solar electricity as the representative renewable energy source in the integrated LCA model.

Device-type scenarios compared the smartphone and laptop electricity demand during platform interaction. In these scenarios, user-device electricity demand changed depending on the selected device type, while backend and network electricity demand remained unchanged. The purpose of the comparison was to evaluate whether the type of user device significantly influences the overall environmental profile of the integrated exchange model.

Usage-intensity scenarios represented different levels of platform activity by varying user utilisation level. The base-case utilisation scenario was based on the total number of successful garment exchanges recorded by GiverTAG. The low utilisation scenario estimated two times lower platform activity compared to the base- case scenario, while the high utilisation scenario calculated two times higher platform activity. In these scenarios, backend electricity changed according to interaction intensity, while user-device and network electricity demand remained constant.

Table 2. Scenarios used in the integrated LCA model

Scenario category	Scenario	Modified parameter	Description
Electricity source	EU electricity mix	Electricity grid mix	Base case electricity scenario
	Lithuania electricity mix	Electricity grid mix	National electricity profile
	Renewable electricity	Electricity grid mix	Renewable-based electricity supply
Device type	Smartphone	User-device electricity	Baseline user-device scenario
	Laptop	User-device electricity	Higher device electricity demand
Usage intensity	Low usage	Interaction time + data traffic	Lower platform activity
	Base case	Interaction time + data traffic	Average platform activity

	High usage	Interaction time + data traffic	Higher platform activity

2.7.Modelling Lifespan Extension and Substitution

An extra service period, represented by ΔL, was defined to show the lifespan extension. ΔL represented the extra period during which the garment continued to be used by a secondary user beyond the reference service life. The environmental benefit of reuse was compared to a reference system representing the full life cycle of cotton t-shirt. In this context, extending the life of existing clothing reduced the need for additional production, thereby avoiding some of the environmental burden associated with producing a new product.

(σ) Was applied as substitution factor; this factor indicated the extent to which the long-term use of a garment replaced the purchase of a new garment. A value of σ = 1 indicated complete substitution, i.e., a reused garment completely replaced the need for a new garment.In this research, σ was not treated as a fixed value but was defined as a range between 0.3 and 1.0 based on literature and typical assumptions in reuse studies [15].

The avoided impacts were estimated in formula 11:

$$I_{avoided} = \sigma \times \frac{\Delta L}{L_{ref}} \times I_{new} \tag{11}$$

Where;

- σ – substitution factor
- ΔL – additional lifespan of the garment due to reuse (months)
- L_{ref}– reference lifespan of the garment in the baseline scenario (months)
- I_{new}– climate change impact of baseline LCA model

This approach allowed avoided impacts to increase proportionally with longer additional use periods while still accounting for partial substitution behaviour. In the scenario analysis, ΔL values of +3, +6, and +12 months were tested, while σ was varied between 0.3 and 1.0 range. 0.3 was chosen as low rate while, 0.5 was considered as moderated and 1.0 was estimated as full cycle substation rate. Extending the use phase of the garment beyond its initial baseline lifetime were further explored through sensitivity analysis.

2.7.1. Net Environmental Impact Calculation

Environmental performance of the swapping system was evaluated using net environmental impact calculations. Net impacts were calculated by subtracting avoided-production benefits from the integrated system impacts as equation (12):

$$I_{net} = I_{integrated} - I_{avoided} \tag{12}$$

Where;

- I_{net} - net environmental impact;
- $I_{integrated}$- environmental impact of the integrated LCA model;

- $I_{avoided}$- = avoided environmental impact associated with reduced production of new garments due to reuse and lifespan extension.

This approach allowed the evaluation of whether the environmental benefits generated through garment lifespan extension was sufficient to offset the additional ICT-related burden which came from integrated LCA model. The results showed how substitution rate effected on net impact performance.

2.8. Sensitivity Analysis

A sensitivity analysis was carried out to evaluate how changes in selected modelling scenarios influence the environmental results of the integrated LCA model. The analysis focused on parameters that were considered uncertain to have a strong influence on avoided environmental impacts, net impact and ICT-related electricity demand. Each parameter was changed separately in order to demonstrate different outcomes. This made it possible to see which factors had the strongest effect on the results.

Table 3. The tested parameters are presented

Parameter	Tested values	Purpose
Lifespan extension (ΔL)	+3, +6, +12 months	To examine how additional garment use duration influences avoided impacts
Substitution factor (σ)	0.3 – 1.0	To represent different levels of replacement rate
Electricity source	EU average, Lithuania, Renewable	To examine how different electricity mixes influence on integrated model associated with digital platfroms acivity
Userge intensity	Different platform utilization levels	To evaluate the influence of server electricity allocation per garment exchange

The sensitivity analysis was later used to support the interpretation of the results and identify the assumptions that have the biggest impact on the environmental performance of the overall integrated model.

2.8.1. Break-even Analysis

In addition to general sensitivity analysis, a break-even analysis was performed to determine the minimum lifespan extension required for the system to remain environmentally beneficial.The break-even condition can be expressed conceptually as formula 13.

$$\Delta\ \mathrm{L}_{\mathrm{BE}} = \underset{fg}{\mathrm{I}_{\mathrm{ICT}_{\mathrm{burden}}}} \times \frac{L_{ref}}{\sigma} \times I_{new} \qquad (13)$$

Where;

- $\Delta\ \mathrm{L}_{\mathrm{BE}}$- break-even additional lifespan;

- $\mathrm{I}_{\mathrm{ICT}_{\mathrm{burden}}}$ - additional impact caused by digital platform operation;
- L_{ref} - reference garment lifespan, 12 months;
- σ - substitution factor;
- I_{new}-baseline impact of one new cotton T-shirt.

The analysis was conducted for different substitution scenarios to evaluate how user behaviour influences the environmental feasibility of garment swapping. This helped identify the conditions under which digital swapping is sustainable. Break –even analysis porpuse was to identify how many additional months of garment use are needed before the avoided production benefit becomes equal to the additional ICT-related burden.

2.9. Interpretation Approach

The interpretation focused on comparing the environmental benefits of extended garment use with the impacts associated with digital platform energy consumption. The relationship between avoided production and additional energy use was analysed. Hotspots were identified by examining which components contributed most significantly to total energy consumption. This included comparing user devices, data transmission, and backend systems. The results were also interpreted in terms of practical implications, particularly regarding platform design and user behaviour, highlighting potential areas for improving environmental performance.

3. Results and Discussion

3.1. Platform mapping in Baltic Sea Region

Several digital platforms are analysed according to their reuse strategy and operation model. The geographical scope focuses mainly on platforms operating in the Baltic Sea region, including Lithuania, Latvia, and the Nordic countries. In total, five platforms are identified and compared in terms of their circular exchange model, monetary mediation, potential substitution effect, and user participation. The strengths and weaknesses of each platform are evaluated to understand how they operate and how their design may influence clothing reuse and textile lifespan extension.

Table 4. Platform mapping

Platform	Country scope	Type	Exchange model	Strengths	Limitations
Vinted	Lithuania/ Europe	Resale	Sell–buy (indirect exchange)	Large user base and easier matching between sellers and buyers	May increase consumption instead of replacing new purchases
Textale	Lithuania	Hybrid	Credit-based exchange	Flexible system without direct matching	The substitution effect is indirect
Tise	Nordic/ Europe	Resale	Regional exchange	Expands access to second-hand markets	Cross-border transport may increase environmental impacts
Sellpy	Sweden/ Europe	Managed resale	Platform-managed logistics	Simplifies reuse and reduces user effort	Users have limited control over redistribution outcomes
GiverTag	Lithuania	Swapping	Non-monetary exchange	Supports free reuse and accessibility	Operates at smaller scale

Table 4 provides insight into how different platform designs support clothing reuse. The comparison shows that resale platforms may have a more uncertain environmental effect because they can encourage additional consumption rather than directly replacing new purchases. As a result, the substitution effect depends strongly on user behaviour and may not always lead to a reduction in textile production. However, swapping platforms based on non-monetary exchange may be more closely connected to direct reuse strategies because these platforms focus on free garment exchange without financial transactions, which creates a stronger connection to reuse-oriented consumption behaviour rather than commercial resale activity such as GiverTag. Thus, GiverTag is selected as the reference platform for the present study because its operational structure is suitable for modelling direct clothing exchange and reuse. The platform also provides operational information related to user interaction, exchange activity, and server utilisation, which is necessary for the ICT energy modelling stage of the research. Furthermore, its relatively simple exchange structure allows clearer identification of digital activities associated with one successful garment transfer.

3.2.Digital Platform Energy Demand

The digital platform energy demand was calculated to estimate the electricity required to support one successful clothing exchange through the GiverTag platform.

3.2.1. Platform activity data used for energy modelling

The digital energy model was developed using operational data provided by the GiverTag platform. Several platform activity indicators were required to estimate the electricity demand associated with one successful exchange. These included average session duration, average number of sessions per exchange, total data traffic, and annual backend electricity consumption (see Table 1). These operational parameters formed the basis for the calculation of user-device, network, and backend electricity demand.

3.2.2. User device electricity demand

The first component of the digital electricity demand represents the electricity consumed by the user device during interaction with the platform. In the base-case scenario of the Integrated LCA model, users were assumed to access the platform via a smartphone with an average active power demand of 2.5 W and the EU electricity mix grid as the energy provider. This value represents active device use, such as browsing listings, messaging, viewing photos, and interacting with the application interface.

First, the average session duration was converted into minutes according to formula 2:

$$T_{sessions} = \frac{6+17}{60} = 6{,}28\ min \tag{14}$$

The total exchange interaction time was calculated per successful exchange according to formula 3:

$$T_{exchange} = 6.28\ \times 2.84 = 17{,}84\ min \tag{15}$$

To calculate electricity demand, the exchange interaction time was converted into hours according to formula 4:

$$T_h = \frac{17.84}{60} = 0.297\ h \tag{16}$$

The total user-device electricity demand of the smartphone was calculated using formula 5 and then converted to kWh:

$$E_{device} = 2.5\ \times 0.297 = 0.743\ \mathrm{Wh} = 0.00074\ \mathrm{kWh/exchange} \tag{17}$$

The result shows that the electricity demand associated with active smartphone use remained very small due to the short interaction time required for one successful exchange.

3.2.3. Network electricity demand

The second component of the digital system represents the electricity required for internet data transmission between users and the platform infrastructure. The average data traffic associated with one successful transfer was 0.0887 GB as indicated in Table 1.

A literature-based electricity intensity value of 0.06 kWh/GB was applied for internet data transmission. Network electricity demand was calculated using formula 6:

$$E_{network} = 0.0887 \times 0.06 = 0.00532 \text{ kWh/exchange} \qquad (18)$$

The calculation shows that network electricity demand is larger than the user-device electricity demand but remained relatively small compared with backend electricity consumption.

3.2.4. Backend electricity demand

Backend electricity represents the electricity consumed by the server infrastructure supporting platform operation. Formula (7) was not involved in the backend calculation process, because detailed server activity data such as API requests, database queries, storage activity, and CDN traffic were not available.

The backend electricity demand was estimated based on the server's annual energy and the number of successfully exchanged garments in 2024, as detailed in Table 2. Calculation was carried out by using formula 6:

$$E_{backend} = \frac{263}{117} = 2.25 \text{ kWh/exchange} \qquad (19)$$

The result indicates that backend electricity demand was substantially larger than both user-device and network electricity demand. This occurred because the continuously operating server infrastructure was allocated across a relatively limited number of successful exchanges.

3.2.5. Total digital electricity demand

The total digital electricity demand was calculated by combining user-device, network, and backend electricity demands using formula 1. The calculation represents the total digital energy required for one successful garment exchange on the selected platform.

$$E_{digital} = 0.00074 + 0.00532 + 2.25 = 2.256 \text{ kWh/exchange} \qquad (20)$$

The results show that the backend electricity consumption accounts for the largest share of the total digital electricity demand, while the user device and network electricity contributed relatively little (see Table 5). This suggests that the continuously running server infrastructure and platform maintenance activities have a greater impact on the total digital energy demand than individual user interactions such as browsing, messaging or image uploads.

Table 5. Digital electricity demand per exchange

Component	Electricity demand	Unit
User device	0.00074	kWh/exchange
Network transmission	0.00532	kWh/exchange
Backend server operation	2.25	kWh/exchange
Total	2.256	kWh/exchange

The calculated total electricity demand was then integrated into an LCA model in OpenLCA to assess the environmental impacts associated with the operation of the digital platform in conjunction with the clothing reuse system. The integrated model allowed us to assess how extending the life of the clothing by replacing the ICT-related electricity demand with the overall environmental performance.

3.3.Life Cycle Assessment of Models

3.3.1. Structure of Baseline LCA Model of Cotton T-shirt

The baseline LCA model represents the environmental profile of a reference 100% cotton T-shirt prior to the integration of ICT-related energy burdens associated with clothing swapping. The purpose of this baseline is twofold. First, it provides the conventional life-cycle profile of the garment under standard conditions. Second, it establishes the reference system for the later calculation of environmental impacts of prolonged garments via digital swapping due to additional digital-platform electricity consumption. In this sense, the baseline model is not the final analytical endpoint of the thesis, but the necessary benchmark against which the environmental significance of swapping was evaluated.

The garment is modelled as a single item with a mass of 0.12 kg. This value is supported by literature and reflects a realistic estimate for a basic cotton T-shirt [30]. The mass is used consistently throughout the model to define material flows, transport demand, and waste outputs.

The system utilises Ecoinvent 3.11 as its background database within OpenLCA. The boundary of the system includes six stages:

(i) knitted cotton fabric input from the database,
(ii) dyeing and finishing of knitted cotton fabric,
(iii) cutting, sewing and garment finishing,
(iv) distribution to retail,
(v) consumer use,
(vi) end-of-life treatment.

Background datasets from Ecoinvent are used for knitted cotton fabric, electricity, industrial heat, road transport, tap water, wastewater treatment, and selected proxy chemicals. Foreground processes are manually created for dyeing and finishing, garment collection, distribution, consumer use, and end-of-life. The inventory table (Appendix 1) defines all input and output flows per single cotton t-shirt.

Production stage

The modelling begins at the dyeing stage because knitted cotton fabric is already available as a background dataset. Later, the dyeing and finishing process includes inputs:

- electricity (0.129 kWh),
- industrial heat (8.6 MJ),
- tap water (22.3 kg),
- reactive dyes (0.006 kg),
- textile auxiliaries (0.162 kg).

The outputs include dyed fabric (0.1364 kg), wastewater (0.0101 m^3), and processing waste (0.0043 kg) as shown in the inventory table (Appendix 1). These flows represent the main resource textile wet processing. This reqires large amounts of water and energy and involves chemical use, contributing to wastewater impacts. Both earlier studies and recent reviews confirm the importance of the wet processing stage in the LCAs of cotton T-shirts [8,42].

The amount of knitted cotton fabric entering the dyeing process was calculated using a mass-balance approach based on reported production losses from the literature. Montoya Flores and Salhofer (2025) reported approximately 1% material loss during fabric manufacturing, 0.05% during wet processing, and around 3% during finishing.

Starting from the final garment mass of 0.12 kg, the required fabric amount for garment assembly was first determined by adding the cutting waste (0.0164 kg), yielding 0.1364 kg of finished dyed fabric. This value represents the output of the dyeing and finishing stage.

The input to the dyeing stage was then calculated by adjusting for wet processing and finishing losses, resulting in 0.1407 kg of knitted cotton fabric. This approach ensures that material flows remain same across stages and that all losses are explicitly accounted for in the model.

The second process is cutting, sewing, and finishing. This stage converts dyed fabric into the final T-shirt. According to the inventory table, this process uses 1.18 kWh of electricity and 0.003 kg of cotton yarn as a proxy for sewing thread. The outputs included one finished T-shirt (0.12 kg) and 0.0164 kg of cutting waste.

Distribution Stage

The distribution stage represents the transport of the finished garment from production to retail. In the model, this stage is simplified as road freight transport over a distance of 1000 km.

The PEFCR notes that the distribution stage is generally less important than the main production and use stages for apparel, but it remains part of the standard life-cycle structure and should not be omitted without justification [5]. The present baseline therefore includes a screening transport step rather than a detailed logistics model. The transport demand is calculated based on the garment mass which is equal tyo 0.12 tonne-kilometres (see formula 9).

Use Phase

The use phase is especially important for this study because the central research question concerns the environmental results of extending garment life.

Care conditions for T-shirts, including 40°C washing for both “all materials” and “cotton and blends”, as well as default assumptions for the share of garments that are ironed or steamed and the average time spent per garment. For T-shirts, the PEFCR reports that 40% of garments are ironed or steamed per use and that the average time spent is 2.6 minutes [5]. Earlier T-shirt-specific PEFCR work also uses a standardised service life of 52 washes as the reference cleaning lifetime of a T-shirt.

In the present model, the use phase is represented through cumulative inventory flows over the modelled service life of one T-shirt;

- washing,
- tumble drying,
- ironing,

- tap-water consumption,
- detergent use
- wastewater generation

The use-phase process, therefore, includes low-voltage electricity for the mentioned flows above. After the use phase, the disposed garment is transferred to incineration with energy recovery as the end-of-life treatment stage.

3.3.2. Environmental Profile and Contribution Analysis of Baseline Model

This section presents the environmental profile of the baseline cotton T-shirt model before the inclusion of digital platform activities. The results represented the conventional life cycle of one cotton T-shirt, providing clothing functionality over a 12-month reference service life. The system includes raw material production, textile manufacturing, garment assembly, distribution, consumer use, and the end-of-life stage. The baseline system provides the reference environmental burden against which the integrated LCA model is evaluated. In addition, avoided production and potential environmental savings from garment lifespan extension were calculated based on the impact results of the baseline model.

Baseline characterisation results

The analysis results showed that the environmental impacts of climate change, water consumption, fossil resource scarcity, and land use (see Table 6.)

Table 6. Baseline environmental impacts of cotton t-shirt

Impact category	Result	Unit
Climate change	4.91	kg CO_2 eq
Water consumption	0.816	m^3
Fossil resource scarcity	1.39	kg oil eq
Land use	1.17	m^2a crop eq

Contribution analysis (see Fig. 8) explaines that textile production-related processes, such as cotton cultivation, manufacturing processes, and electricity usage throughout the life cycle of the t-shirt, strongly influenced the selected impact category results. As seen on the Table 6 climate change impact of the baseline garment reaches 4.91 kg CO_2 eq, indicating the importance of electricity use, industrial heat demand, and upstream textile production processes. Fossil resource scarcity results also reflect the dependence of textile manufacturing and transportation activities on energy-intensive systems and fossil-based resources. Water consumption is mainly generated from cotton cultivation and textile wet processing. Similarly, land use impacts are strongly connected to agricultural land occupation related to cotton production.

Additionally, Fig. 8. indicates the reasons of contiributors, thus the largest contribution to climate-change impacts comes from knitted cotton fabric production, dyeing, and finishing processes. Dyeing and finishing alone represent a particularly important hotspot because of its combined use of heat, electricity, water, and chemical auxiliaries. Garment assembly processes, including cutting, sewing, and finishing, also contribute noticeably to total impacts through electricity consumption and material losses during production. Distribution impacts remaine comparatively small within the baseline system due to the relatively low transport demand associated with a single t-shirt. The use phase contributes additionally through household electricity consumption for washing, drying, and ironing, as well as detergent use and wastewater generation. Among these processes, ironing and laundering electricity represent the largest use-phase contributions in energy-related categories. The contribution analysis also showes small negative contributions associated with end-of-life incineration processes. This occurres because energy recovery from municipal waste incineration partially offset some environmental burdens within the system.

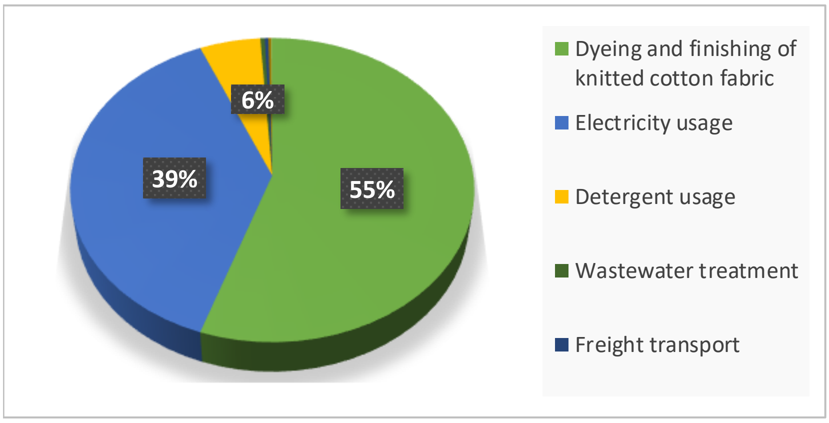

Fig. 8. Contribution analysis and environmental

The normalised results in Fig. 9. provide additional information on the relative environmental importance of the selected impact categories. While the average results provide absolute ecological burdens, normalisation allows comparisons between categories by relating results to global reference impacts.

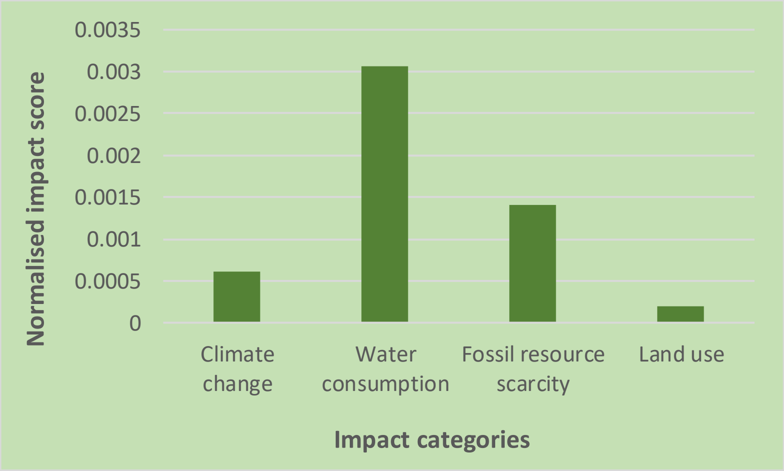

Fig. 9. Normalised environmental impacts of the baseline model

The normalised analysis showes that water consumption represented the most environmentally significant category in the baseline model, followed by scarcity of residual resources. This reflects the high water and energy use during textile wet processing, in addition to the intensive irrigation requirements of cotton cultivation. Climate change impacts remaine ecologically significant, but after normalisation, showes a lower relative importance compared to water consumption impacts. Land use shows the lowest normalised significance among the selected categories, despite the agricultural usage of cotton production. It is obvious that water and energy-related impacts have more pressure than land occupation on the environment within the analysed baseline model.

3.3.3. Life Cycle Assessment of Integrated LCA Model

The Integrated LCA model combines by basline model plus additional energy consumption. including user-device electricity, network transmission, and backend server operation caused by swapping of cotton t-shirt with digital platforms. Baseline model remains the same with its inputs and outputs, then the electricity amount is added as an input to the system as Total digital electricity demand (see Table 5). Integration evaluates the additional environmental burden of digital platform operation relative to the overall garment life cycle.

3.3.4. Comparison of Baseline Model and Integrated Model

The comparison results in Table 7. show that environmental impacts across all analysed categories increased due to digital platform operation in the integrated model.

Table 7. Comparison of impact categories

Impact category	Baseline model	Integrated model	Unit
Climate change	4.91	5.68	kg CO_2 eq
Fossil resource scarcity	1.39	1.59	kg oil eq
Water consumption	0.816	0.827	m^3
Land use	1.17	1.19	m^2a crop eq

The integrated system produces higher climate change and fossil resource scarcity impacts compared with the baseline garment scenario. Climate change impacts increase from 4.91 kg CO_2 eq to 5.68 kg CO_2 eq after including digital platform operation. A similar increase is observed for fossil resource scarcity, water consumption and land use as described in Table 7. The findings indicate that textile production processes continue to be the primary contributors to overall environmental impacts, although ICT electricity demand increases climate change and fossil resource scarcity impacts. These changes are indicated in Fig. 10. which shows a relative increase caused by digital platforms. The relative increase was calculated using Formula 10.

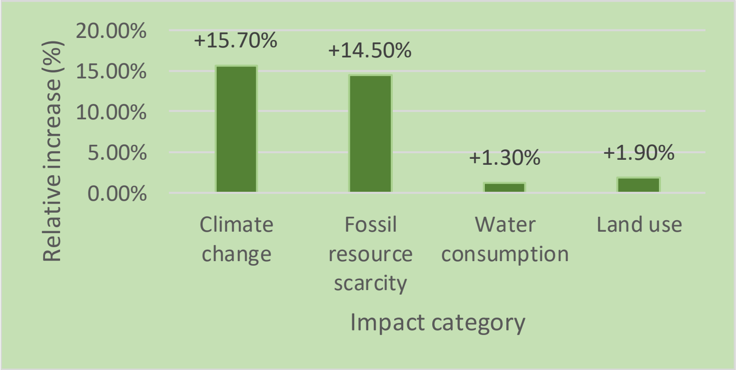

Fig. 10. Relative increase in environmental impacts due to digital platform operation

Climate change impacts increases by approximately 15.7% after integrating digital platform operation into the garment system. Fossil resource scarcity increases by approximately 14.5%, reflecting the importance of electricity production and backend server operation within the digital platform model. By comparison, water consumption increases by only 1.3%, while land use increased by 1.9%. These smaller increases explain that the contribution of electricity from digital platforms to total water and land-related impacts remain limited compared with the agricultural and textile production stages of the garment system. The results suggest that the environmental impacts associated with digital platform operation are generated from mainly energy-related categories rather than dominant categories such as cotton cultivation and textile processing.

Furthermore, OpenLCA contribution analysis (Table 8) confirms that backend electricity dominates the environmental profile of the digital platform system. Backend operation accounts for approximately 99.73% of the total digital electricity demand, while network transmission contributes approximately 0.24% and user-device electricity only 0.03%.

Table 8. Contribution Analysis of components

Component	Contribution
User device	0.03%
Network transmission	0.24%
Backend server operation	99.73%
Total	100%

3.4. Scenario development

3.4.1. Scenario Analysis of Digital Platform Energy Use

This section analyses how different electricity supply assumptions influence the environmental impacts of the integrated model of the cotton t-shirt. Energy providers for the total electricity demand of digital platforms are changed in software in order to observe the different impacts of electricity suppliers on the environmental impact.

Three electricity source scenarios were evaluated:

- EU electricity mix (base case scenario),
- Lithuania electricity mix,
- Renewable electricity scenario.

The characterisation results indicate that the renewable electricity scenario consistently produces the lowest impacts across most energy-related categories, while the Lithuania electricity mix scenario generated the highest impacts in several categories associated with electricity production (see Table 9).

Table 9. Characterisation impact comparison of electricity source scenarios

Impact category	EU electricity mix	Lithuania's electricity mix	Renewable electricity	Unit
Climate change	5.679	5.919	5.129	kg CO_2 eq
Fossil resource scarcity	1.591	1.689	1.443	kg oil eq
Land use	1.193	1.214	1.175	m^2a crop eq

Water consumption	0.827	0.824	0.824	m^3

Compared with the EU electricity mix scenario, renewable electricity reduces climate change impacts noticeably, while the Lithuanian electricity mix slightly increases total emissions. A similar pattern is observed for fossil resource scarcity. The renewable electricity scenario reduces dependence on fossil-based electricity production, resulting in lower fossil resource depletion impacts. In contrast, the Lithuanian electricity mix produces the highest fossil resource scarcity results among the analysed scenarios. This proves that the renewable electricity source reduced dependence on electricity sources associated with nuclear-based energy production. Water consumption and land use show comparatively less differences between scenarios. Because these categories remain dominant mainly by garment production processes, rather than by the electricity demand associated with digital platform operation. Generally.the characterisation comparison demonstrates that electricity generation assumptions influence the environmental profile of the integrated model, specially in categories directly associated with energy production and fossil fuel use.

3.4.2. Normalisation comparison of electricity scenarios

Normalisation analysis provides additional insight into the relative environmental significance of the electricity source scenarios in Table 2.

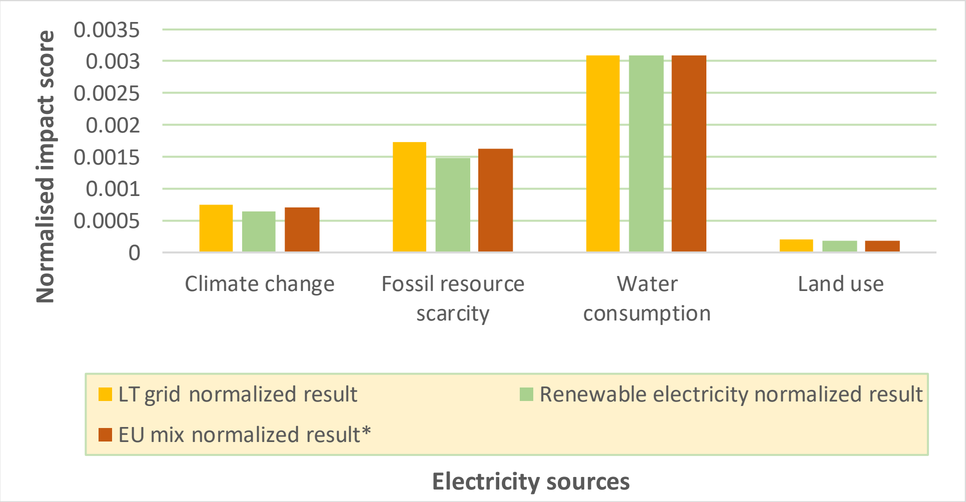

Fig. 11. Normalised results of electricity source scenarios

The normalised results (Fig.11) show that the Lithuanian grid scenario has a slightly higher impact on climate change and fossil resource scarcity than the renewable electricity scenario. This is due to the fact that the Lithuanian electricity system is still partly dependent on fossil-based electricity generation and imported electricity with a relatively higher carbon intensity. In particular, natural gas and imported residual electricity lead to an increase in greenhouse gas emissions and fossil energy demand in the integrated LCA model, according to the Electricity Grid Review Lithuania (2025).

In contrast, the renewable electricity scenario has lower normalised impacts in energy-related categories, as solar photovoltaic electricity generation operates without direct fossil-fuel combustion during electricity production. Water consumption and land use remain relatively similar across all electricity scenarios, as these categories continue to be dominated by cotton cultivation and textile wet processing activities, rather than ICT electricity demand.

3.4.3. Device Type Scenarios

This section compares the environmental impacts of the integrated LCA mode with 2 type of devices are compared the environmental impacts Integrated LCA model.

Two user-device scenarios were analysed:
- smartphone scenario,
- laptop scenario.

In both scenarios, the same platform activity time, network data traffic, and backend electricity allocation are maintained. Only the user-device electricity demand is modified. The smartphone scenario requires approximately 0.00074 kWh of device electricity per exchange, while the laptop scenario requires approximately 0.00891 kWh, as calculated based on formula (5). Both scenarios' electricity source is the EU mix grid. However, both values remain very small compared with the backend electricity demand of 2.25 kWh per exchange.

3.4.4. Comparison of the Impacts of Smartphone and Laptop

Table 10. shows that only very small differences between the smartphone and laptop scenarios across all analysed impact categories. Although laptop electricity demand is higher than smartphone electricity demand, the overall environmental profile of the integrated system remains nearly unchanged.

Table 10. Characterisation comparison of smartphone and laptop scenarios

Impact category	**Smartphone scenario**	**Laptop scenario**	**Unit**
Climate change	5.679	5.682	kg CO_2 eq
Fossil resource scarcity	1.591	1.592	kg oil eq
Land use	1.193	1.194	m^2a crop eq
Water consumption	0.827	0.825	m^3

Climate change impacts increase slightly from 5.679 kg CO_2 eq in the smartphone scenario to 5.682 kg CO_2 eq in the laptop scenario, while fossil resource scarcity, land use, and water consumption results remain almost the same. These limited differences indicate that user-device electricity contributes only a very small share of the total environmental burden associated with the integrated model, because backend server electricity dominates the total digital electricity demand, which is the same for both devices. Normalisation results also confirm that the overall environmental profile of the integrated systems stays almost unchanged between the two scenarios (see Fig. 12). In summary, these findings suggest that the efficiency of platform infrastructure plays a more important role in determining environmental impacts than the choice of user device or interpretation of device contribution.

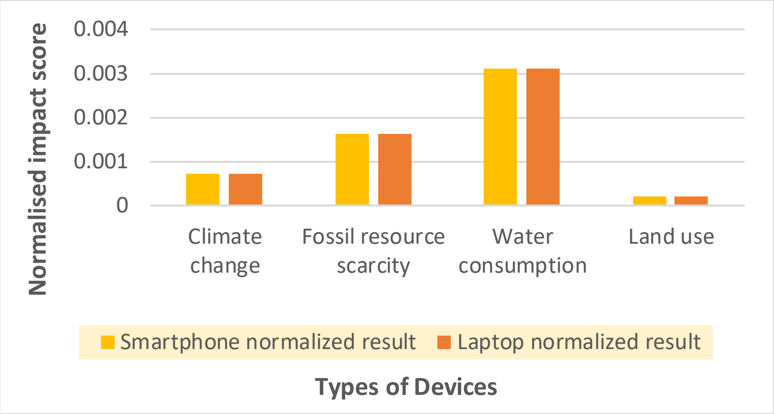

Fig. 12. Normalised results of devices

3.4.5. Platform Utilisation Scenarios

This section evaluates how platform utilisation influences the environmental performance of the integrated digital clothing exchange system. Since backend server operation represents the dominant contributor to total digital electricity demand, changes in the number of successful exchanges directly affect the amount of backend electricity allocated per exchange.

Three utilisation scenarios are analysed:

- low utilisation scenario,
- base utilistion scenario,
- high utilisation scenario.

The base utilisation scenario represents the integrated model with the EU electricity mix and smartphone usage. Base utilisation scenario means 117 successful transfers during the year. In the low-utilisation scenario, the number of successful exchanges is assumed to be 2 times lower than in the base case, while in the high-utilisation scenario, it is assumed to be 2 times higher. Backend energy consumption was calculated according to Formula 8 and Table 11. indicates results of calculation.

Table 11. Electricity inventory values used for platform utilization scenarios

Scenario	**User device electricity**	**Network electricity**	**Backend electricity**	**Total digital electricity**	**Unit**
Low utilisation	0.00074	0.00532	4.5	4.506	kWh/exchange
Base utilisation	0.00074	0.00532	2.25	2.256	kWh/exchange
High utilisation	0.00074	0.00532	1.12	1.126	kWh/exchange

Table 11. demonstrates that backend allocation is the most influential ICT parameter. In the low-utilisation scenario, total digital electricity increases to 4.506 kWh/exchange because fewer exchanges were assumed to share the continuously operating server burden. In the high-utilisation scenario, total digital electricity decreases to 1.126 kWh/exchange because the same infrastructure

burden is shared across more successful exchanges. This is an environmental economy-of-scale effect: the platform becomes more efficient per garment, not necessarily by consuming less annual electricity, but by producing more successful exchanges from the same infrastructure.

Table 12. Characterisation comparison of platform utilisation scenarios

Impact category	**Low-utilisation scenario**	**Base-utilisation scenario**	**High-utilisation scenario**	**Unit**
Climate change	6.447	5.918	5.296	kg CO_2 eq
Fossil resource scarcity	1.759	1.689	1.489	kg oil eq
Land use	1.218	1.214	1.181	m^2a crop eq
Water consumption	0.838	0.824	0.822	m^3

Characterisation results show clear differences between utilisation scenarios (see Table 12). The impacts of climate change increase significantly in the low-usage scenario, as the less successful exchanges share the backend server infrastructure that is continuously operating. In contrast, the high-usage scenario reduces climate-related impacts due to the lower distribution of backend electricity per clothing exchange. A similar trend is observed for the scarcity of fossil resources.

Land use and water consumption changed relatively less between scenarios, as these categories continue to be dominated by cotton cultivation and textile wet processing activities, rather than ICT electricity demand. The results show that platform usage has an impact on energy-related environmental categories, mainly related to backend electricity consumption.

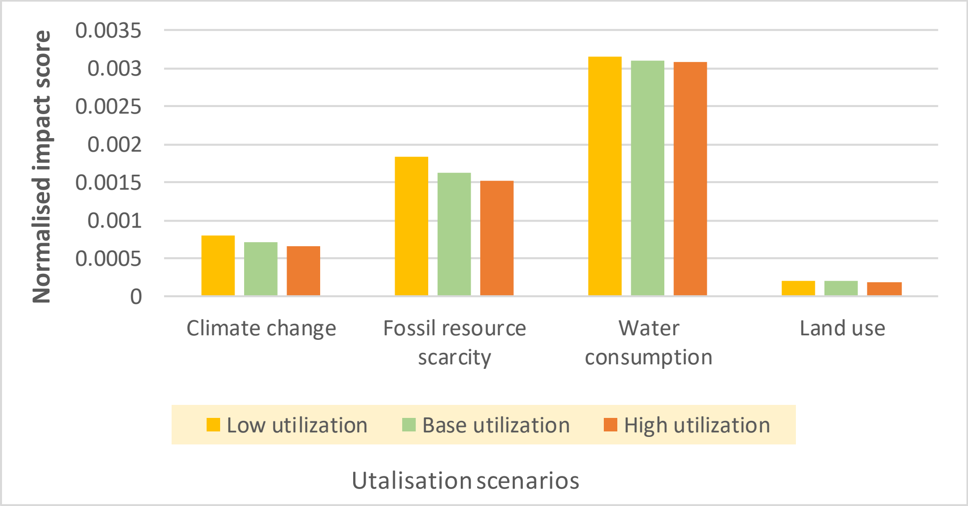

Fig. 13. Normalised environmental results for platform utilisation scenarios

Fig. 13. shows that the low-utilisation scenario generates the highest normalised impacts, while the high-utilisation scenario produces the lowest results across all selected categories. The largest variation is observed for climate change and fossil resource scarcity, indicating the strong influence of backend electricity allocation on energy-related impacts. In contrast, water consumption and land

use remain relatively stable because these categories continue to be dominated mainly by textile production processes.

The analysis of the usage scenario shows that platform efficiency plays a significant role in determining the environmental performance of digital clothing exchange systems. Low platform utilisation significantly increases the environmental burden per successful exchange, as the backend server infrastructure continues to operate regardless of exchange activity.

3.5.Avoided Production and Net Environmental Benefits

While the previous sections focused on the additional environmental burden introduced by digital platform operation, this section analyses whether reuse can offset these impacts by reducing the need for new garment production. The assessment is based on the assumption that extending the lifespan of a garment decreases the demand for new garment.

3.5.1. Avoided production impacts

The baseline lifespan of the cotton T-shirt is assumed to be 12 months. Three additional lifespan scenarios are analysed:

- 3-month lifespan extension,
- 6-month lifespan extension,
- 12-month lifespan extension.

The substitution factor represents the extent to which reuse replaces the purchase of a new garment. A value $\sigma=1$, which indicates full substitution, meaning that one reused garment completely replaces the production of one new garment. Lower substitution factors represent more conservative and realistic consumer behaviour assumptions, where reuse does not always directly prevent the purchase of a new item.

Three substitution scenarios were therefore evaluated:

- low substitution scenario $\sigma=0.3$,
- moderate substitution scenario $\sigma=0.5$,
- full substitution scenario $\sigma=1$.

The calculation was performed according to Formula 11 and by testing different substitution scenarios. Calculation results are shown in Table 13. The results support that the avoided impact results increase proportionally with both garment lifespan extension and substitution factor. Higher substitution factors and longer reuse periods generate larger avoided environmental impacts because more new garment production is displaced.

Table 13. Avoided production calculation of climate change impacts under different reuse assumptions

Additional lifespan	**σ =0.3**	**σ =0.5**	**σ =1.0**	**Unit**
3 months	0.37	0.61	1.23	kg CO_2 eq
6 months	0.74	1.23	2.46	kg CO_2 eq
12 months	1.47	2.46	4.91	kg CO_2 eq

Under the 3-month lifespan extension scenario, avoided impacts range from 0.37 kg CO_2 eq in the low-substitution scenario to 1.23 kg CO_2 eq under full substitution. For the 6-month extension scenario, avoided impacts increase further, reaching 2.46 kg CO_2 eq at full substitution.

The highest avoided impact is observed under the 12-month lifespan extension and full substitution scenario, where avoided production reached 4.91 kg CO_2 eq. This value is equivalent to the full climate change impact of the baseline garment because the model assumed complete replacement of fully one new produced cotton T-shirt.

So the results indicate that longer garment use periods together with stronger substitution behaviour generates larger environmental savings by reducing the need for new textile production.

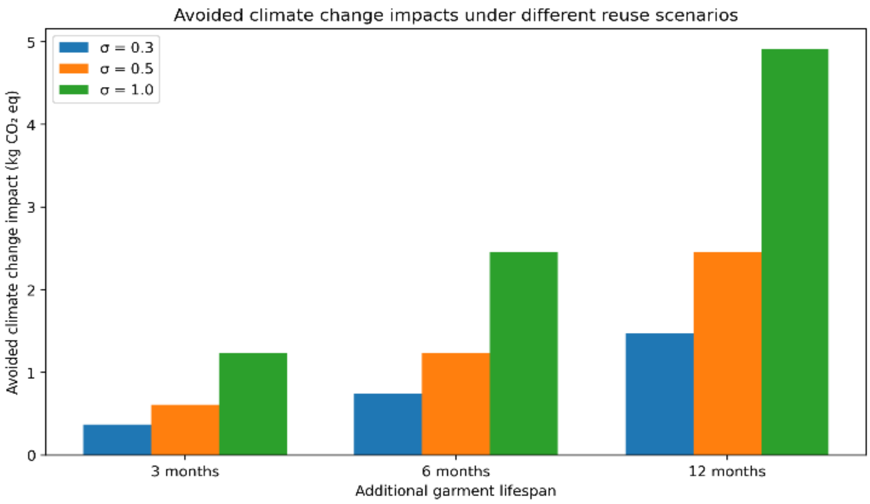

Fig. 14. Avoided climate change impacts under different reuse scenarios

Fig. 14. clearly illustrates how environmental benefits increase with both reuse periods and substitution behaviour.

3.5.2. Net Environmental Benefits

After calculating the avoided production impacts, the next step is to evaluate whether these environmental savings are large enough to offset the additional environmental burdens caused by digital platform operation. For this purpose, a net environmental impact assessment is carried out. The net environmental impact represents the final environmental balance of the swapping system after subtracting the avoided impacts associated with reduced new garment production.

The net impact results were calculated using the following equation 10 (see Table 14).

The final net environmental impact depends on whether the avoided production benefits are larger or smaller than this additional ICT-related burden. 1

Table 14. Net climate change impacts under different reuse scenarios (kg CO_2 eq)

Additional lifespan	**σ = 0.3**	**σ = 0.5**	**σ = 1.0**
+3 months	5.31	5.07	4.45
+6 months	4.94	4.45	3.22

+12 months	4.21	3.22	0.77

The findings show a clear relationship between garment lifespan extension, substitution behaviour, and overall environmental performance. Under short lifespan extension conditions (+3 months), the environmental benefits remained limited, particularly under low and moderate substitution scenarios. In these cases, the additional ICT-related burden associated with digital platform operation remains environmentally significant; however, as garment lifespan extension increases, the avoided production benefits become substantially larger. Under the +6 month and +12 month scenarios, especially under moderate and full substitution conditions, the environmental savings exceed the additional digital platform impacts, resulting in lower overall climate impacts than the baseline garment system.The +12 month lifespan extension scenario with full substitution ($\sigma = 1.0$) produces the lowest net climate impact, demonstrating that long-term garment reuse can significantly outweigh the environmental burden associated with ICT infrastructure and digital platform energy consumption.

Moreover, Fig. 15. illustrates the comparison between the baseline garment system and the net climate impacts calculated under different lifespan extension and substitution scenarios. Scenarios with results lower than the baseline value of 4.91 kg CO_2 eq indicate that the environmental savings from avoided garment production are sufficient to offset the additional impacts caused by digital platform operation.

In contrast, scenarios with impacts higher than the baseline system do not fully compensate for the additional ICT-related burden. This is observed mainly under short-lifespan extensions and low substitution conditions, where the environmental benefits from reuse remain limited.

Comparison shows that the environmental performance of the swapping system improved as both garment lifespan extension and substitution factor increased. The lowest net climate impact is observed under the +12-month lifespan extension and full substitution scenario, indicating that long-term reuse and effective replacement of new garment production generated the largest environmental benefit.

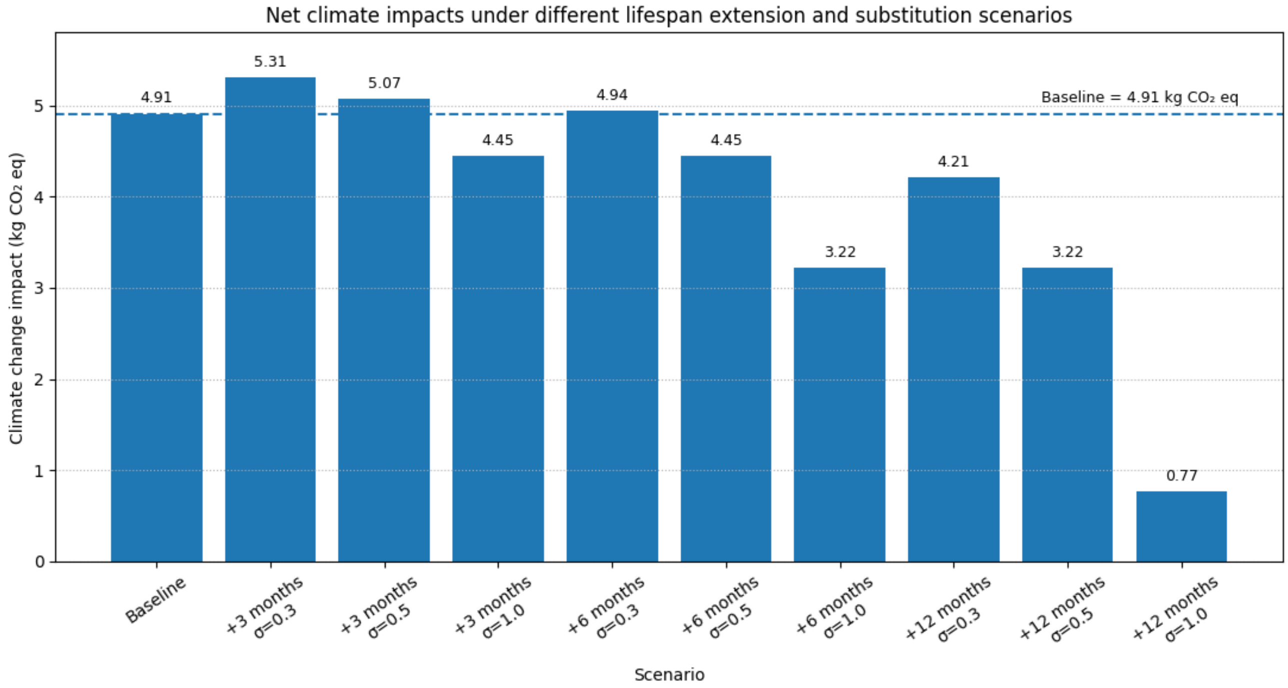

Fig. 15. Net Climate Change Impacts Under Different Lifespan Extension and Substitution Scenarios

3.6. Break-even Analysis

Break-even analysis is performed to identify the minimum additional garment use required for the swapping system to become environmentally beneficial. Unlike the previous net-impact assessment, which evaluates fixed lifespan extension scenarios (+3, +6, and +12 months), the break-even analysis estimates the exact additional use period needed to compensate for the environmental burden caused by digital platform operation.

In this study, break-even is reached when the avoided production impact becomes equal to the additional ICT-related environmental burden generated by the integrated swapping system.

The break-even additional lifespan for climate change was calculated as formula 11:

For the climate change category, the baseline cotton T-shirt impact is: $I_{baseline}$ = 4.91 kg CO_2 eq, while the integrated system generated: $I_{integrated}$ = 5.679 kg CO_2 eq . The additional ICT-related burden therefore reaches: 5.679−4.91=0.769 kg CO2 eq.

This means that garment reuse after swapping needs to avoid at least 0.769 kg CO_2 eq of new garment production to fully compensate for the additional digital platform burden.

Table 15. Break-even lifespan extension required to offset ICT-related climate impacts

Substitution factor	**Break-even additional lifespan**	**Environmental outcome**
σ =0.3	6.26 months	Longer reuse is required to offset ICT burden

σ =0.5	3.76 months	Moderate reuse is sufficient to offset the ICT burden
σ =1.0	1.88 months	Short reuse period sufficient to offset ICT burden

The results show that the break-even point depends strongly on the substitution factor (see Table 15). Under low substitution conditions (σ=0.3), the garment needed to remain in active use for more than 6 additional months after swapping to compensate for the environmental burden associated with digital platform operation.

Under moderate substitution (σ=0.5), the required additional use period decreases to approximately 4 months. In contrast, under full substitution (σ=1.0), less than 2 additional months of garment use are sufficient to offset the ICT-related burden.

These results indicate that digital platform electricity consumption become environmentally significant mainly when garments are used for only a short time after swapping or when reuse does not effectively replace the purchase of new garments. However, when garments remain in active use for longer periods and successfully displace new production, the avoided production benefits exceed the additional impacts associated with digital platform operation.

3.7.Sensitivity analysis

Sensitivity analysis is performed to evaluate how changes in key assumptions influenced the environmental performance of the integrated swapping system.

Table 16. Summary of sensitivity analysis results

Parameter	Sensitivity level	Main affected categories
Electricity source	Moderate	Climate change, fossil resource scarcity
User-device type	Low	Minor influence on all categories
Platform utilisation	High	Climate change, fossil resource scarcity
Substitution factor	Very high	Net environmental impacts
Lifespan extension	Very high	Net environmental impacts

The outcomes support that platform utilisation, substitution factor, and garment lifespan extension had the strongest influence on environmental performance (see Table 11). In contrast, smartphone and laptop-device scenarios produce only small differences in environmental impacts.

Electricity source is mainly affected by climate change and fossil resource scarcity categories, while water consumption and land use remain dominated mainly by textile production processes. The sensitivity analysis indicates that environmental performance depends more strongly on reuse behaviour and platform efficiency than on user-device electricity consumption.

3.7.1. Comparison with Previous Studies

The findings of this study are generally consistent with previous studies on clothing reuse, clothing life extension, and the environmental impact of digital technologies. The findings indicate that the environmental impact of clothing replacement depends heavily on how long clothes are reused and how often they are used instead of new clothes. This is in line with previous research by Farrant et al. (2010), which shows that the environmental advantages of second-hand clothing are closely linked to the amount of new clothing production that is replaced. Likewise, Hurmekoski (2024) notes that a textile system's environmental benefits are not given; rather, they depend on the kind of replacement of traditional textile production that occurs. The current study supports these observations, showing a significant difference in environmental savings between scenarios with higher and lower replacement factors.

The climate change impact of the baseline cotton T-shirt in the present study is estimated at 4.91 kg CO_2 eq per garment. This value is comparable with previous cotton T-shirt life cycle assessment studies. For example, Zhang et al. (2015) reports climate change impacts in the range of approximately 5–8 kg CO_2 eq per cotton T-shirt depending on production assumptions and system boundaries. Although the value obtained in this study is slightly lower, both studies identify textile production processes, particularly cotton cultivation, fabric production, dyeing, and finishing, as key factors influencing environmental impacts.

The outcomes also highlight the importance of extending the life of clothing. Higher re-use rates resulted in higher production value and lower net environmental impacts. This result aligns with earlier studies that have already identified extended garment use as one of the best practices to minimise environmental impacts in the textile industry. According to WRAP (2017), if garments are prolonged by a few months, the carbon footprint, water footprint, and waste footprint can be reduced, while Niinimäki et al. (2020) confirm extending the life of garments to be one of the most important measures to take to improve the sustainability of the fashion industry. The present study also shows that environmental performance improves with additional wear time. For example, under full substitution conditions, the avoided climate change impact increases from approximately 1.47 kg CO_2 eq in the +3-month scenario to 4.91 kg CO_2 eq in the +12-month scenario.

The results also confirm findings from other works on circular economy strategies in the textile industry. In general, reuse offers greater environmental benefits than recycling, as it avoids the environmental impacts associated with new production, as found by Abagnato et al. (2024) and Keßler et al. (2021). In the present study, the largest environmental savings are achieved by avoiding garment production rather than by changing waste management or end-of-life treatment. This highlights that it can be desirable to prioritise the active use phase of garments in circular textile systems.

At the same time, the findings show that digital platforms cannot be viewed as environmentally friendly. The inclusion of ICT-related electricity consumption increased environmental impacts across all analysed categories, particularly climate change and fossil resource scarcity. Climate change impacts increase from 4.91 kg CO_2 eq in the baseline system to 5.68 kg CO_2 eq in the integrated system, corresponding to an increase of approximately 15.7%. Fossil resource scarcity increases by approximately 14.5%, while water consumption and land use increased by only 1.3% and 1.9%, respectively. This observation is consistent with the findings of Itten et al. (2020), Gröger et al. (2024), and Charfeddine and Umlai (2023), who emphasise that digital services rely on energy-consuming infrastructure, including user devices, communication networks, and data centres.

However, despite introducing additional environmental burdens, the digital platform impacts remain smaller than the environmental benefits generated through successful garment reuse under favourable conditions. This supports the view that digital technologies can simultaneously generate environmental impacts and enable more sustainable consumption practices. The analysis of the contribution reveals that the back-end server accounts for approximately 99.73% of total ICT electricity demand associated with a successful garment exchange, while network transmission contributes approximately 0.24% and user-device electricity only 0.03%. In line with previous ICT life cycle assessment studies, the results above outline that important contributors to the environmental footprint of digital services include cloud infrastructure and data processing (Itten et al., 2020; Gröger et al., 2024). These results indicate that optimising the efficiency of the platforms and boosting the number of successful exchanges per platform could be more environmentally friendly than simply reducing user-device power usage.

Summarising the comparison with previous research, it can be stated that the ICT-related impacts of digital clothing-swapping systems play a secondary, but still relevant, role, with the main ones being substitution and extension of garment use-life, which are mainly user behaviour-related. This result confirms previous studies that indicate the environmental consequences of reuse can be significant and builds on these with the results of this study that quantify the contribution of electricity consumption by digital platforms to the environmental footprint of clothes-swapping systems.

3.8.Limitation of Research

Several limitations should be considered when interpreting the results of this study. First, the analysis was based mainly on secondary data sources and literature assumptions, as detailed primary data from digital clothing-swapping platforms was not publicly available. As a result, some estimates user behaviour were based on existing literature and scenario assumptions. The study also used an attributional LCA approach. This approach assesses environmental impacts within a specific product system under fixed conditions. Therefore, it did not fully capture broader market effects and indirect changes in behaviour. For instance, the study assumed that reusing garments would replace the production of new ones based on selected substitution factors, but real consumer behaviour might differ.

Another limitation involved uncertainty around garment lifespan extension and substitution behaviour. The environmental impact of the swapping system was very sensitive to these assumptions. The actual duration of reuse and purchasing behaviour can vary between different users, platforms, and clothing types. Additionally, the digital platform model mainly focused on operational electricity demand from user devices, network use, and backend infrastructure. It did not include detailed information on other potential impacts, such as hardware manufacturing, data centre construction, or platform maintenance. In addition, the environmental results may vary across regions due to differences in electricity generation mixes. Although scenario analysis was performed for alternative electricity sources, the results remain dependent on the selected electricity assumptions and geographical context. Finally, the study used one typical cotton T-shirt as the reference garment. Different materials, garment types, or washing habits may lead to different environmental outcomes.

Conclusions

1. The baseline cotton T-shirt system generated 4.91 kg CO_2 eq climate impacts, while the integrated swapping system increased the impact to 5.679 kg CO_2 eq after including digital platform electricity demand. The additional ICT-related burden therefore reached 0.769 kg CO_2 eq. Among the ICT components, backend server operation represented 99.73% of total digital electricity demand, while network transmission and user-device electricity contributed 0.24% and 0.03%**,** respectively.
2. Digital platform electricity increased climate change impacts by 15.7% and fossil resource scarcity by 14.5%**,** whereas water consumption and land use increased by only 1.3% and 1.9%**,** respectively. whereas water consumption and land use remained dominated mainly by cotton cultivation and textile wet-processing activities. Normalisation analysis showed that water consumption represented the most environmentally significant category within both baseline and integrated systems.
3. Scenario analysis demonstrated that electricity source and platform utilisation significantly influenced environmental performance. The renewable PV electricity scenario produced lower climate-related impacts than the Lithuanian grid scenario. In addition, low platform utilisation led to greater impacts because backend server electricity was distributed across fewer successful garment exchanges, whereas high utilisation reduced impacts through more efficient infrastructure allocation.
4. The comparison between smartphone and laptop-device scenarios showed only minor differences in environmental impacts. This indicated that user-device electricity demand represented a relatively small share of the total ICT burden within the integrated system.
5. The results showed Under full substitution ($\sigma = 1.0$) and a 12-month lifespan extension, net climate impacts decreased to 0.77 kg CO_2 eq, whereas under low substitution ($\sigma = 0.3$) the integrated system remained above the baseline impact level. Under short reuse periods and low substitution rates, the environmental savings from avoided production were insufficient to offset the additional ICT-related burden.
6. Break-even analysis showed that the integrated swapping system required approximately 6.3 additional months of garment use under low substitution ($\sigma = 0.3$), 3.8 months under moderate substitution ($\sigma = 0.5$), and less than 2 months under full substitution ($\sigma = 1.0$) to offset the additional environmental burden caused by digital platform operation.

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Appendices

Appendix 1. Life Cycle Inventory of the Baseline Cotton T-shirt Model

Table 17. Life cycle inventory of the baseline model of cotton T-shirt

Stage	Flow	Amount	Unit	Source / rationale
Functional unit	One cotton T-shirt providing clothing functionality over a reference service life.	1	item	Defined for this thesis baseline; used as the benchmark for later avoided-production and ICT-integration analysis.
Garment mass	Cotton T-shirt mass	0.12	kg	Screening assumption within the range reported for cotton T-shirts in the literature [30].
Dyeing and finishing	Knitted cotton fabric	0.1407	kg	Calculated from the final garment mass and literature-informed production-loss logic.
Dyeing and finishing	Electricity, medium voltage	0.129	kWh	Foreground process value used in OpenLCA; adapted from process-level cotton T-shirt literature and rescaled to the 0.12 kg T-shirt. Supported by the identification of dyeing as a major hotspot [42].
Dyeing and finishing	Heat, district or industrial	8.6	MJ	Foreground process value used for textile wet treatment; included because wet processing is energy-intensive. [42]
Dyeing and finishing	Tap water	22.3	kg	Foreground process value representing water demand in wet processing. [42].
Dyeing and finishing	Reactive dye, at plant	0.006	kg	Proxy foreground flow because no exact dye dataset was available in the selected database.
Dyeing and finishing	Textile dyeing auxiliaries, at plant	0.162	kg	Proxy foreground flow because exact auxiliaries datasets were unavailable.
Dyeing and finishing	Dyed and finished knitted cotton fabric	0.1364	kg	Main output from the wet-treatment stage; calculated to maintain mass balance.
Dyeing and finishing	Cotton fabric waste, wet processing	0.0043	kg	Modelled waste output from textile finishing.
Dyeing and finishing	Wastewater from textile production	0.0101	m^3	Modelled wastewater output from the wet-treatment stage.

Cutting, sewing and finishing	Dyed and finished knitted cotton fabric	0.1364	kg	Input from previous foreground stage.
Cutting, sewing and finishing	Electricity, medium voltage	1.18	kWh	Foreground process value reflecting garment assembly and finishing; consistent with earlier cotton T-shirt LCA evidence that making-up is a relevant contributor [42].
Cutting, sewing and finishing	Yarn, cotton (thread proxy)	0.003	kg	Proxy for sewing thread.
Cutting, sewing and finishing	Cotton T-shirt	1	item	Main assembled garment output.
Cutting, sewing and finishing	Cutting waste, cotton fabric	0.0164	kg	Waste output representing losses during garment assembly.
Distribution to retail	Cotton T-shirt	1	item	Input from assembly stage.
Distribution to retail	Transport, freight, lorry	0.12	tkm	Based on a 0.12 kg garment mass and an assumed 1000 km distribution distance, the screening transport stage is recommended by the apparel PEFCR framework.
Distribution to retail	Cotton T-shirt distributed	1	item	Output entering use phase.
Use phase	Cotton T-shirt distributed	1	item	Input from the distribution stage.
Use phase	Electricity, low voltage (washing)	0.632	kWh	Modelled household electricity for washing over the baseline service life. Supported by standardised T-shirt care assumptions in Product environmental footprint (PEF)-based work.
Use phase	Tap water	30.8	kg	Modelled household washing water over the baseline service life.
Use phase	Detergent, at plant	0.0546	kg	Proxy foreground flow representing detergent use over the baseline service life.

Use phase	Electricity, low voltage (tumble drying)	0.161	kWh	Modelled household electricity for tumble drying over the service life.
Use phase	Electricity, low voltage (ironing)	3.4	kWh	Modelled household electricity for ironing over the service life; supported by PEF care logic that T-shirts may be ironed/steamed, with 40% of garments ironed per use and 2.6 min per garment in the current PEFCR [5]
Use phase	Wastewater, average	0.0308	m^3	Modelled wastewater output from laundering.
End-of-life	Cotton T-shirt after use	1	item	Input from the use stage.
End-of-life	Waste textile, soiled	0.12	kg	Simplified 100% municipal-incineration route due to the lack of a suitable post-consumer cotton-textile recycling dataset in the selected database; European Environment Agency (EEA) and PEFCR data support the importance of municipal waste in the European textile EoL context [5].
End-of-life	Cotton T-shirt disposed, EU	1	item	Final reference output of the current baseline system.

Appendix 2. Life Cycle Inventory of the Integrated Cotton T-shirt Model Including ICT Energy Consumption

Table 18. LCA inventory of Integrated Model of cotton t-shirt

Component	**Parameter / flow**	**Value**	**Unit**	**Source / basis**	**Role in model**
Functional unit	One cotton T-shirt providing clothing functionality over a reference service life.	1	item	This study	Reference output
User activity	Average session duration	6.28	min	GiverTag data	Input for time calculation
User activity	Sessions per transfer	2.84	sessions	GiverTag data	Input for time calculation
User activity	Total active time per transfer	17.84	min	Duration × sessions	Intermediate
User device	Device type	Smartphone	-	Base case assumption	Defines device modelling
User device	Device power	2.5	W	Representative value	Energy calculation
User device	Electricity per transfer	0.00074	kWh	Time × power	Input to OpenLCA
Network activity	Data transferred per transfer	0.0887	GB	GiverTag data	Input for network energy
Network activity	Energy intensity	0.06	kWh/GB	Literature-based estimate	Energy calculation
Network activity	Electricity per transfer	0.00887	kWh	Data × intensity	Input to OpenLCA
Backend	Annual server electricity	263	kWh/year	GiverTag data	Input for per-transfer electricity calculation
Backend	Exchanged transfers (2024)	117	transfers/year	GiverTag data	Input for per-transfer electricity calculation
Backend	Electricity per transfer	2.25	kWh	263 / 117	Input to OpenLCA

Electricity supply	Electricity dataset	Europe without Switzerland	-	ecoinvent	Background system

Appendix 3. Use of Artificial Intelligence Tools

ChatGPT (OpenAI) was used for language editing, grammar correction, and text readability improvement during the preparation of the thesis. The tool was not used for data collection, calculations, life cycle assessment modeling, generating results, or producing scientific conclusions.

Prompt used:

"Please check the following paragraph for grammar, tense, and academic writing style without changing the scientific meaning."

All generated suggestions were reviewed, evaluated, and approved by the author before being included in the thesis.