Highlights of Sustainability

ISSN 2696-628X, A Peer-Reviewed Open Access Journal by Highlights of Science
https://www.hos.pub/ho/sustainability

Best Practice for Right to Repair and Supply Chain Regulations: High-reparability Modular Smartphone Usage Model Mitigates Environmental Hotspots

by Anna C. Schomberg, Clemens Mostert and Stefan Bringezu

Cite this Article

Schomberg, A. C., Mostert, C., & Bringezu, S. (2025). Best Practice for Right to Repair and Supply Chain Regulations: High-reparability Modular Smartphone Usage Model Mitigates Environmental Hotspots. *Highlights of Sustainability*, *4*(1), 38–55. https://doi.org/10.54175/hsustain4010003

Highlights of Science

Publisher of Peer-Reviewed Open Access Journals
https://www.hos.pub
Barcelona, Spain

Highlights of Sustainability

Article

Best Practice for Right to Repair and Supply Chain Regulations: High-reparability Modular Smartphone Usage Model Mitigates Environmental Hotspots

Anna C. Schomberg *, **Clemens Mostert** and **Stefan Bringezu**

Center for Environmental Systems Research, Kassel Institute for Sustainability, University of Kassel, 34117 Kassel, Germany

* For correspondence: anna.schomberg@uni-kassel.de

Abstract Two-thirds of the global population own mobile phones or smartphones. Yet their short service life—often limited to just a few years—leads to frequent replacements, excessive raw material consumption, and rising electronic waste. This study evaluates the environmental benefits of a highly modular and repairable smartphone, based on real-world usage. Compared to conventional smartphones with an average lifespan of 2.5 years, this device achieves a lifespan of five years, enabled by user engagement and a modular design that facilitates easy repairs. This finding is substantiated by customer surveys. Verified through manufacturer data, our life cycle assessment reveals a 40% reduction in climate emissions, energy use, material consumption, water usage, and land occupation. A high-resolution hotspot analysis reveals significant reductions in environmental impacts along the supply chain, particularly in mining and energy-intensive processes. The advanced usage model—aligns with the European Commission's "Right to Repair" and supply chain legislations—provides a scalable best-practice example to enhance smartphone sustainability and alleviate global supply chain pressures.

Keywords smartphone; modularity; right to repair; environmental footprints; supply chain

1. Introduction

Mobile phones and smartphones have become ubiquitous in the 21st century, with most people worldwide owning one. By 2011, the number of mobile devices surpassed the global population, highlighting their pervasive nature [1,2]. Annually, approximately two billion smartphones are produced (as of 2014, meanwhile more [3]), necessitating continuous extraction of primary resources, particularly rare and precious metals like antimony, beryllium, palladium, and platinum [4]. The extraction process poses numerous environmental challenges, including emissions of pollutants, water contamination, and land degradation [5]. Additionally, the production of smartphone components involves the use of toxic chemicals [6], exacerbating environmental damage. The social and economic impacts of smartphone production are also significant, with regions like the DR Congo witnessing health hazards and human rights abuses associated with unregulated artisanal mining [7]. Below a certain threshold of usage duration environmental costs during the production phase outweigh those during use [8]. Consequently, electronic waste has become the fastest-growing waste stream globally [9], with only a fraction being collected and processed for material recovery [10]. The rest accumulates in landfills [10], such as Agbogbloshie in Ghana, posing health risks to nearby residents due to rudimentary e-waste recycling practices [11].

Modular smartphones aim to mitigate these challenges by enhancing reparability and significantly extending their operational lifespan [12]. Prolonged use can reduce the demand for new appliances and the amount of waste resulting from the disposal of old ones. Both reduce the environmental impacts associated with the production of primary raw materials and the disposal of electronic waste, as for example life cycle assessment (LCA) studies can reveal [13]. The European Commission has also recently addressed this issue by launching the "Right to Repair" initiative, a legislative effort aimed at empowering consumers to demand repairs beyond legal guarantees. On 22 March 2023, a regulation has been proposed mandating manufacturers to design products that are easier to repair and to provide spare parts for a minimum period post-purchase [14], and it has been approved by the European Parliament and Council on 23 April

Open Access

Received: 7 October 2024
Accepted: 28 January 2025
Published: 20 February 2025

Academic Editor
Anna Mazzi, University of Padova, Italy

2024. This legislation aligns with broader circular economy goals, aiming to minimize environmental impacts by various measures. This also includes the stringent new European and national supply chain legislation, introduced by the European Union (EU) and Germany to promote corporate responsibility and sustainability. The European Union's Corporate Sustainability Reporting Directive (CSRD), which entered into force in January 2023, mandates large companies to disclose information on their social and environmental impact, including human rights and sustainability practices throughout their supply chains. It aims to enhance transparency and ensure that companies are accountable for the entire lifecycle of their products, from raw material extraction to end-of-life disposal. In mid-March 2024, the European supply chain law, the Corporate Sustainability Due Diligence Directive (CSDDD), was passed by a qualified majority of EU member states, which goes beyond reporting obligations and imposes due diligence obligations on companies. The European law is closely based on the German Supply Chain Due Diligence Act, effective from January 2023, in important respects, requiring companies to implement due diligence processes to identify and address and ultimately reduce human rights and environmental risks within their supply chains.

However, there are not yet many suppliers of high-reparability smartphones by design. Also, market shares are very low compared to conventional smartphones. Accordingly, the potential of modular smartphones to save natural resources and emissions has also been poorly analyzed as our literature review has revealed. High-reparability modular smartphones are currently still a niche product and, with a few exceptions such as those on the Fairphone, most studies to date have focused on conventional smartphones. Likewise, life cycle assessments usually present classic environmental impacts, especially greenhouse gas emissions, while newer indicators, such as input-oriented footprint indicators, are not yet so widespread [15–17]. Also, many studies concentrate on end-of-life (EoL) strategies to minimize environmental impacts after use, such as refurbishment [18,19] and "repurposing" [20], rather than on intrinsic design concepts that allow resource savings during use, also referred to as "anti-obsolescence measures" [21–23]. In addition, LCA results in the investigated studies are given cumulatively without a highly detailed breakdown of the individual steps along the supply chain that contribute to the overall result and the associated locations allowing for identification of the impact of individual process steps. Our literature review indicates that there are no existing studies on the supply chain benefits of modular smartphones, particularly regarding extended lifespans and their impact on natural resource use and emissions. However, this is essential for identifying hotspots that make the greatest contributions to the overall environmental impact, a knowledge which can help manufacturers to derive the most effective measures for reducing environmental impacts considering their supply chains. This is also important in the context of supply chain legislation.

Another important consideration is that repairability alone is not sufficient to extend smartphone lifespans—user behavior plays a critical role [24]: many smartphones are replaced while still functional, often in pursuit of devices with higher technical standards, but also for economic reasons, for example, see [25]. To address the topic comprehensively, we present a high-reparability modular smartphone (HRMS), which is designed, developed, and distributed by a German niche smartphone manufacturer. Thirteen replaceable modules allow for disassembly and repair through the user without specialized knowledge or tools, prolonging the lifetime of the device: users typically utilize it for five years, doubling the average standard lifetime of smartphones [26]. To the best of our knowledge, it is one of the most modular smartphone designs worldwide. Combined with altered user habits and an innovative circular economy business and marketing strategy, this results in what we call the "HRMS usage model" from here on. It has achieved a doubling of the lifespan of conventional smartphones highlighting its potential to reduce supply chain environmental impacts and serves as a best-practice example for the industry.

We present a life cycle assessment of the HRMS usage model introducing a novel functional unit that enables a meaningful comparison of information and communication technology in general. With an integrated hotspot analysis, we apply an innovative and differentiated evaluation method for LCA results, which allows for a spatial and activity-based representation of hotspots of various environmental impacts. In comparing the HRMS usage model with a conventional smartphone use model, we determine its contribution to enhanced sustainability and specifically observe where and how environmental hotspots along the supply chain are relieved based on real-world usage information.

2. Methods

2.1. Phases of the Life Cycle Assessment

An LCA follows four steps outlined in DIN ISO EN 14040 [27]. In the goal and scope determination (phase 1), the object of study is identified as the smartphone SHIFT6m manufactured by the company SHIFT GmbH. Two use cases are considered: M2×2.5 assumes a 2.5-year lifetime, serving as a reference model for a standard smartphone or mobile phone [26]. M5 assumes a 5-year lifetime through replacement of defective modules and based on 2018 to 2022 repair statistics provided by SHIFT GmbH (Supplementary Table S1). When developing the HRMS usage model M5, we relied on a customer survey conducted by SHIFT GmbH, acknowledging that its customer community represents non-conforming actors with high intrinsic motivation to extend smartphone usage. The causes and related aspects of this behavior were not further analyzed but are considered a foundational assumption for our environmental assessment. Hence, our results represent an innovative, yet uncommon smartphone usage model. Key pillars of this model include intrinsically motivated long-term users, a modular design that enhances repairability and supports user motivation, and an innovative business and marketing strategy by the manufacturer. The environmental savings of this real-world HRMS usage model can serve as a best-practice example. To ensure comparability, both models are assessed over a 5-year period which is taken as lifetime in the HRMS usage model within this study. Surveys in 2022 have shown that users are still using their SHIFT6m, which has been sold from 2018 on, and intend to continue using it for up to five years. We rely on the information provided by the users for this study and refer to it as real-world data. Random inquiries in the Shiftphone community in the meantime have indeed confirmed that SHIFT6m users use their smartphones for at least five years. However, it is not possible for us to verify in this way whether users do not use their smartphones contrary to their statements.

The functional unit for this study is defined as one year of smartphone usage, encompassing both production and operational phases (A1–A5, B1, B3, B4, and B6), as per DIN EN 15804:2022-03 [28]. Life cycle phases C and D are not considered, as the relatively new SHIFT6m is still predominantly in use and the company has not yet implemented any end-of-life strategies. Old devices that are returned to the company have so far been collected and stored so that no waste streams leave the company, and recycling is not yet carried out. SHIFT GmbH aims to fully recover old devices in order to avoid uncontrolled waste streams, especially of devices that are still in working order and has installed a device deposit of 22 euros, which customers receive when they return their old devices. As not all devices have been returned yet, the usage time could be even longer than five years if devices have not been thrown away. However, the close contact with the customer community through several online forums and their feedback gives no reason to believe this. The fact that there are still many open questions regarding usage behavior at the EoL and that the life cycle of the SHIFT6m may not yet have ended is another reason to not consider the EoL phase.

Inventory analysis (phase 2) is conducted using the ecoinvent 3.8 database with openLCA 1.11.0 software (https://www.openlca.org). Processes for replaceable modules are modeled based on SHIFT GmbH's supply chain analysis, incorporating real transport routes. Product systems are developed to connect models with LCA datasets, accounting for eight mineral resources with modified upstream value chains [29]. Impact assessment (phase 3) evaluates models using selected midpoint footprint indicators, analyzing their contributions to environmental impact categories and preparing results for spatially explicit hotspot analysis. Evaluation (phase 4) compares models and analyses supply chains spatially, while uncertainties are assessed using Monte Carlo Simulations.

2.2. Life Cycle Inventory Analysis

Both models primarily rely on input from the SHIFT6m, modeled based on regionalized supply chain analysis by SHIFT GmbH down to Tier 3. Information on manufacturer's types and locations is integrated into the model. Exchanged camera lenses and audio ports are omitted due to missing LCI datasets (Supplementary Figure S5). Inventory data is sourced primarily from ecoinvent 3.8, supplemented by literature, component weighing, and assumptions (Supplementary Figure S5). SHIFT6m model parts are used to depict exchange modules for M5, accompanied by their transport processes assuming direct supplier purchase. This contrasts with SHIFT GmbH's reality, where replacement modules may originate from returned customer equipment, potentially deemed burden-free under the LCA cut-off approach. This practice's dynamic nature warrants further research. Electricity consumption per year during the usage phase is calculated based on SHIFT6m battery charging capacity and an estimated average of 114 charging cycles.

2.3. Regionalization of Supply Chains of Selected Mineral Commodities

Up to Tier 3 of upstream processing, the SHIFT6m supply chain is known (Supplementary Figure S5, per SHIFT GmbH), but not the raw material origins. By updating Schomberg et al. (2022) [29] dataset to ecoinvent 3.8, we regionalize supply chains for mineral commodities like aluminum, copper, coal, cement, iron and steel, lithium, and phosphorus down to the mine site level. To manage global mine sites effectively, individual sites are clustered based on geology and regional water stress, resulting in five sites per country added to ecoinvent 3.8 and linked to existing datasets. This linkage, considering country-level and mine site production figures, models country and global markets for listed commodities, covering 80% of world production. Details of this procedure are outlined by Schomberg et al. (2022) [29]. Supply chains modeled using these datasets reflect the most probable origin of mineral commodities in the global supply system unless more specific information becomes available.

2.4. Life Cycle Impact Assessment

For impact assessment, resource footprints for energy, land, material, and water are selected, accompanied by the climate footprint [30] (Table 1). Compared to other LCA studies and the scope of available LCA indicators and impact categories, the number of five environmental footprints may seem small. However, it has been shown that these footprints taken together can already explain 80% of the variance across a very large number of LCA indicators and impact categories [31]. This makes them a suitable set for describing and evaluating as many environmental impacts as possible while at the same time not overloading the number of indicators for communication with politics, companies and society as also demonstrated previously [29].

Footprints are weighted values determined with specified criteria [32] and assessed using selected LCIA methods to quantify inputs along the smartphone supply chain. The climate footprint [30] is determined based on the updated IPCC 2013 LCA implementation using the latest IPCC data from 2021 [33]. We utilize the climate change impact category Global Warming Potential over a 100-year horizon (GWP_{100}) [34] to quantify carbon dioxide equivalents and other greenhouse gas emissions per unit. The energy footprint relies on Cumulative Energy Requirements Analysis [35,36] from Hischier et al. (2010) [34], focusing on fossil cumulative energy demand including coal, oil, gas, etc., assessed in MJ equivalents per unit via multiplication with relevant characterization factors. The land footprint is described by the total area of land occupied through the supply chain of the smartphone in $m^2 \times a$. Here, no assessment is performed in the absence of a suitable method recommended by the Life Cycle Initiative [29]. The material footprint [37] comprises Raw Material Input (RMI) and Total Material Requirement (TMR) sub-indicators, considering both abiotic and biotic materials. The RMI is calculated using the ratio of extracted raw material to the corresponding material in the extracted raw material measured in kg raw material per kg material. The TMR uses extracted primary material (used and unused extraction) measured in kg primary material per kg material [38]. The water footprint [39] includes Quantitative Water Scarcity Footprint (WSF_{quan}) and Qualitative Water Scarcity Footprint (WSF_{qual}) sub-indicators, assessing quantitative water consumption and virtual water volume respectively, using the AWARE LCIA (life cycle impact assessment) method to evaluate water stress at the country level. Results of indicator sub-categories are aggregated, with negative values from rounding errors in the ecoinvent 3.8 database removed from WSF_{quan}.

2.5. Hotspot Analysis of LCIA Results

With an LCIA, the overall footprint results are shown and also the individual contributions of activities in the upstream supply. The following is a systematic analysis of the LCIA data to make the essential information comparable:

1) The smartphone's supply chain comprises approximately 14,000 activities, with only those contributing over 1% of the total footprint included for further analysis. This accounts for at least 44%, averaging 80 % (excluding outliers) of total footprint results (Supplementary Figure S4). The term "total environmental burden" refers to the investigated proportion, not necessarily 100%.

2) To ensure comparability among activities with varied units, results are normalized per footprint. Individual activity results are normalized against the median of all activities from both use cases. Normalized values are calculated as the quotient of individual activity results and the median.
3) Normalized values indicate how many times larger or smaller an activity result is compared to the median. Values below 1 suggest activities with lower impacts than the median and are not considered hotspots. A color scale classifies hotspots by severity, adapting the scale to reflect a smartphone's less distinct hotspots compared to case studies in Schomberg et al. (2022) [29].
4) Summation of individual normalized activity results is conducted for each location, considering instances where locations occur multiple times due to varying activities or multiple exposures.
5) Regionalization quality depends on input data quality, ranging from point to global coordinates denoting unknown locations. International supply chain analysis may contain inaccuracies; hence a quality index classifies locations: 1 for point coordinates, 2 for countries or sub-countries, and 3 for regions spanning multiple countries. Quality 4 designates unknown sites labeled as global or rest-of-world, excluded from spatial hotspot analysis (Supplementary Figure S6).
6) Grouping activities into categories allows for assessing their significance to overall environmental burden independently of spatial information. Activity hotspots are identified, displayed, and evaluated similarly to spatial hotspots.

More details as well as an analysis of the impact and spatial coverage of the hotspot analysis are given in Supplementary Section S2.

2.6. Data Quality Evaluation, Assumptions and Limitations

Apart from SHIFT GmbH's supply chain analysis up to Tier 3, specific manufacturer data on components and manufacturing processes are unavailable. The LCA model structure is based on component weighing to accurately reflect the composition of the smartphone under consideration. Adapted ecoinvent 3.8 data, mostly non-specific to smartphone components, and a few smartphone-specific datasets populate the model. Literature data or estimates fill gaps, with camera lenses and audio ports excluded due to insufficient LCI data. Using nonspecific data alongside estimates introduces data uncertainty, assessed via an LCA data quality matrix (Supplementary Tables S5 and S6), evaluating reliability, completeness, and temporal, geographical, and technological correlations. We thoroughly reviewed all data directly associated with the smartphone product system, including component production and transport processes, to ensure suitability. Where necessary, the data was supplemented with the latest available information, including manufacturer-provided data. The same approach was applied to our regionalized mining supply chain. For any other supply chain processes, we relied on ecoinvent data and their internal quality assessments, which were not independently verified by us. This approach is deemed appropriate, given the complexity of evaluating all processes contained in ecoinvent that contribute to our product system. Most data exhibit medium to high quality, though temporal correlation often lacking. However, except for our own data, this represents the quality information stored in the ecoinvent data that we have not independently verified. The model is based on ecoinvent 3.8, which was the most up-to-date database at the time of the study. While a newer version of the database is now available, the updates related to electronic and smartphone components are not substantial enough to necessitate adjustments to our model. Comprehensive model validation, such as element composition analyses, exceeds this study's scope and warrants further research.

3. Results

A life cycle assessment of the HRMS usage model is conducted covering production and usage phases (A1–45, B1, B3, B4, B6 according to DIN EN 15804:2022-03 [28]). The EoL phase is omitted, mainly due to limited data availability (see Section 2 for details), and the resulting implications for the results are discussed accordingly. The focus of this study is on the comparison of a non-modular and a modular smartphone usage model, which could benefit equally from an increase in the secondary input rate of gold, leaving the relative savings of the modular usage model untouched. The climate, energy, land, material, and water footprints are calculated using selected LCIA indicators (Table 1). The focus of this study is not on the absolute footprint results but on the comparison of a non-modular and a modular smartphone usage model and the relative environmental impact of the two models.

Table 1. LCIA methods and terminology throughout this study. FP: Footprint; * if named differently.

Footprint	LCIA Method	Indicators	Impact Categories	Unit (This Study)	This Study*
climate FP	IPCC 2013 [34], updated according to IPCC 2021 [33]	Global Warming Potential (GWP)	GWP_{100a}	Kg CO_2-eqv.	
energy FP	Cumulative Energy Demand (CED) [34]	CED, fossil	non-renewable energy resources, fossil	MJ eqv. (kWh)	
			non-renewable energy resources, nuclear	MJ eqv. (kWh)	
			non-renewable energy resources, primary forest	MJ eqv. (kWh)	
land FP	Land occupation [40]	Land occupation	Land occupation	m^2	
material FP	Product Material Footprint (PMF) [38]	Raw Material Input (RMI)	Raw material input (RMI)	kg	raw material
		Total Material Requirement (TMR)	Total material requirement (TMR)	kg	primary material
water FP	Water Scarcity Footprint (WSF) [39]	Quantitative Water Scarcity Footprint (WSF_{quan})	evapotranspiration	m^3	quantitative water FP
			product-incorporated water	m^3	
			water transfers	m^3	
		Qualitative Water Scarcity Footprint (WSF_{qual})		m^3	qualitative water FP

To quantify the effect of the smartphone's usage model, two use cases are distinguished: Use case M2×2.5 assumes a typical smartphone lifetime of 2.5 years and serves as reference model for a standard smartphone, whereas use case M5 assumes a lifetime of five years through replacement of defective modules and is specific to the HRMS usage model of this study (Supplementary Figure S1). We rely on a customer survey conducted by the niche manufacturer, acknowledging that its customer community represents non-conforming actors with high intrinsic motivation to extend smartphone usage. The causes and related aspects of this behavior were not further analyzed but are considered a foundational assumption for our environmental assessment. Hence, our results represent an innovative, yet uncommon smartphone usage model. Key pillars of this model include intrinsically motivated long-term users, a modular design that enhances repairability and supports user motivation, and an innovative business and marketing strategy by the manufacturer. The environmental savings of this real-world HRMS usage model can serve as a best-practice example. To ensure comparability, M2×2.5 is also referenced to five years by the input of two smartphones and per functional unit. As an application-oriented functional unit, a smartphone use for one year considering the production and the use phase is chosen. The manufacturer, in collaboration with research partners, has developed an innovative circular economy-oriented EoL strategy, which is still under development and lacks usable data. To avoid generating misleading results through a standard database approach, we have not included this phase in our analysis. The climate, energy, land, material, and water footprint are calculated for the production phase of one HRMS and per functional unit (representing the HRMS usage model). Some of these footprints consist of several sub-indicators covering different categories of environmental impact (Table 1). Spatial and activity hotspots are determined by normalizing footprint results of selected individual activities along the LCA supply chain, which contribute at least 1% to a total footprint result, with the median of all results. For spatial hotspots, the normalized results from all footprints are summarized per location if known, for activity hotspots, they are summarized per activity category.

3.1. Footprints of the Production Phase of a Highly Modular Smartphone

The production phase of the HRMS is responsible for 20 kg emissions of CO_2 equivalents (eq.), consumes 72 kWh equivalents of energy, 1 m^2 a land, 38 kg raw material, 78 kg primary material as well as 7 m^3 water, and requires 20,000 m^3 of water to virtually dilute water pollution below specific thresholds (Figure 1, Supplementary Data S1). It is difficult to compare the results with other smartphones because comparable studies have used other indicators for evaluation and other LCA databases. However, differences are hardly to be expected here, as the HRMS does not use special production methods or alternative materials.

A comparison with other studies, e.g., 36 kg CO_2 eq. for the Fairphone 3 [41], 35 kg for the Fairphone 4 [42], 21 kg (48 kg for 2.25 smartphone units, here referenced to one unit) [16], 48 kg for the Sony Z5 [15], 30 and 39 kg for an Orange and Huawei smartphone [43], shows that the climate footprint of the HRMS is in most cases smaller. Such differences may for example result from a different goal and scope definition of the LCA or the use of a different database, confirmed by the finding of high ranges, for example, 16–70 kg CO_2 eq. [43], when comparing different smartphone LCAs. However, this could also indicate a systematic underestimation of the climate footprint due to an unknown cause here. We are unable to further resolve this issue by comparing the other footprint results to other studies, as we employ a unique methodological framework that, to the best of our knowledge, has not yet been used by other authors for evaluating smartphones. For our further analysis and discussion, this would imply that a potential distortion of the results must be taken into account.

This is also one of the reasons why our study focuses on a relative evaluation and a more comparable functional unit of smartphone use per year from here on: the analysis and results of the production phase of the HRMS form the basis for the comparison of the use cases. To avoid comparisons with other smartphone LCAs, which are not directly feasible due to differing scopes, our two use cases—conventional versus HRMS usage model—are based on the same dataset. The calculated savings of the HRMS usage model should be understood as relative savings.

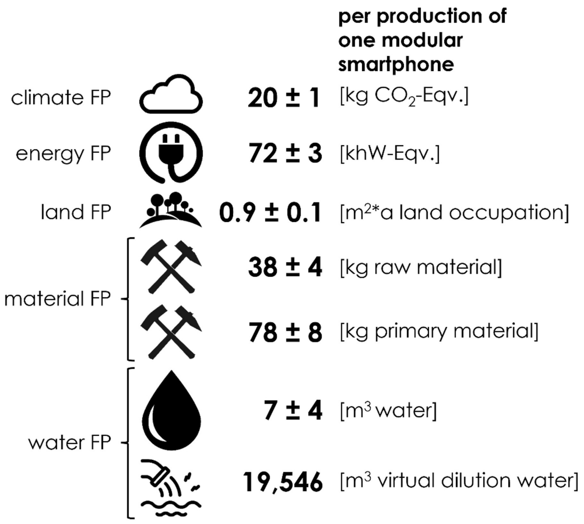

Figure 1. Footprints of the production phase of one highly modular smartphone, where "production phase" refers to A1–A5 according to DIN EN 15804:2022-03 [28]. Symbols from top to bottom refer to the climate, energy, land, material (raw material and primary material), and water footprint (quantitative and qualitative, referring to water use volume and pollution volume, respectively, both measured in m^3).

3.2. Footprints of the Use Cases

The footprints of the standard usage model M2×2.5 are in the range of 35% to 42 % larger than those of the HRMS usage model M5 (Table 2, Supplementary Data S2 and S3) per functional unit. The functional unit here is the smartphone use for one year, considering production and use phases. In comparison with the standard usage model, the modular case shows the largest savings in the material footprint (RMI 42 and TMR 43%), of which metallic raw materials have a share of at least 60%. The smallest savings are possible in the land footprint (36%). The special role of the material footprint in savings potential can be explained by a closer look at the inputs of the two use cases: for M5, to extend the lifetime to five years, one HRMS and various replacement modules are needed, e.g., 0.06 displays per functional unit (Supplementary Table S1), while for M2×2.5 two HRMS are needed. The inventory analysis shows that the display and the mainboard contain comparatively the most gold of all modules directly or in the supply chain. M5 saves gold compared to M2×2.5 by consuming only 0.27 displays per functional unit (0.4 in

M2×2.5) and 0.2 mainboards per functional unit (0.4 in M2×2.5). This saving has an above-average effect on the material footprint, as the characterization factor of gold in the material footprint is exceptionally high. The analysis of the activity hotspots provides more detailed information on this.

Table 2. Footprint results of the reference use case M2×2.5 and the HRMS usage model M5 per smartphone use for one year. FP: footprint, RMI: raw material input, TMR: total material requirement, quant.: quantitative, qual.: qualitative, sd: standard deviation.

Footprint	unit, per smartphone use for one year	M2.5	sd	M5	sd	savings [%]
climate FP	kg CO_2-Eqv.	8.6	±0.3	5	±1	37
energy FP	kWh-Eqv.	33	±6	21.4	±0.1	38
land FP	m^2*a land occupation	0.40	±0.04	0.26	±0.04	36
material FP (RMI)	kg raw material	16	±1	9.8	±0.2	42
material FP (RMI, metal)	kg raw material	9	±1	5.1	±0.3	44
material FP (TMR)	kg primary material	32	±2	19.0	±0.5	43
material FP (TMR, metal)	kg primary material	24	±2	14	±1	44
water FP (quant.)	m^3 water	3	±2	2	±1	40
water FP (qual.)	m^3 virtual dilution water	8119	±5185	4914	±3616	42

3.3. Identification of Activity Hotspots

Activity hotspots of the standard usage model M2×2.5 are mining, mainly gold mining, energy supply as well as waste treatment. The HRMS usage model M5 relieves the mining hotspots by saving a total of more than 5 kg of raw material (RMI) and more than 14 kg of primary material (TMR) per functional unit.

Activity hotspots are determined within the framework of a hotspot analysis, which examines the LCA results in more detail according to the type of activities along the supply chain. To this end, the results of the single footprints must first be made comparable: for each footprint, the median value of all activities of the two use cases M2×2.5 and M5 is determined and used to normalize each single activity result through division (Supplementary Data S4). A normalized value represents the ratio of the raw value to the median. Normalized single footprints are combined into the dimensionless index environmental burden by summing up results of the same activity category, namely mining (of gold, other metals and minerals), energy supply (through hard coal mining, petroleum and gas production, wood chips from forestry, electricity and heat production as well as diesel use), waste treatment, display production, transport, on-site activities (referring to the location of the SHIFT GmbH) and other activities. The environmental burden per activity category is considered as hotspot if it exceeds a threshold value of 5, which means that the environmental burden is five times as large as a median footprint result.

Activity hotspots of the standard usage model M2×2.5 are mining with a share of 31%, of which 22% is gold mining alone, energy supply, mainly based on hard coal, petroleum and gas and electricity and heat, with 38% as well as waste treatment with a share of 18 % of the total environmental burden (Figure 2, Supplementary Table S2). The category "other" is also a hotspot according to its numerical value, but only because it combines different activities which are not relevant when considered individually.

It is important to note that the low climate footprint of the HRMS usage model compared to other studies could indicate a systematic underestimation caused by an unknown factor. For instance, if upstream processes in the supply chain are underestimated, this may result in an overestimation of mining hotspots in absolute terms. Additionally, the selection of the LCIA method influences the assessment of metal-related impacts [44], which are critical in determining the extent of these hotspots. This, however, does not affect the relative results.

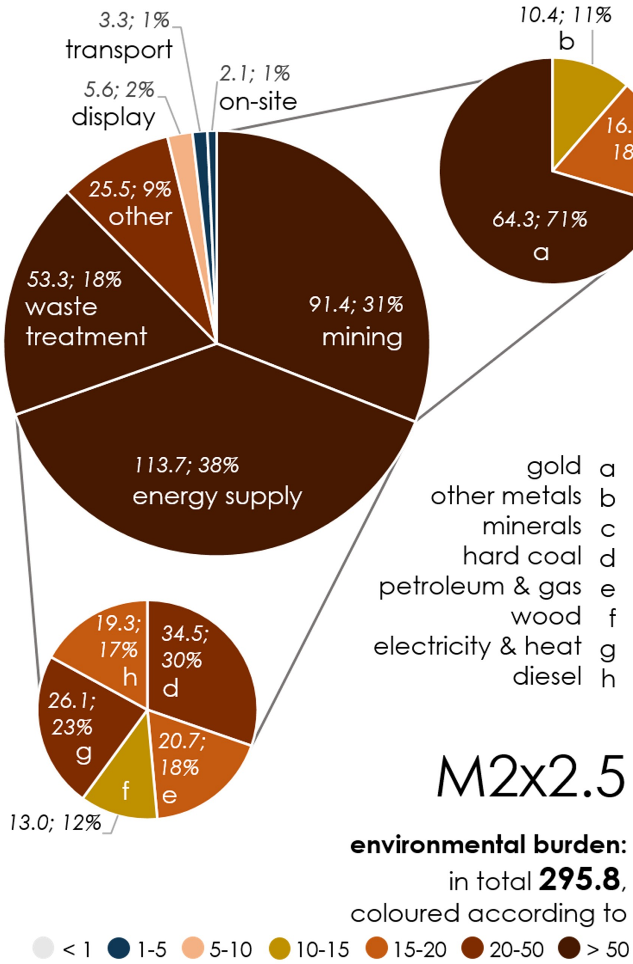

Figure 2. Composition of the environmental burden by activity categories of standard smartphone use case (M2×2.5). The environmental burden is a dimensionless index which is calculated based on normalized single footprints which are combined by summing up results of the same activity categories. Colors divide the hotspots according to severity into emerging (1–5), low (5–10), medium (10–15), high (15–20), very high severity (20–50), and extreme severity (>50). The product terms used in some cases are representative of the activity for the production of these products, e.g., gold stands for gold mining. Exception: diesel stands for diesel use. Composition of M5 and differences see Supplementary Table S2 and Figure S2.

3.4. Reduction of Activity Hotspots through the HRMS Usage Model

The HRMS usage model M5 shows a smaller absolute environmental burden than M2×2.5 of 190 compared to 295. This reduction applies to all categories, i.e., not only the total environmental burden decrease, but also the environmental burden of all categories with the highest absolute reduction of 28 in the category gold mining. The shares of the individual categories vary between M2×2.5 and M5 and the biggest difference is that in M5 metal mining has a 24 % lower relative share (differences in the generic category "other" not considered).

In absolute numbers, the highest reductions of the dimensionless index environmental burden originate from the activity categories gold mining (27.8, Supplementary Figure S2 and Table S2), waste treatment (21.1), hard coal mining (13.1) as well as electricity and heat production (10.9). All mining activities taken together (except for energy carriers), the HRMS usage model M5 leads to a reduction of the environmental burden from 91 to 38 by saving 2.9 kg, 0.7 kg, and 0.3 kg of raw material (RMI) in the activity hotspots gold mining, other metal mining and mineral mining compared to M2×2.5 per functional unit (Figure 3). In terms of primary material (TMR), the savings are 8.9 kg, 1.4 kg, and 0.7 kg (Figure 3). The environmental burden of the hotspot energy supply is reduced from 114 to 74 through reduced use of hard coal, petroleum and gas, electricity and heat, and wood chips. As regards the composition of the activity categories, compared to the reference use case M2×2.5, an 11% higher share of non-metal mining and an 18% higher share of diesel use are prominent in the HRMS usage model M5. This contrasts with a 12% and 24% lower share of gold and other metal mining, a 23% lower share of on-site activities, and a 9%

and 10% lower share in the use of energy wood, and electricity and heat production. Thus, there is a shift in the activity categories with the HRMS usage model M5. Since M5 has a lower environmental burden in absolute terms in all categories, this does not lead to a shift of burden. The proportionate decrease in gold and hard coal production represents a real relief for the mining and energy supply hotspots.

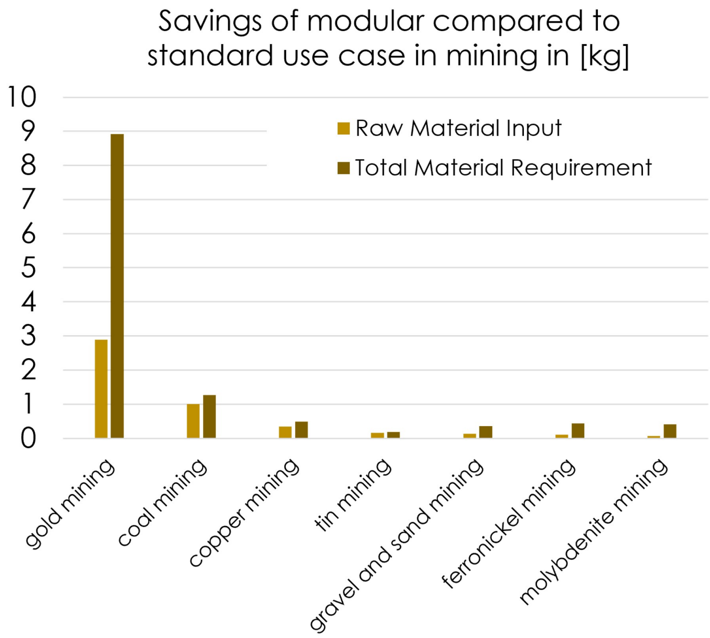

Figure 3. Savings of the modular smartphone use case (M5) compared to the standard smartphone use case (M2×2.5) in the material footprint for *mining* per functional unit. The functional unit is one year of smartphone use, covering production and usage phases. M5 assumes a 5-year lifetime through the replacement of defective modules and M2×2.5 a 2.5-year lifetime, serving as a reference model for a standard smartphone or mobile phone (system diagram see Supplementary Figure S1). The savings potential is the difference between the material footprint results of M2×2.5 and M5 per functional unit.

3.5. Relief of Spatial Hotspots by the Modular Use Case

Spatial hotspots in the M2×2.5 reference case are mainly linked to production, notably gold and copper mining and associated tailings treatment, followed by energy supply along the chain. M5 reduces and resolves numerous hotspots (Figure 4). Spatial hotspots are identified similarly to activity hotspots, where values exceeding 5 denote significant environmental impacts. These hotspots can range from point coordinates (manufacturer's site in Germany and three coal mines in China, Figure 4) to regions spanning multiple countries, reflecting regionalization quality of the LCI.

A hotspot is usually formed by the environmental impacts of several activities (Supplementary Table S3), but most hotspots related to M2×2.5 stem from mining activities and associated tailings treatment across Australia, Canada, China, Mexico as well as the United States (gold), Russia (copper) and South Africa (gold, hard coal).

Energy production, more precisely the provision of energy carriers such as hard coal from Europe, China, and Chinese mines (circles located within China in Figure 4) and natural gas and petroleum from Algeria, the Middle East, Russia, and the United States, is the second largest contributor. Sweden also appears here due to the provision of energy wood.

Colombia appears as an emerging hotspot because of electricity production from reservoir hydropower plants, which occupy relatively large areas of land with artificial lakes, and North America because of uranium production. That mining and energy production plays the most important role is also confirmed if hotspots are analyzed separately for each footprint (Supplementary Figures S3 and S4): the energy and qualitative water footprint (associated with the treatment of tailings from mining) are responsible for contributions with a value greater than 5, while all others remain below 5. In M5, analyzed separately by footprints, almost all locations have a value below 5. This is because M5 needs less input of primary resources and energy and relieves all hotspots.

An emerging hotspot in India, attributed to tap and decarbonized water production, indirectly relates to smartphone manufacturing, particularly in wafer production. M5 mitigates hotspots across several regions, indicating its lower environmental impact compared to M2×2.5. Notably, hotspots predominantly reside in upstream supply chains, highlighting their relevance over direct activities. However, spatial analysis overlooks certain activities like non-metal mining and diesel production, constituting a significant portion of the environmental burden. Gold mining, natural gas, petroleum production, and forestry are also underrepresented due to limited spatial resolution. Enhancing spatial resolution could reveal additional hotspots, emphasizing the need for better data coverage to comprehensively assess environmental impacts.

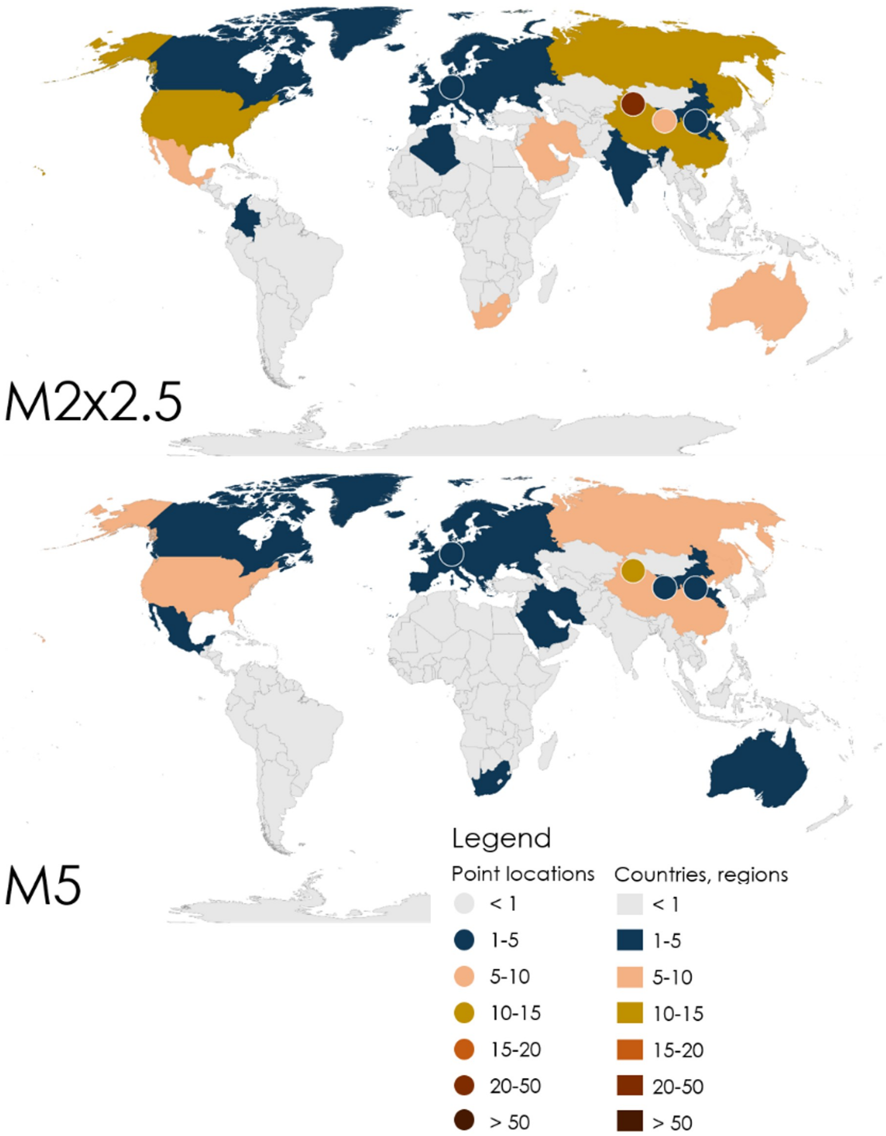

Figure 4. Spatial hotspots of M2×2.5 and M5 in comparison. Values represent the sum of normalized activity values with the same location across all footprints. Normalized activity values are gained through normalizing individual LCIA footprint results per activity and location against the median of all activities from both use cases. Dimensionless normalized values are calculated as the quotient of individual activity results and the median indicating how many times larger or smaller an activity result is compared to the median. Values below 1 suggest activities with lower impacts than the median and are not considered relevant. Maps for single footprints see Supplementary Figures S3 and S4. Activities without location are not considered. Circles represent point coordinates, i.e., the manufacturer's site in Germany and three coal mines in China.

3.6. Variance Analysis of the LCA

Monte Carlo Simulations of the footprints of the HRMS as well as of both use cases are carried out with the software openLCA using 5000 iterations and a cut-off value (0.00053 for the

HRMS model and 0.00005 for the use cases). Results show that most standard deviations are in the range of 2% to 18% of the footprint results. However, standard deviations of the water footprint are noticeably higher and can reach 74% for the qualitative water footprint (Figure 1, Table 2). This is because the water footprint is calculated as regionalized LCIA whereby there are significantly more uncertainties to consider.

4. Discussion

4.1. Contribution of an Alternative Smartphone Usage Model to Sustainability Goals

As the results of this study show, a high-reparability modular smartphone usage model can reduce environmental impacts and supply chain risks under certain circumstances. A combination of usage behavior focusing on long-term usage, highly modular design, which is an important key to high reparability and supports long-term usage [25,45], and complementary or supportive business and marketing measures can be a suitable and effective approach to achieve the targets set by the European Commission's "Right to Repair" of saving resources and reducing emissions, among others. Beyond that, the usage model contributes to different sustainability goals, such as the UN Sustainable Development Goals, the Paris Agreement's goals for reducing natural resource consumption [46] as well as national and European supply chain legislations by reducing supply chain risks [43]. The method presented is a valuable tool for the reporting of environmental impacts and carrying out risk analyses in supply chain management as as demanded by the European Union's CSRD and corresponding national legislations.

However, despite the high relative savings and consequent contributions to sustainability goals, the absolute quantities remain low because the production of the examined smartphone model and the application of the specific usage behavior are limited. Yet there lies great potential hidden here: in the period between 2018 and 2022, an average of 22 million smartphones were sold in Germany per year. The climate and material footprint (RMI) of highly-modular smartphone use scaled up to 22 million accounts for 0.02% of the total German climate and material footprints, while savings can be achieved here comparatively easily purely through a change in design in combination with adapted usage behavior. The potential total CO_2 savings are in the order of 150,000 medium-haul flights (at 500 kg CO_2-eqv. per flight according to the German Federal Environment Agency), while resources (RMI) can be saved in the order of 220 multi-family houses (at 900 t RMI [47] per house) in total. The savings potential in relation to the globally produced quantity of two billion smartphones in 2022 amounts to almost 13 million medium-distance flights and the construction of approximately 20,000 multi-family houses. Increasing the reparability of short-lived small electrical devices to extend their lifetime can make an important contribution to saving resources and emissions and reduce waste if widespread adoption succeeds [48]. This is also relevant with regard to valuable metal resources, which are comparatively assessed in the material footprint, but whose potentially limited availability in the supply chain context was not recorded and would also have to be taken into account.

Realizing the economy-wide savings potential of the HRMS usage model requires scaling its adoption, prompting the critical question of feasible strategies to achieve this. The model is based on three key elements: intrinsic motivation of users to extend device usage, modular design from the outset that supports the first aspect by enhancing repairability and interchangeability so that technical defects do not hinder prolonged use, and an innovative business and marketing model by the manufacturer, which specifically targets the aforementioned user group. Within the scope of our study, we did not investigate why these users are motivated differently than conventional users, nor to what extent the business and marketing model can further stimulate motivation. The presented model is intended to serve as a best-practice example for an overall more sustainable smartphone use. Modular design is one aspect of the HRMS usage model that other smartphone manufacturers could directly implement. However, it is important to note that modular design may contribute to environmental savings through increased repairability resulting in prolonged service life, only if corresponding user behavior is also present as studies on other alternative smartphone models have found [49]. Additionally, it must be considered that modularity can have trade-offs such as increased costs or complexity [50] and may be associated with higher "environmental activation energy" [51]. The development of an HRMS-oriented alternative usage model for other smartphone and ICT manufacturers, which would be necessary for scaling savings and realizing their full potential in the context of sustainability transformation, undoubtedly requires greater efforts, the details of which we cannot assess within the scope of this study. Further research is needed to both make HRMS usage models applicable beyond non-conforming user groups, which generally also require social change as part of a sustainability transformation [52], and to establish a more sustainable product portfolio even with non-niche manufacturers. Our case study can serve as a guide and best practice in order to contribute to supply chain benefits worldwide [47] aligning with the UN Sustainable Development Goals, the Paris Agreement's goals for reducing natural resource consumption [46], the "Right to Repair" and national and European supply chain legislations.

4.2. Limitations of the Study and the Study Design

The basis of our comparison for calculating the savings of the HRMS usage model is a lifetime of 2.5 years for the conventional smartphone and five years for the HRMS usage model. For the first value, we relied on a study that reported 1.8 years for smartphone usage and 2.5 years for mobile phone usage [26]. To avoid overestimating savings, we opted for the optimistic scenario. The 5-year value is based on user surveys from the manufacturer of the HRMS presented in this study. Both values are crucial for the relative savings, and we consider them directionally sound within the scope of this study to demonstrate the savings potential of an alternative smartphone usage model. When applying this best-practice example to other manufacturers and ICT sectors, these values may need to be adjusted. This will be the subject of further research in this area.

One key limitation of this study is the exclusion of the EoL phase; incorporating gold recycling at this stage could significantly alleviate the environmental burden associated with primary gold mining. However, the niche manufacturer follows an innovative approach, which is currently under development, aiming at establishing greater control and transparency in the recycling process compared to the current state. Until these structures are fully implemented, returned smartphones are collected from the customers with the help of a deposit to prevent uncontrolled waste streams that may, in the worst case, even escape recycling. After all, studies show that approximately 352,474 metric tons of e-waste are shipped from European Union countries to developing countries each year, with destinations including sites like Agbogbloshie in Ghana [53]. It is to be expected that an innovative recycling strategy, as is currently being developed by the manufacturer in collaboration with research partners and progressive recycling companies, will contribute to an above-average recycling rate. Currently, the documented global collection and recycling rate for e-waste is about 22.3%, with projections indicating a potential drop to 20% by 2030 due to the widening gap between recycling efforts and the rapid growth of e-waste generation [54]. However, as long as no data and facts are available, we have decided to skip this phase. The extent to which higher recycling rates reduce supply chain risks in relation to primary gold mining is still unclear in this context, because even if the proportion of recycled gold increases, the secondary input rate must also increase at the same time in order to bring about relief. At least in the production of electronic components in China, while recycling initiatives are expanding, the incorporation of recycled materials into electronic component manufacturing has not yet seen a significant increase [55]. The focus of this study is on the comparison of a non-modular and a modular usage model, which could benefit equally from an increase in the secondary input rate of gold, leaving the relative savings of the modular usage model untouched.

The functional unit "smartphone use for one year" is presented in this study as an application-oriented unit intended to make the production and use phase of different devices easily comparable. It can also be suitable for other electrical devices; however, it needs to be supplemented by an identification of the technological level: different smartphone models show very different performance, e.g., with respect to the quality of the camera. Within this study, such a distinction is not necessary, as the reference use case and modular use case are based on the same dataset and have identical technical specifications. However, to put the magnitude of savings in the context of technical maturity, which plays an important role for consumers when choosing a smartphone model, a corresponding modification of the functional unit together with an extension of the comparison to other smartphone models is necessary [50].

The quality of the input data is largely good, but there are also some gaps from which uncertainties result. In particular, the spatial and temporal resolution of data from the ecoinvent database is still too low overall, as more than half of the supply chain activities stored in the database are not spatially resolved at all. Likewise, a validation of the model is still pending. This could for example be done by determining the element contents of individual components and comparing these with the inventory results to be able to precisely determine the content of critical metals. Both together, the low quality of the spatial mapping and the lack of validation of the inventory, can lead to both an underestimation and an overestimation of the number and severity of hotspots, although an underestimation is more likely, and we assume to present the minimum environmental burden here.

Higher life-cycle costs arising from the sustainable design process were not considered in this study. Schischke et al. (2019) [22] assume that the life-cycle-wide impacts are about 10% higher than compared to a conventional, non-modular smartphone. Even if these results are not directly comparable with those of this study due to different framework conditions of the LCA analysis, the savings quantified here are already considerably higher at 40% per smartphone use per year.

4.3. Further and other Savings Opportunities

Smartphone repair, if enabled, alone can save large amounts of natural resources and emissions, as the results of this study show. Nevertheless, further savings and savings in other areas are also possible:

1) According to the repair statistics of the manufacturer and supported by other studies [25] and a huge number of newspaper surveys and similar, the display breaks down most frequently, which alone is associated with high resource and energy costs due to its high weight in relation to the entire smartphone. Even if customers are already encouraged to use armored glass and bumpers to protect the display, it is advisable to make further efforts to reduce the failure rate per functional unit. Possibilities include raising customer awareness, increasing the modularity of the display so that it can also be repaired, and evaluating and testing better display protection techniques. Since a few components typically dominate the material resource requirements of entire electrical and electronic devices, it may be worthwhile to extend such strategies to other components [56]. However, the repair statistics of the HRMS show that after the display and the battery, it is mainly less material-intensive, small components that are replaced.

2) Gold mining is responsible for the most and most severe hotspots. These could be relieved if it were possible to integrate recycled gold into the supply chain of the production phase of the HRMS or at least increase the share. This would require a more in-depth analysis of the supply chain and cooperation with suppliers. As we have also noticed in the context of this study, this is generally difficult, but for example, within the framework of research projects, appropriate incentives can be created among manufacturers to participate. A look at the growing extraction of primary raw materials worldwide and the associated problems makes it clear that there is an urgent need for action here to limit the consumption of natural resources that does not stop at national borders [46]. Such measures can also be successful indirectly, for example, when the manufacturer brings recycled gold from its old equipment back into the cycle as compensation for the gold extracted to produce new HRMS. Such an initiative can also contribute to reducing the environmental burden of other raw materials, but it is advisable to focus on the largest hotspot, gold, first. Quantifying the potential of these measures is the subject of future work. Previous research has demonstrated that neither extending product lifespans nor recycling—whether individually or in combination—can currently provide a radical solution to mitigate in particular metal scarcity and criticality [57]. This highlights the need for new approaches and positions the issue as a significant and emerging research challenge.

3) The possibility of integrating still functioning components from old devices into new devices has not been considered yet. In the case of the LCA cut-off approach, their environmental impact would not be credited to the new device. Refurbed devices, where only defective components need to be replaced to make them functional again beyond five years, can also lead to a further reduction in the environmental burden. Such end-of-life measures are already being implemented or planned as part of the circular economy strategy of SHIFT GmbH seeking to implement value-retention processes, but the quantification of their effect is the subject of future research. As repairing devices while using new components is not automatically the most resource-efficient way, other options for extending the lifetime and best possible utilization of the existing components and devices should also be modeled and compared [56].

5. Conclusions

This study has quantified for the first time the supply chain benefits of a high-reparability modular smartphone design based on real-world usage data, i.e., the use case of a German niche manufacturer's device. Within a comprehensive LCA hotspot analysis, a 40% reduction in resource use and emissions per year per smartphone is revealed. Hotspots along the supply chain can be notably mitigated, particularly in gold mining, a process associated with significant environmental and social costs [58]. High-reparability modular smartphone designs support the European Commission's "Right to Repair" by saving resources and reducing emissions, while also contributing to European and national sustainability programs and supply chain risk reduction. Although the production volume of the studied smartphone model is limited, scaling modular designs to broader use could result in significant savings, such as reducing CO_2 emissions and conserving valuable resources and subsequently relieving supply chain hotspots. Leading smartphone manufacturers are encouraged to prioritize modular design as a means to enhance reparability, thereby aligning with the European Commission's "Right to Repair", the Corporate Sustainability Reporting Directive, and broader goals of circular economy as well as aligning with the UN Sustainable Development Goals and the Paris Agreement.

Funding

This research work was performed as part of the project "Closing the loop: SHIFTPHONE is ready for circular economy", loopPHONE (033RK087B), carried out with the support of the Federal Ministry of Education and Research (BMBF).

Data Availability

The LCI of the SHIFT6m and updated LCIA methods are available from Mendeley Data at https://doi.org/10.17632/w3gyzc4x5s.1

Author Contributions

A.C.S. and C.M. designed the LCA models and the conceptual approach. A.C.S. performed the analyses, wrote the paper, and created the figures and the SI. C.M. and S.B. comprehensively reviewed and edited the manuscript. All authors discussed on the LCA models, the analysis and the manuscript at all stages.

Supplementary Materials

Supplementary materials are available from Mendeley Data at https://doi.org/10.17632/w3gyzc4x5s.1

Acknowledgements

We thank Thomas Krause and Leon von Zepelin, who provided comprehensive insights into SHIFT GmbH, provided data and proofread all passages on the smartphone under study. We thank María Motiño and Tabea Schneider, who have assisted with creating the LCA inventory and literature research.

Conflicts of Interest

The authors have no conflict of interest to declare.

References

1. Bekaroo, G., & Seeam, A. (2016). Improving wireless charging energy efficiency of mobile phones: Analysis of key practices. In *2016 IEEE International Conference on Emerging Technologies and Innovative Business Practices for the Transformation of Societies (EmergiTech)* (pp. 357–360). IEEE. https://doi.org/10.1109/EmergiTech.2016.7737366
2. Bekaroo, G., Bokhoree, C., & Pattinson, C. (2016). Impacts of ICT on the natural ecosystem: A grassroot analysis for promoting socio-environmental sustainability. *Renewable and Sustainable Energy Reviews*, *57*, 1580–1595. https://doi.org/10.1016/j.rser.2015.12.147
3. Gurita, N., Fröhling, M., & Bongaerts, J. (2018). Assessing potentials for mobile/smartphone reuse/remanufacture and recycling in Germany for a closed loop of secondary precious and critical metals. *Journal of Remanufacturing*, *8*, 1–22. https://doi.org/10.1007/s13243-018-0042-1
4. OECD Environment Directorate. (2010). *Materials Case Study 1: Critical Metals and Mobile Devices*.
5. UNEP International Resource Panel. (2013). *Global Metal Flows Working Group Report 3: Environmental Risks and Challenges of Anthropogenis Metals Flows and Cycles*.
6. Park, S.-H., Shin, J.-A., Park, H.-H., Yi, G. Y., Chung, K.-J., Park, H.-D., et al. (2011). Exposure to volatile organic compounds and possibility of exposure to by-product volatile organic compounds in photolithography processes in semiconductor manufacturing factories. *Safety and Health at Work*, *2*(3), 210–217. https://doi.org/10.5491/SHAW.2011.2.3.210

7. Banza Lubaba Nkulu, C., Casas, L., Haufroid, V., De Putter, T., Saenen, N. D., Kayembe-Kitenge, T., et al. (2018). Sustainability of artisanal mining of cobalt in DR Congo. *Nature Sustainability*, *1*, 495–504. https://doi.org/10.1038/s41893-018-0139-4
8. Parajuly, K., Kuehr, R., Kumar Awasthi, A., Fitzpatrick, C., Lepawsky, J., Smith, E., et al. (2019). *Future E-Waste Scenarios*. The StEP Initiative, UNU-ViE SCYCLE, and UNEP IETC.
9. Perkins, D. N., Brune Drisse, M.-N., Nxele, T., & Sly, P. D. (2014). E-waste: A global hazard. *Annals of Global Health*, *80*(4), 286–295. https://doi.org/10.1016/j.aogh.2014.10.001
10. Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. *The Global E-Waste Monitor 2020: Quantities, flows and the circular economy potential*. United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam.
11. Kyere, V. N., Greve, K., Atiemo, S. M., Amoako, D., Aboh, I. J. K., Cheabu, B. S. (2018). Contamination and health risk assessment of exposure to heavy metals in soils from informal e-waste recycling site in Ghana. *Emerging Science Journal*, *2*(6), 428–436. https://doi.org/10.28991/esj-2018-01162
12. Nasr, N., Russell, J., Bringezu, S., Hellweg, S., Hilton, B., Kreiss, C., et al. (2018). *Re-defining Value – The Manufacturing Revolution. Remanufacturing, Refurbishment, Repair and Direct Reuse in the Circular Economy. A Report of the International Resource Panel*. United Nations Environment Programme.
13. Romare, M., Harris, S., Zhang, Y., Steen, B., & Hennlock, M. (2021). *Investigating the Potential Circularity of a Phone Using Life Cycle Assessment.* IVL Swedish Environmental Research Institute.
14. European Commission. (2023). *Proposal for a Directive of the European Parliament and of the Council on Common Rules Promoting the Repair of Goods and Amending Regulation*.
15. Ercan, M., Malmodin, J., Bergmark, P., Kimfalk, E., & Nilsson, E. (2016). Life Cycle Assessment of a Smartphone. *Proceedings of ICT for Sustainability 2016*, 124–133. https://doi.org/10.2991/ict4s-16.2016.15
16. Cordella, M., Alfieri, F., & Sanfelix, J. (2021). Reducing the carbon footprint of ICT products through material efficiency strategies: A life cycle analysis of smartphones. *Journal of Industrial Ecology*, *25*(2), 448–464. https://doi.org/10.1111/jiec.13119
17. Ercan, E. M. (2013). *Global Warming Potential of a Smartphone Using Life Cycle Assessment Methodology* [Master's Thesis]. Royal Institute of Technology.
18. Wiche, P., Pequeño, F., & Granato, D. (2022). Life cycle analysis of a refurbished smartphone in Chile. *E3S Web of Conferences*, *349*, 01011. https://doi.org/10.1051/e3sconf/202234901011
19. Pamminger, R., Glaser, S., & Wimmer, W. (2021). Modelling of different circular end-of-use scenarios for smartphones. *International Journal of Life Cycle Assessment*, *26*, 470–482. https://doi.org/10.1007/s11367-021-01869-2
20. Zink, T., Maker, F., Geyer, R., Amirtharajah, R., & Akella, V. (2014). Comparative life cycle assessment of smartphone reuse: Repurposing vs. refurbishment. *International Journal of Life Cycle Assessment*, *19*, 1099–1109. https://doi.org/10.1007/s11367-014-0720-7
21. Proske, M. (2022). How to address obsolescence in LCA studies – Perspectives on product use-time for a smartphone case study. *Journal of Cleaner Production*, *376*, 134283. https://doi.org/10.1016/j.jclepro.2022.134283
22. Schischke, K., Proske, M., Nissen, N. F., & Schneider-Ramelow, M. (2019). Impact of modularity as a circular design strategy on materials use for smart mobile devices. *MRS Energy and Sustainability*, *6*, E16. https://doi.org/10.1557/mre.2019.17
23. Nissen, N. F., Schischke, K., Proske, M., Ballester, M., & Lang, K.-D. (2017). How modularity electronic functions can lead to longer product lifetimes. In C. A. Bakker & R. Mugge (Eds.), *PLATE: Product Lifetimes and The Environment* (Vol. 6, pp. 303–308). IOS Press. https://doi.org/ 10.3233/978-1-61499-820-4-303
24. Tröger, N., Wieser, H., & Hübner, R. (2017). *Smartphones Are Replaced More Frequently than T-Shirts. Patterns of consumer use and reasons for replacing durable goods*. AK Europa.
25. Cordella, M., Alfieri, F., Clemm, C., & Berwald, A. (2021). Durability of smartphones: A technical analysis of reliability and repairability aspects. *Journal of Cleaner Production*, *286*, 125388. https://doi.org/10.1016/j.jclepro.2020.125388
26. Abbondanza, M. N. M., & Souza, R. G. (2019). Estimating the generation of household e-waste in municipalities using primary data from surveys: A case study of Sao Jose dos Campos, Brazil. *Waste Management*, *85*, 374–384. https://doi.org/10.1016/j.wasman.2018.12.040
27. Deutsches Insitut für Normung e.V. (2016). *DIN EN ISO 14040:2006: Umweltmanagement – Ökobilanz – Grundsätze Und Rahmenbedingungen* (in Germany).
28. DIN-Normausschuss Bauwesen. (2023). *Nachhaltigkeit von Bauwerken - Umweltproduktdeklarationen - Grundregeln for Die Produktkategorie Bauprodukte; Deutsche Fassung EN 15804:2012+A2:2019 + AC:2021* (in Germany).
29. Schomberg, A. C., Bringezu, S., Flörke, M., & Biederbick, H. Spatially explicit life cycle assessments reveal hotspots of environmental impacts from renewable electricity generation. *Communications Earth & Environment*, *3*, 197. https://doi.org/10.1038/s43247-022-00521-7
30. Egenolf, V., & Bringezu, S. (2019). Conceptualization of an indicator system for assessing the sustainability of the bioeconomy. *Sustainability*, *11*(2), 443. https://doi.org/10.3390/su11020443

31. Steinmann, Z. J. N., Schipper, A. M., Hauck, M., & Huijbregts, M. A. J. (2016). How Many Environmental Impact Indicators Are Needed in the Evaluation of Product Life Cycles? *Environmental Science & Technology*, 50(7), 3913–3919. https://doi.org/10.1021/acs.est.5b05179
32. Deutsches Insitut für Normung e. V. (2016). *DIN EN ISO 14046:2016-07: Umweltmanagement – Wasser-Fußabdruck – Grundsätze, Anforderungen Und Leitlinien (ISO 14046:2014)* (in Germany).
33. Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., et al. (2021). The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 923–1054). Cambridge University Press. https://doi.org/10.1017/9781009157896.009
34. Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., et al. (2010). *Implementation of Life Cycle Impact Assessment Methods*. Swiss Centre for Life Cycle Inventories.
35. Pimentel, D., Hurd, L. E., Bellotti, A. C., Forster, M. J., Oka, I. N., Sholes, O. D., et al. (1973). Food production and the energy crisis. *Science*, *182*(4111), 443–449. https://doi.org/10.1126/science.182.4111.443
36. Boustead, I., & Hancock, G. F. (1979). *Handbook of Industrial Energy Analysis*. John Wiley & Sons.
37. Sameer, H., Weber, V., Mostert, C., Bringezu, S., Fehling, E., & Wetzel, A. (2019). Environmental Assessment of Ultra-High-Performance Concrete Using Carbon, Material, and Water Footprint. *Materials*, *12*(6), 851. https://doi.org/10.3390/ma12060851
38. Mostert, C., & Bringezu, S. (2019). Measuring Product Material Footprint as New Life Cycle Impact Assessment Method: Indicators and Abiotic Characterization Factors. *Resources*, *8*(2), 61. https://doi.org/10.3390/resources8020061
39. Schomberg, A. C., Bringezu, S., & Flörke, M. (2021). Extended life cycle assessment reveals the spatially-explicit water scarcity footprint of a lithium-ion battery storage. *Communications Earth & Environment*, *2*, 11. https://doi.org/10.1038/s43247-020-00080-9
40. Kaiser, S., Prontnicki, K., & Bringezu, S. (2021). Environmental and economic assessment of global and German production locations for CO2-based methanol and naphtha. *Green Chemistry*, 23, 7659–7673. https://doi.org/10.1039/D1GC01546J
41. Proske, M., Sánchez, D., Clemm, C., & Baur, S.-J. (2020). *Life Cycle Assessment of the Fairphone 3*. Fraunhofer IZM.
42. Sánchez, D., Proske, M., & Baur, S.-J. (2022). *Life Cycle Assessment of the Fairphone 4*. Fraunhofer IZM.
43. Andrae, A. S. G., & Vaija, M. S. (2014). To Which Degree Does Sector Specific Standardization Make Life Cycle Assessments Comparable?—The Case of Global Warming Potential of Smartphones. *Challenges*, *5*(2), 409–429. https://doi.org/10.3390/challe5020409
44. André, H., Ljunggren Söderman, M., & Nordelöf, A. (2019). Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse. *Waste Management*, *88*, 268–279. https://doi.org/10.1016/j.wasman.2019.03.050
45. Jaeger-Erben, M., Wieser, H., Marwede, M., & Hofmann, F. (Eds). (2023). *Durable Economies - Organizing the Material Foundations of Society*. Transcript.
46. Bringezu, S. (2022). *Das Weltbudget. Das Weltbudget* (in Germany). Springer Wiesbaden. https://doi.org/10.1007/978-3-658-37774-8
47. Sameer, H., & Bringezu, S. (2021). Building information modelling application of material, water, and climate footprint analysis. *Building Research & Information*, *49*, 593–612. https://doi.org/10.1080/09613218.2020.1864266
48. Peters, E.-J. (2022). *The Economic and Ecological Impact of Shifting to a Modular Smartphone Design* [Bachelor's Thesis]. University of Twente.
49. Haucke, F. V. (2018). Smartphone-enabled social change: Evidence from the Fairphone case? *Journal of Cleaner Production*, *197*, 1719–1730. https://doi.org/10.1016/j.jclepro.2017.07.014
50. Revellio, F., Shi, L., Hansen, E. G., & Chertow, M. (1 September 2020). *Sustainability paradoxes for product modularity: the case of smartphones*. Electronics Goes Green 2020+, Berlin, Germany.
51. Schischke, K., Proske, M., Pamminger, R., Glaser, S., Nissen, N. F., & Schneider-Ramelow, M. (2022). The "Environmental Activation Energy" of Modularity and Conditions for an Environmental Payback. In Z. S. Klos, J. Kalkowska, & J. Kasprzak (Eds.), *Towards a Sustainable Future - Life Cycle Management* (pp. 15–25). Springer, Cham. https://doi.org/10.1007/978-3-030-77127-0_2
52. Mutchler, L. A., Shim, J. P., & Ormond, D. K. (2011). Exploratory Study on Users' Behavior: Smartphone Usage. *AMCIS 2011 Proceedings - All Submissions*, 418.
53. Njoku, A., Agbalenyo, M., Laude, J., Ajibola, T. F., Attah, M. A., & Sarko, S. B. (2024). Environmental Injustice and Electronic Waste in Ghana: Challenges and Recommendations. *International Journal of Environmental Research and Public Health*, *21*(1), 25. https://doi.org/10.3390/ijerph21010025
54. Baldé, C. P., Kuehr, R., Yamamoto, T., McDonald, R., D'Angelo, E., Althaf, S., et al. (2024). *Global E-waste Monitor 2024*. International Telecommunication Union (ITU) and United Nations Institute for Training and Research (UNITAR).
55. Deng, Y., Wu, W., Zhang, X., Li, S., Song, X., & Wang, J. (2024). Overview of China's Waste Electrical and Electronic Equipment Recycling in the Last Two Decades. *Sustainability*, *16*(23), 10683. https://doi.org/10.3390/su162310683
56. von Gries, N., & Bringezu, S. (2022). Using New Spare Parts for Repair of Waste Electrical and Electronic Equipment? The Material Footprint of Individual Components. *Resources*, *11*(2), 24. https://doi.org/10.3390/resources11020024

57. Ljunggren Söderman, M., & André, H. (2019). Effects of circular measures on scarce metals in complex products – Case studies of electrical and electronic equipment. *Resources, Conservation and Recycling*, *151*, 104464. https://doi.org/10.1016/j.resconrec.2019.104464
58. Mestanza-Ramón, C., Cuenca-Cumbicus, J., D'Orio, G., Flores-Toala, J., Segovia-Cáceres, S., Bonilla-Bonilla, A., et al. (2022). Gold Mining in the Amazon Region of Ecuador: History and a Review of Its Socio-Environmental Impacts. *Land*, *11*(2), 221. https://doi.org/10.3390/land11020221